# Handbook for Designing Roadways for the Aging Population

Highway-Rail Grade Crossings

Intersections

Roadway Segments

Interchanges


Construction/ Work Zones

U.S. Department of Transportation
**Federal Highway Administration**

# Foreword

The proportion of the United States population age 65 and over will increase significantly in the coming decades. The effects of aging on people as drivers and pedestrians are highly individual. Challenges that may impact people as they age include declining vision, decreased flexibility and psychomotor performance, and changes in perceptual and cognitive performance. Design practices that explicitly recognize these changes will better serve this growing segment of the nation's population.

This *Handbook for Designing Roadways for the Aging Population* provides practitioners with a practical information source that links aging road user performance to highway design, operational, and traffic engineering features. This *Handbook* supplements existing standards and guidelines in the areas of highway geometry, operations, and traffic control devices.

The information in this *Handbook* should be of interest to highway designers, traffic engineers, and highway safety specialists involved in the design and operation of highway facilities. In addition, this *Handbook* will be of interest to researchers concerned with issues of aging road user safety and mobility.

The *Handbook* is also available online at http://safety.fhwa.dot.gov/older_users/#training.

Tony Furst
Associate Administrator for Safety
Federal Highway Administration

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**16. Abstract**

The original *Older Driver Highway Design Handbook* was published by FHWA in 1998 (FHWA-RD-97-135). The 2nd edition, titled *Highway Design Handbook for Older Drivers and Pedestrians* (FHWA-RD-01-103) was published in 2001. This 3rd edition, under a new title, incorporates new research findings and treatments to improve the safety of the transportation system for the aging population.

The *Handbook* is divided into three sections. The first section explains how to use the *Handbook* to select treatments to address problems for aging drivers and pedestrians. The second section includes treatments for 51 proven and promising traffic control and design elements distributed among five categories: Intersections, Interchanges, Roadway Segments, Construction/Work Zones, and Highway-Rail Grade Crossings. The final section of the *Handbook* includes the rationale and supporting evidence for the treatments.

A website including all of the content of the *Handbook* is available at http://safety.fhwa.dot.gov/older_users/#training.

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# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yard | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| | | NOTE: volumes greater than 1000 L shall be shown in $m^3$ | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| $^oF$ | Fahrenheit | 5 (F-32)/9 or (F-32)/1.8 | Celsius | $^oC$ |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |

## APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.314 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| $^oC$ | Celsius | 1.8C+32 | Fahrenheit | $^oF$ |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

# Preface

The increasing numbers and percentages of aging persons using our nation's streets and highways in the decades ahead will pose many challenges to transportation engineers who focus on safety and operational efficiency. According to the Administration on Aging, the 65-and-older age group, which numbered 39.6 million in the United States in 2009, will grow to more than 55 million in 2020. By 2030, there will be approximately 72.1 million aging persons, accounting for roughly one-fifth of the population of driving age in this country. In effect, for many aspects of road planning and design, the "design driver" and the "design pedestrian" of the early 21st century will likely be 65 or over.

There are important consequences of these changing demographics, and life for aging persons depends to an extraordinary degree on remaining independent. Independence requires mobility. In our society the overwhelming choice of mobility options is the personal automobile. Other mobility options that may be utilized include public transit and walking. This means that there will be a steadily increasing proportion of drivers and pedestrians who experience declining vision; slowed decision-making and reaction times; exaggerated difficulty when dividing attention between traffic demands and other important sources of information; and reductions in strength, flexibility, and general fitness.

In a proactive response to this pending surge in aging road users, the Federal Highway Administration (FHWA) published the *Older Driver Highway Design Handbook* in 1998. The 1998 *Handbook* provided highway designers and engineers with the first practical information source linking age-related declines in functional capabilities to enhanced design, operational, and traffic engineering treatments, keyed to specific roadway features. Experience with these enhanced treatments, including extensive feedback from local and State-level practitioners, led to the release of the *Highway Design Handbook for Older Drivers and Pedestrians* in 2001. Now, a third edition of this resource has been prepared, under a new title, which incorporates new research, expands the range of applications covered by the *Handbook*, and introduces format changes—including a web-based version—that will facilitate access and use by engineering professionals to improve our streets and highways in the years ahead.

Part I of this *Handbook* retains its focus on five broad categories of roadway features, each containing a number of specific design elements for which guidance is presented. The top priority is *intersections*, reflecting aging drivers' most serious and enduring crash problem area, as well as the greatest exposure to risk for pedestrians. Next, well-documented difficulties with merging/weaving and lane changing maneuvers focus attention on *interchanges*. *Roadway segments,* with an emphasis on curves and passing zones, plus highway *construction/work zones*, are included due to heightened tracking (steering) demands that may increase a driver's workload along with an increased potential for unexpected events that require a rapid response. Finally, *highway-rail grade crossings* merit consideration as sites where conflicts are rare, and thus unexpected, and where problems of detection (with passive controls) may be exaggerated due to sensory losses with advancing age.

The treatments presented in Part I are followed by a more lengthy section, Part II, presenting the rationale and supporting evidence. Within each of these two major *Handbook* sections, material is organized in terms of five subsections, corresponding to the categories of roadway features noted above. Preceding the treatments, a chapter titled "How To Use This *Handbook*" explains codes used throughout the document to cross-reference the *Manual on Uniform Traffic Control Devices* (*MUTCD)*, *A Policy on Geometric Design of Highways and Streets* (the *Green Book)* and other manuals and guides. In addition, a guide for interpreting graphics used in the *Handbook* and a table for translating speeds and distances into "preview times" for driver decision and response selection are presented; and, a structured approach to help engineering professionals decide when to implement *Handbook* treatments is described. A supplementary discussion about how to determine the visibility of roadway elements is appended to this edition of the *Handbook.* The *Handbook* concludes with a glossary providing definitions of selected terms and a reference list.

Most of the treatments in this *Handbook* are based on supporting evidence drawn from a comprehensive review of field and laboratory research addressing human factors and highway safety. The supporting information presented in Part II represents the latest relevant information and data available to the authors at the time the document was assembled. Some research findings have been carried forward from previous *Handbooks*, while other findings are new since the release of the 2001 *Handbook*. A number of additional treatments were considered but ultimately dropped or deferred because of gaps or deficiencies in the supporting studies. This edition also includes some "Promising Practices"—treatments that are being used by one or more agencies, which although they have not been evaluated formally, are generally believed to benefit the aging population of roadway users based on subjective assessment by the staff participating in the development of this *Handbook*. This conservative approach also dictated that the *Handbook's* treatments relate to the demonstrated performance deficits of *normally aging* drivers and pedestrians. It deserves mention that diminished capabilities that result from the onset of Alzheimer's disease and related dementias, which may afflict over 10 percent of those age 65 and older and over 40 percent of those age 85 and older, are not explicitly targeted in these guidelines. Neither are the compromises in performance that are associated with drowsiness, fatigue or distraction.

This resource can be applied preemptively to enhance safety wherever there are aging road users in a given jurisdiction, or it may be employed primarily as a "problem solver" at crash sites. The implementation of these treatments will translate into real gains in safety and mobility for our nation's aging citizens, and indeed for all users of our surface transportation system. **Readers of this *Handbook* must note, however, that the treatments presented in this *Handbook* do not constitute a new standard of required practice. The final decision about when and where to apply the treatments presented in this *Handbook* remains at the discretion of State and local design and engineering professionals.**

# Acknowledgements

The quality and usefulness of the *Handbook for Designing Roadways for the Aging Population* is a direct result of the many highway engineering practitioners and researchers who provided their comments and suggestions to the authors of this edition of the *Handbook*, as well as the previous two editions. The authors wish to acknowledge the following individuals for their assistance and support in making this third edition a success:

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# Table of Contents

# Abbreviations and Acronyms

| | |
|---|---|
| **AAAFTS** | American Automobile Association Foundation for Traffic Safety |
| **AADT** | annual average daily traffic |
| **AASHTO** | American Association of State and Highway Transportation Officials |
| **ASTM** | American Society for Testing and Materials |
| **ATSSA** | American Traffic Safety Services Association |
| **cd** | candela |
| **CIE** | Commission Internationale de l'Eclairage |
| **CIL** | complete interchange lighting |
| **CMS** | changeable message sign |
| **CSSB** | concrete safety-shaped barrier |
| **DS** | diverge steering |
| **DSD** | decision sight distance |
| **FARS** | Fatality Analysis Reporting System |
| **FHWA** | Federal Highway Administration |
| **fL** | footlambert |
| **GSA** | gap search and acceptance |
| **IA** | initial acceleration |
| **IIHS** | Insurance Institute for Highway Safety |
| **ISD** | intersection sight distance |
| **ISBL** | in-service brightness level |
| **ISTEA** | Intermodal Surface Transportation Efficiency Act |
| **ITE** | Institute of Transportation Engineers |
| **LI** | legibility index |
| **LPI** | leading pedestrian interval |
| **MOE** | measure of effectiveness |
| **MRVD** | minimum required visibility distance |
| **MSC** | merge steering control |
| **MUTCD** | *Manual on Uniform Traffic Control Devices for Streets and Highways* |
| **NCHRP** | National Cooperative Highway Research Program |
| **NHTSA** | National Highway Traffic Safety Administration |
| **NTOR** | no turn on red |

| | |
|---|---|
| **NTSB** | National Transportation Safety Board |
| **PIL** | partial interchange lighting |
| **PMD** | post-mounted delineator |
| **PRT** | perception-reaction time |
| **RT** | reaction time |
| **RPM** | raised pavement markers |
| **RTOR** | right turn on red |
| **SC** | steering control |
| **SCL** | speed-change lane |
| **SSD** | stopping sight distance |
| **STV** | small target visibility |
| **SU** | single unit (truck) |
| **TCD** | traffic control device |
| **TRB** | Transportation Research Board |
| **TVA** | transient visual adaptation |
| **TWLTL** | two-way, left-turn lane |
| **VC** | visual clear |

## CHAPTER 1

# How to Use this *Handbook*

## Organization of the *Handbook*

The *Handbook* consists of two parts. Part I includes recommended treatments for 33 traffic control or geometric design elements divided among five categories. The five categories of treatment are as follows:

- Intersections,
- Interchanges,
- Roadway Segments,
- Construction/Work Zones, and
- Highway-Rail Grade Crossings.

These treatments are recommended because they have been shown through research to be a benefit to the aging road user. In addition, 18 “Promising Practice” treatments are included. These are treatments being utilized by transportation agencies that should benefit aging road users as determined by a subjective assessment by staff participating on the development of this *Handbook*. Current trends indicate these practices have a positive impact on aging road user safety. These promising treatments are placed at the end of each category to which they apply.

Part II includes the rationale and supporting evidence for each of the treatments. This part of the *Handbook* is also divided into these same five categories.

The treatments for each design element are presented as shown in Figure 1 and consist of the following components:

**Category** — At the top of each page is a header showing the category of treatment (i.e., Intersections, Interchanges, Roadway Segments, Construction Work Zones and Highway-Rail Grade Crossings).

**Design Element** — Each element has a unique number for quick reference to the Table of Contents.

**Treatments** — Each treatment within a design element is clearly identified by a unique letter, followed by a recommendation on how that treatment should be used.

**Figure(s)** — Many of the concepts described in the treatments are illustrated in figures—as photographs, figures extracted from the MUTCD or other publications, or as drawings. **The drawings are for illustrative purposes only; they are not to scale and should not be used for design purposes. It is important to note that the lettering styles, arrows and symbols used in this Handbook are not always consistent with those prescribed in the MUTCD**. When employing treatments included in this *Handbook*, only MUTCD-approved lettering styles, arrows and symbols should be used. Additionally, any highway agency wishing to implement a treatment that has not been

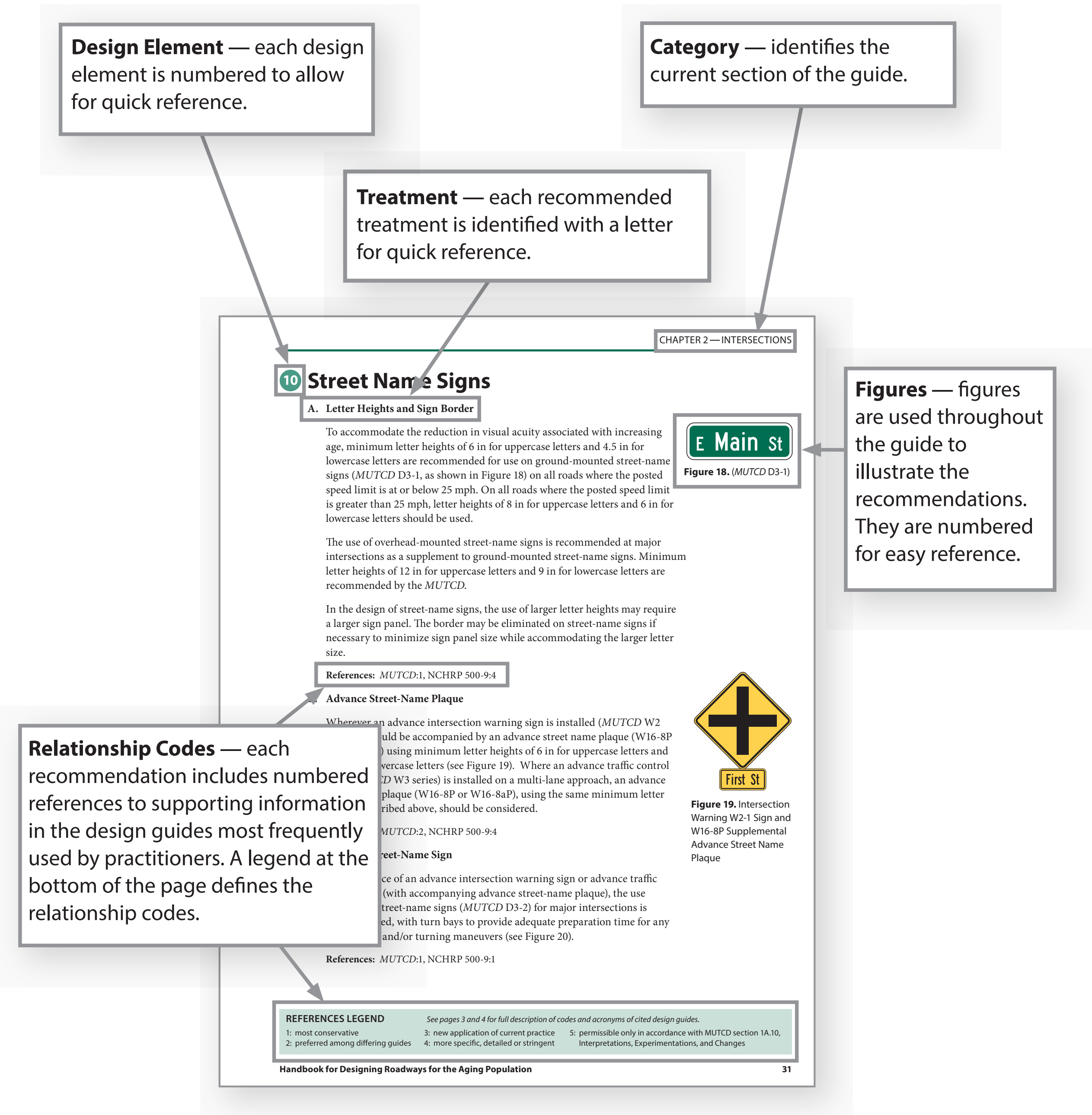


**Figure 1.** Elements included for each *Handbook* treatment

included in the most recent edition of the MUTCD, and thus denoted by a relationship code of "5" (see Table 1), must request experimentation approval from the FHWA.

**References and Relationship Codes** — References placed below each treatment indicate its relationship (by a numeric relationship code) to the design guides most frequently referenced by practitioners, as determined by the *Handbook* authors. A legend is provided at the bottom of each treatment page to remind users (in an abbreviated format) of the meaning of the numerical values. The complete definitions for these relationship codes are provided in Table 1.

**Table 1.** Definitions for the relationship codes between the recommendations and existing design guides or other manuals.

| Code | Definition |
|---|---|
| 1 | *Handbook* treatment selects the most conservative design value among present options in the standard manual/ guideline. (*Example*: Using a larger sign size identified as an "option" in the *MUTCD*). |
| 2 | *Handbook* treatment indicates the preferred design value where a discrepancy exists among two or more manuals/ guidelines. (*Example*: Limit skew to 75° as per TEH instead of 60° as per *Green Book*). |
| 3 | *Handbook* treatment extends a current practice to a new application or operation. (*Example*: Use of fluorescent sheeting on wrong-way control signing, for increased conspicuity). |
| 4 | *Handbook* treatment advances a specific design value or concept where only general guidance now exists, or provides more detailed or more stringent design criteria than are currently specified. (*Example*: It is recommended that an advance street-name plaque be used wherever an advance intersection warning sign is installed. The use of this supplemental plaque is an option per engineering judgment in the 2009 *MUTCD*.) |
| 5 | *Handbook* treatment is permissible at this time only in accordance with the provisions of *MUTCD* Section 1A.10, *Interpretations, Experimentations, Changes and Interim Approvals*. These treatments represent advances in technology which research indicates will result in improved safety and efficiency of operations. (Example: It is recommended that the Roundabout Circulation Plaque (R6-5P) be placed immediately below the R1-2 Yield sign on both sides of the road at each entrance to a roundabout.) |

The design guides, manuals, and other resources referenced by the relationship codes in the treatments and throughout the *Handbook* are shown in Table 2. The most current published edition of each guide was consulted in the preparation of the *Handbook*, with the exceptions as noted. The latest version of the MUTCD can be accessed at http://mutcd.fhwa.dot.gov.

In addition to the design guides shown in Table 2, there are a number of other resources and supporting tools available to assist in improving the roadway environment for aging (and all) road users. Some key resources include:

- ***Interactive Highway Safety Design Model (IHSDM):*** A suite of software analysis tools for evaluating safety and operational effects of geometric design decisions on two-lane rural highways (http://www.fhwa.dot.gov/research/tfhrc/projects/safety/comprehensive/ihsdm/).
- ***Highway Safety Manual (HSM), 1st Edition, Volumes 1, 2 and 3, 2010:*** This resource provides safety knowledge and tools to facilitate improved decision-making based on safety performance (http://www.highwaysafetymanual.org).
- ***SafetyAnalyst:*** Analytical tools for use in the decision-making process to identify and manage a system-wide program of site-specific improvements to enhance highway safety by cost-effective means (http://www.safetyanalyst.org/).
- ***Human Factors Guidelines for Road Systems, NCHRP Report 600:*** This report is designed to help non-experts in human factors to consider more effectively the roadway user's capabilities and limitations in the design and operation of highway facilities (http://www.trb.org/Main/Blurbs/167909.aspx).
- ***NCHRP Report 500:*** Guidance for Implementation of the AASHTO Strategic Highway Safety Plan: A series of guides to assist transportation agencies in reducing specific types of crashes in targeted emphasis areas outlined in the AASHTO Strategic Highway Safety Plan (http://www.trb.org/main/blurbs/152868.aspx).

**Table 2.** Abbreviations used for the references cited in the recommendation chapters.

| Abbreviation Key | Reference Citation |
|---|---|
| *Green Book* | *A Policy on Geometric Design of Highways and Streets (Green Book)*. American Association of State Highway and Transportation Officials, 2011. |
| HCM | *Highway Capacity Manual*. Transportation Research Board, 2010. |
| MUTCD | *Manual on Uniform Traffic Control Devices for Streets and Highways*. (2009 Edition). Federal Highway Administration, 2009. |
| NCHRP 279 | *Intersection Channelization Design Guide*, (NCHRP Report 279). National Cooperative Highway Research Program, 1985. |
| NCHRP 500-9 | *Guidance for Implementation of the AASHTO Strategic Highway Safety Plan, Volume 9: A Guide for Reducing Collisions Involving Older Drivers*, (NCHRP Report 500, Volume 9). National Cooperative Highway Research Program, 2004. |
| NCHRP 672 | NCHRP Report 672, *Roundabouts: An Informational Guide* (Second edition). |
| NCHRP 674 | *Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities*, (NCHRP Report 674). National Cooperative Highway Research Program, 2010. |
| RLH | *FHWA Lighting Handbook*, Federal Highway Administration, 2012. |
| RRX | *Railroad-Highway Grade Crossing Handbook*, Revised 2nd Edition. Federal Highway Administration, 2007. |
| TEH | *Traffic Engineering Handbook*, 5th Edition. Institute of Transportation Engineers, 2009. |

- ***Pedestrian Road Safety Audit Guidelines and Prompt Lists:*** A guide for conducting formal safety examinations of future roadway projects or in-service facilities with a focus on identifying and addressing pedestrian safety concerns (http://www.walkinginfo.org/library/details.cfm?id=3955). Similarly, a guide is available for conducting more general road safety audits (http://safety.fhwa.dot.gov/rsa/).

- ***AASHTO Guide for the Planning, Design, and Operation of Pedestrian Facilities:*** Guidelines are included for the construction and design of sidewalks, street crossings, and many aspects of pedestrian trails. The document is available for purchase at https://bookstore.transportation.org/.

- ***PEDSAFE:*** Pedestrian Safety Guide and Countermeasure Selection System: This interactive system is intended to help practitioners choose the most appropriate engineering, education, and enforcement countermeasures to address pedestrian safety and mobility issues (www.walkinginfo.org/pedsafe).

For additional resources, visit the FHWA Office of Safety web site at http://safety.fhwa.dot.gov/.

# Time-Speed-Distance Table

A number of treatments presented in the *Handbook* identify the placement of a device or treatment in terms of the preview time that should be provided to the driver for its application. These values are typically expressed in seconds, such that the recommended placement of the device or treatment depends upon the speed at which traffic is moving. To facilitate application of *Handbook* treatments of this nature, Table 3 provides the advance placement distance needed to achieve a desired preview time at a particular operating speed.

**Table 3.** Advance placement distances required to achieve desired preview times at designated operating speeds.

| Preview Time (seconds) | Operating Speed (mph) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 |
| 2.5 | 110 | 128 | 147 | 165 | 183 | 202 | 220 | 238 | 257 | 275 | 293 |
| 3.0 | 132 | 154 | 176 | 198 | 220 | 242 | 264 | 286 | 308 | 330 | 352 |
| 3.5 | 154 | 180 | 205 | 231 | 257 | 282 | 308 | 334 | 359 | 385 | 411 |
| 4.0 | 176 | 205 | 235 | 264 | 293 | 323 | 352 | 381 | 411 | 440 | 469 |
| 4.5 | 198 | 231 | 264 | 297 | 330 | 363 | 396 | 429 | 462 | 495 | 528 |
| 5.0 | 220 | 257 | 293 | 330 | 367 | 403 | 440 | 477 | 513 | 550 | 587 |
| 5.5 | 242 | 282 | 323 | 363 | 403 | 444 | 484 | 524 | 565 | 605 | 645 |
| 6.0 | 264 | 308 | 352 | 396 | 440 | 484 | 528 | 572 | 616 | 660 | 704 |
| 6.5 | 286 | 334 | 381 | 429 | 477 | 524 | 572 | 620 | 667 | 715 | 763 |
| 7.0 | 308 | 359 | 411 | 462 | 513 | 565 | 616 | 667 | 719 | 770 | 822 |
| 7.5 | 330 | 385 | 440 | 495 | 550 | 605 | 660 | 715 | 770 | 825 | 880 |
| 8.0 | 352 | 411 | 469 | 528 | 587 | 645 | 704 | 763 | 822 | 880 | 939 |

# Knowing When to Implement these Recommendations

Implementation of the treatments in this Handbook provide benefits for design challenges that disproportionately affect aging road users due to changes in functional ability experienced with normal aging. These may be most urgently needed where a crash problem with aging drivers or pedestrians has already been demonstrated; however, the greater benefit arguably lies in designing safer new roads and identifying and modifying problems with existing roads before statistics reveal a crash problem. Not only does this practice minimize the risk and severity of crashes, it minimizes the need for remedial works after construction, thus reducing the whole-life cost of projects. This is the central premise of the road safety audit process supported by FHWA and it holds the key for applying the *Handbook* treatments as well.

The engineering enhancements described in this document should benefit all road users. Special justification may be required for implementation of *Handbook* practices. This section was developed to support engineering judgment in this regard. It suggests a three-step procedure using checklist responses plus brief written comments, as explained below. A set of optional worksheets for documenting each step is also provided.

**Step 1: Problem Identification** [*see Project Review Worksheet on* *page 7*]

During the planning stage for each project, practitioners are asked to determine whether a problem with the safe use of the facility by aging road users currently exists or may reasonably be expected based on current and projected use patterns. Using the first worksheet that follows this discussion, problem identification can be accomplished by checking YES or NO to the following four questions:

Q1. "Is there a demonstrated crash problem with aging road users?"

Q2. "Has any aspect of design or operations at the project location been associated with complaints to local, municipal, or county-level officials from aging road users or are you aware of a potential safety concern for aging road users at this location, either through observation, agency documentation, or engineering judgment?"

Q3. "Is this project located on a direct link to a travel origin or destination for which, in the judgment of local planning/zoning authorities or other local officials, aging persons constitute a significant proportion of current users?"

Q4. "Is the project located in a census tract or zip code designation that has experienced an increase in the proportion of (non-institutionalized) residents age 65 and older, for the most recent period in which the population was sampled?"

To answer these questions, practitioners will need to obtain reliable crash data from the appropriate division or bureau of their departments of transportation. At least the three most recent years for which data are available should be examined, and the data should be sorted by age, at a minimum. Sources of information outside of the State DOT also may be required to answer the problem identification questions. Potential sources include, but are not limited to:

- Local government officials/Board of Supervisors/city council representatives.
- Local and State police.
- The (State) Department of Aging and/or county Area Agency on Aging.
- The (State) Department of Health and Human Services and Department of Public Welfare.
- The regional planning commission.

**Step 2: Identification of Design Elements and Treatments** [*see worksheet on* *page 9*]

For each project where a practitioner has answered YES to one or more of the problem identification questions in Step 1, the next step is consider all categories (i.e., intersection, interchanges, roadway segments, construction/work zones, and highway-rail grade crossings) on the facility. Then, for each category, consider each design element and treatment that could be applied. For each one, the engineer should indicate whether the

# Project Review Worksheet

Project Title/ID: ____________________________________________________________

Person Completing Worksheet: ________________________________________________ Date: ________________________

| Q1. | "Is there a demonstrated crash problem with aging road users?" | YES ☐ | NO ☐ |
|---|---|---|---|
| | Source(s) | Date of Contact | |
| | | | |
| | | | |

| Q2. | "Has any aspect of design or operations at the project location been associated with complaints to local, municipal, or county-level officials from aging road users or are you aware of a potential safety concern for aging road users at this location, either through observation, agency documentation, or engineering judgment?" | YES ☐ | NO ☐ |
|---|---|---|---|
| | Source(s) | Date of Contact | |
| | | | |
| | | | |

| Q3. | "Is this project located on a direct link to a travel origin or destination for which, in the judgment of local planning/zoning authorities or other local officials, aging persons constitute a significant proportion of current users?" | YES ☐ | NO ☐ |
|---|---|---|---|
| | Source(s) | Date of Contact | |
| | | | |
| | | | |

| Q4. | "Is the project located in a census tract or zip code designation that has experienced an increase in the proportion of (non-institutionalized) residents age 65 and older, for the most recent period in which the population was sampled?" | YES ☐ | NO ☐ |
|---|---|---|---|
| | Source(s) | Date of Contact | |
| | | | |
| | | | |

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recommended practice differs from standard State or local practices, and if yes, what additional benefits are expected to result from implementing the applicable *Handbook* treatment(s). One possible example of how such worksheet entries could be made is shown in Table 4.

**Table 4.** Example of Completed Design Elements and Treatments Worksheet.

| Category | Design Element | Applicable *Handbook* Treatment | Differs From Existing State or Local Practice? | | If YES... | |
|---|---|---|---|---|---|---|
| | | | NO | YES | Explain Difference | Identify Expected Benefits |
| Intersections | 1. Intersecting Angle (Skew) | (1C) Skewed Signalized Intersection | | ✔ | According to MUTCD warrants, there is “adequate” sight distance and fewer than 3 RTOR crashes annually on approach. | Should reduce the difficulty for aging drivers to check for approaching traffic, and also reduce aggressive behavior of following drivers who don’t accept an aging driver’s decision not to turn on red. |
| Intersections | 10. Street-Name Signs | (10A) Letter Heights and Sign Border | ✔ | | | |
| Intersections | 16. Roundabouts | (16C) Splitter Islands | ✔ | | | |
| Intersections | 24. Flashing Yellow Arrow | (Promising Practice for permissive left turns) | | ✔ | Current practice uses a green ball for permissive left turns. | Should improve the ability of aging drivers to correctly recognize when permissive left turns are allowed. |
| Construction/ Work Zones | 43. Signing and Advance Warning | (43C) Sign Sheeting | ✔ | | | |

**Step 3: Implementation Decision** [*see worksheet on page 10*]

To begin Step 3, each *Handbook* treatment identified as a candidate for implementation in Step 2 should be properly referenced [e.g., 5D(1)]. Next, any factors relating to increased costs (for an enhanced treatment), added approvals that may be needed, or any other special considerations that impact implementation may be noted in separate columns on the worksheet. The final step is then to proceed to an implementation decision. This is recorded as a judgment by the engineer as to whether implementation of the candidate countermeasure is recommended. The engineer’s judgment is indicated by a check in the space next to YES or NO in the last column on the worksheet, accompanied by his/her initials for verification. Additional comments should be entered as deemed appropriate.

# Identification of Design Elements and Treatments Worksheet

Project Title/ID: ______________________________

Person Completing Worksheet: ______________________________ Date: ______________

Identify design elements for which a treatment exists in the *Handbook* and the applicable treatments. Then, (a) describe differences between the treatment and standard practice, and (b) list benefits expected to result from implementing the *Handbook*.

| Category | Design Element | Applicable *Handbook* Treatment | Differs From Existing State or Local Practice? | | If YES... | |
|---|---|---|---|---|---|---|
| | | | NO | YES | Explain Difference | Identify Expected Benefits |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |

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# Implementation Worksheet

Project Title/ID: ______________________________________________

Person Completing Worksheet: ______________________________ Date: ______________

List each treatment identified as a candidate for implementation. Document whether additional approval is needed (i.e., Environmental, Regulatory, etc.), and whether increased costs or other special considerations may affect implementation. Based on these considerations, decide whether implementation can be recommended, add your initials, and add supplemental comments as appropriate.

| Treatment | Implementation Considerations | | | Implementation Recommended? |
|---|---|---|---|---|
| | **Added Costs?** | **Added Approvals?** | **Other** | |
| | | | | NO _______ Initials _________<br>YES ______<br>Comments: |
| | | | | NO _______ Initials _________<br>YES ______<br>Comments: |
| | | | | NO _______ Initials _________<br>YES ______<br>Comments: |

PART I

# Treatments

## Overview

This section of the *Handbook* is organized in the following categories:

Chapter 2 — Intersections,

Chapter 3 — Interchanges,

Chapter 4 — Roadway Segments,

Chapter 5 — Construction/Work Zones, and

Chapter 6 — Highway-Rail Grade Crossings.

Within each chapter (category), the design elements being presented are listed. This listing is then followed by a concise discussion summarizing the key issues for the aging population. Then, for each design element, the treatments being recommended are presented. After all of the numbered design elements are presented, then the "Promising Practice" treatments are provided. These are treatments that designers and engineers should consider, recognizing that these are being used by one or more agencies, which, though they have not been evaluated formally, are generally believed to benefit the aging population based on a subjective assessment by staff participating in the development of the *Handbook*.

# CHAPTER 2
# Intersections

This section of the *Handbook* provides treatments for 16 different design elements in order to accommodate the needs and enhance the performance of road users with age-related diminished capabilities as they approach and negotiate intersections. Also, after the last element, eight additional promising practices are provided. Drawings are for illustrative purposes only; they are not to scale and should not be used for design purposes.

## Proven Practices

1. Intersecting Angle (Skew)
2. Receiving Lane (Throat) Width
3. Channelization
4. Intersection Sight Distance
5. Offset Left-Turn Lanes
6. Delineation of Edge Lines and Curbs
7. Curb Radius
8. Left-Turn Traffic Control for Signalized Intersections
9. Right-Turn Traffic Control for Signalized Intersections
10. Street Name Signs
11. Stop and Yield Signs
12. Lane Assignment on Intersection Approach
13. Traffic Signals
14. Intersection Lighting
15. Pedestrian Crossings
16. Roundabouts

## Promising Practices

17. Right Turn Channelization Design
18. Combination Lane-Use/Destination Overhead Guide Signs
19. Signal Head Visibility
20. High Visibility Crosswalks
21. Supplemental Pavement Markings for Stop and Yield Signs
22. Reduced Left-Turn-Conflict Intersections
23. Accessible Pedestrian Signal (APS) Treatments
24. Flashing Yellow Arrow

The single greatest concern in accommodating aging road users, both drivers and pedestrians, is the ability of these persons to negotiate intersections safely. For at least two decades, safety experts have keyed on relationships of age and road user type (driver or pedestrian) to understand injury and fatal crash experience at intersections in the United States. The findings of one widely cited analysis of nationwide crash data (Hauer, 1988) are shown in Figure 2.

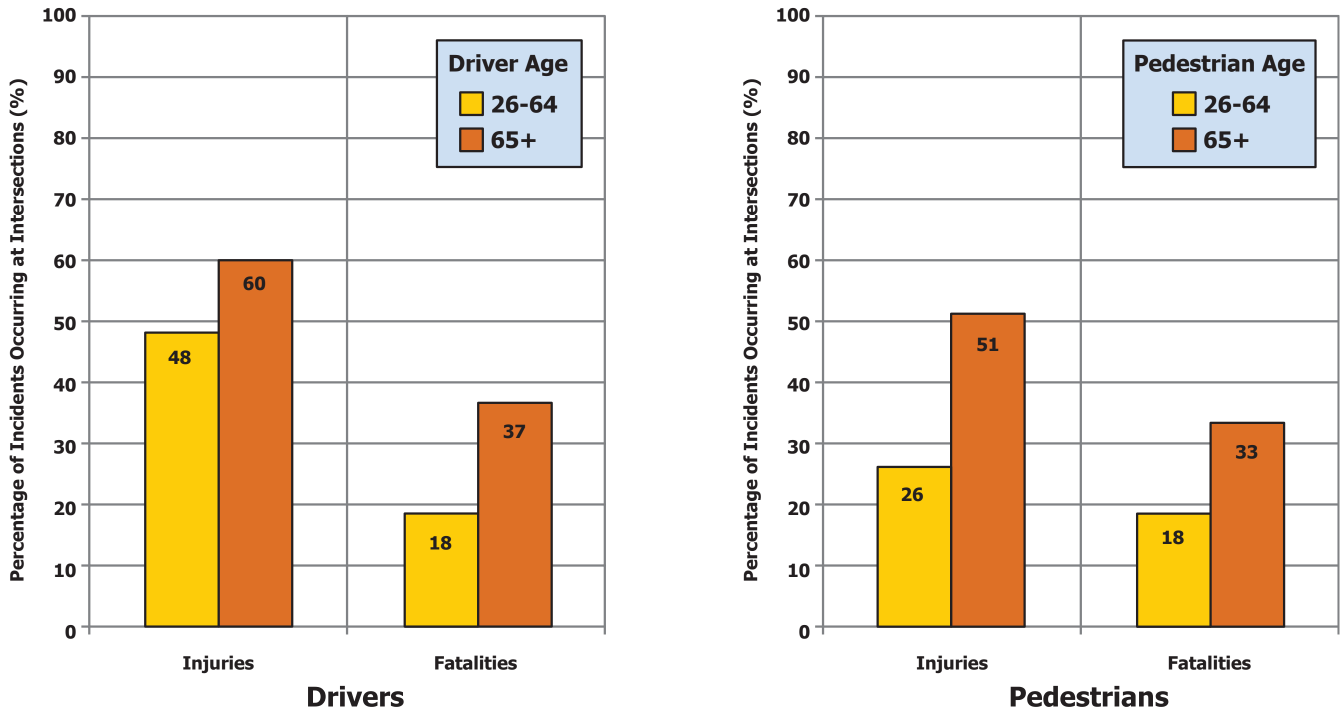


**Figure 2.** Percentage of crashes involving drivers and pedestrians by age at intersections (Hauer, 1988)

The figure illustrates that aging drivers and aging pedestrians are involved in a higher percentage of injury and fatal incidents at intersections.

These same relationships endure today. A higher proportion of passenger vehicle drivers age 70 and older are involved in fatal multiple-vehicle crashes at intersections (40%) than drivers younger than age 70 (22%) (IIHS, 2007). While the number of fatalities, both overall and among aging road users, has declined in recent years, people age 65 and older are still involved in a disproportionate share of fatalities compared to the population as a whole (see Table 5). The number of aging drivers has increased substantially, making up a larger share of the driving population. Therefore, while people age 65 and older make up about 13 percent of the nation's population, they represent about 16 percent of drivers, 16 percent of driver fatalities, and 19 percent of pedestrian fatalities (FARS, 2013). These findings reinforce a long-standing recognition that driving situations involving complex speed-distance judgments under time constraints—the typical scenario for intersection operations—are more problematic for aging road users than for their younger counterparts. Other studies within the large body of evidence showing dramatic increases in intersection crash involvements as driver age increases have associated specific crash types and vehicle movements with particular age groups, linked in some cases to the driving task demands for a given maneuver (Campbell, 1993; Council and Zegeer, 1992; Staplin and Lyles, 1991).

Complementing crash analyses and observational studies with subjective reports of intersection driving difficulties, a statewide survey of 664 aging drivers by Benekohal, et al. (1992) found that the following activities become more difficult for drivers as they grow older (with proportion of drivers responding in parentheses):

- Reading street signs in town (27 percent).
- Driving across an intersection (21 percent).

**Table 5.** Involvement of the Older Population in Traffic Fatalities by Gender, 2002 and 2011 (FARS, 2013)

| | 2002 | | | 2011 | | | Percentage Change, 2002–2011 | |
|---|---|---|---|---|---|---|---|---|
| | Total | Age 65+ | Percentage of Total | Total | Age 65+ | Percentage of Total | Total | Age 65+ |
| **Population (Thousands)** | | | | | | | | |
| Total | 287,625 | 35,522 | 12.4 | 311,592 | 41,394 | 13.3 | 8 | 17 |
| Male | 141,231 | 14,764 | 10.5 | 153,291 | 17,943 | 11.7 | 9 | 22 |
| Female | 146,395 | 20,758 | 14.2 | 158,301 | 23,451 | 14.8 | 8 | 13 |
| **Drivers Involved in Fatal Crashes** | | | | | | | | |
| Total* | 58,113 | 6,323 | 10.9 | 43,668 | 5,469 | 12.5 | -25 | -14 |
| Male | 42,377 | 4,340 | 10.2 | 31,806 | 3,769 | 11.8 | -25 | -13 |
| Female | 14,999 | 1,982 | 13.2 | 11,209 | 1,700 | 15.2 | -25 | -14 |
| **Driver Fatalities** | | | | | | | | |
| Total* | 26,659 | 3,984 | 14.9 | 20,753 | 3,402 | 16.4 | -22 | -15 |
| Male | 19,859 | 2,704 | 13.6 | 15,868 | 2,316 | 14.6 | -20 | -14 |
| Female | 6,799 | 1,279 | 18.8 | 4,881 | 1,086 | 22.2 | -28 | -15 |
| **Total Traffic Fatalities** | | | | | | | | |
| Total* | 43,005 | 6,680 | 15.5 | 32,367 | 5,401 | 16.7 | -25 | -19 |
| Male | 29,466 | 3,840 | 13.0 | 22,860 | 3,261 | 14.3 | -22 | -15 |
| Female | 13,529 | 2,838 | 21.0 | 9,499 | 2,140 | 22.5 | -30 | -25 |
| **Occupant Fatalities** | | | | | | | | |
| Total* | 37,375 | 5,541 | 14.8 | 27,060 | 4,417 | 16.3 | -28 | -20 |
| Male | 25,491 | 3,154 | 12.4 | 19,053 | 2,617 | 13.7 | -25 | -17 |
| Female | 11,875 | 2,386 | 20.1 | 8,000 | 1,800 | 22.5 | -33 | -25 |
| **Pedestrian Fatalities** | | | | | | | | |
| Total* | 4,851 | 1,064 | 21.9 | 4,432 | 845 | 19.1 | -9 | -21 |
| Male | 3,298 | 619 | 18.8 | 3,086 | 522 | 16.9 | -6 | -16 |
| Female | 1,552 | 444 | 28.6 | 1,345 | 323 | 24.0 | -13 | -27 |
| **Passenger Vehicle Occupant Fatalities** | | | | | | | | |
| Total* | 32,843 | 5,314 | 16.2 | 21,253 | 3,970 | 18.7 | -35 | -25 |
| Male | 21,431 | 2,959 | 13.8 | 13,811 | 2,208 | 16.0 | -36 | -25 |
| Female | 11,403 | 2,354 | 20.6 | 7,435 | 1,762 | 23.7 | -35 | -25 |
| **Motorcyclist Fatalities** | | | | | | | | |
| Total | 3,270 | 96 | 2.9 | 4,612 | 301 | 6.5 | 41 | 214 |
| Male | 2,961 | 89 | 3.0 | 4,181 | 285 | 6.8 | 41 | 220 |
| Female | 309 | 7 | 2.3 | 431 | 16 | 3.7 | 39 | 129 |
| **Pedalcyclist Fatalities** | | | | | | | | |
| Total | 665 | 56 | 8.4 | 677 | 90 | 13.3 | 2 | 61 |
| Male | 592 | 53 | 9.0 | 578 | 82 | 14.2 | -2 | 55 |
| Female | 73 | 3 | 4.1 | 99 | 8 | 8.1 | 36 | 167 |

* Total includes unknown gender.

- Finding the beginning of a left-turn lane at an intersection (20 percent).
- Making a left turn at an intersection (19 percent).
- Following pavement markings (17 percent).
- Responding to traffic signals (12 percent).

Benekohal et al. (1992) also found that the following highway features become more important to drivers as they age (with proportion of drivers responding in parentheses):

- Lighting at intersections (62 percent).
- Pavement markings at intersections (57 percent).
- Number of left-turn lanes at an intersection (55 percent).
- Width of travel lanes (51 percent).
- Concrete lane guides (raised channelization) for turns at intersections (47 percent).
- Size of traffic signals at intersections (42 percent).

Comparisons of responses from drivers ages 66–68 versus those age 77 and older showed that the older group had more difficulty following pavement markings, finding the beginning of the left-turn lane, and driving across intersections. Similarly, the level of difficulty for reading street signs and making left turns at intersections increased with age. Turning left at intersections was perceived as a complex driving task. This was made more difficult when raised channelization providing visual cues was absent, and only pavement markings designated which were through lanes versus turning lanes ahead. For the oldest age group, pavement markings at intersections were the most important item, followed by the number of left-turn lanes, concrete guides, and intersection lighting. A study of aging road users completed in 1996 provides evidence that the single most challenging aspect of intersection negotiation for this group is performing left turns during the permissive signal phase (Staplin, et al., 1997).

During focus group discussions (Benekohal et al., 1992), aging drivers reported that intersections with too many islands are confusing; raised curbs that are unpainted (unmarked) are difficult to see; and textured pavements (rumble strips) are of value as a warning of upcoming raised medians, approaches to (hidden or flashing red) signals, and the roadway edge/shoulder lane boundary. Study subjects indicated a clear preference for turning left on a protected arrow phase, rather than making permissive-phase turns. When turning during a permissive phase of signal operation, they reported waiting for a large gap before making a turn, which frustrates drivers behind them. A key finding was the need for more time to react.

Additional insight into the problems aging drivers experience at intersections was provided by focus group responses from 81 aging drivers (Staplin et al., 1997). The most commonly reported problems are listed below:

- Difficulty in turning their heads at skewed (non-90-degree) angles to view intersecting traffic.
- Difficulty in smoothly performing turning movements at tight corners.
- Hitting raised concrete barriers such as channelizing islands in the rain and at night.

- Finding oneself positioned in the wrong lane—especially a "turn-only" lane—during an intersection approach, due to poor visibility (maintenance) of pavement markings or the obstruction of roadside signs designed to inform drivers of intersection traffic patterns.
- Difficulty at the end of an auxiliary (right) turn lane in seeing potential conflicts well and quickly enough to smoothly merge with adjacent-lane traffic.
- Merging with adjacent-lane traffic at a pavement width reduction, when the lane drop occurs near (i.e., within 500 ft of) an intersection.

For aging pedestrians, age-related diminished capabilities may make it more difficult to negotiate intersections. Aging pedestrians face a variety of concerns, including decreased visual acuity, increased risk of falls, slowed walking and crossing speeds, and decreased ability to judge safe gaps and avoid turning vehicles.

Lighting and visibility at intersections are increasingly important to pedestrians as they age. In a survey of aging pedestrians (average age of 75) involved in crashes, 63 percent reported that they failed to see the vehicle that hit them, or to see it in time to take evasive action (Sheppard and Pattinson, 1986). Knoblauch, et al. (1995) noted that difficulty seeing a vehicle against a (complex) street background may occur with vehicles of certain colors, causing them to blend in with their background. Reductions in visual acuity make it more difficult for aging pedestrians to read the crossing signal as well (Bailey, et al., 1992).

With increasing age, there is a concurrent loss of physical strength, joint flexibility, agility, balance, coordination and motor skills, and stamina. These losses contribute to difficulty negotiating curbs and an increased risk of falling as a result of undetected surface irregularities in the pavement and inaccurate estimation of curb heights (Clark, Lord, and Webster, 1993).

The physical limitations of aging pedestrians result in a greater likelihood to delay before crossing; to wait for longer gaps between vehicles before attempting to cross the road (Tobey, Shungman, and Knoblauch, 1983); to spend more time at the curb; to take longer to cross the road (Hoxie and Rubenstein, 1994; Knoblauch, Nitzburg, Dewar, et al., 1995); and to make more head movements before and during crossing (Wilson and Grayson, 1980). Parsonson (1992) reported that the State of Delaware has found that pedestrians do not react well to the short WALK and long flashing DONT WALK timing pattern.

Turning vehicles are also a concern for aging pedestrians. The loss of peripheral vision and "useful field of view" increases an aging pedestrian's chances of not detecting approaching and turning vehicles from the side. The analysis by Council and Zegeer (1992) included an examination of vehicle-pedestrian crashes and the collision types in which aging pedestrians were over-involved. The results showed aging pedestrians to be overrepresented in both right- and left-turn crashes. The young-elderly (ages 65-74) were most likely to be struck by a vehicle turning right, whereas the old-elderly (age 75 and older) were more likely to be struck by a left-turning vehicle.

Together, these findings from research on aging road users reinforce the overriding design principles to "clarify" and "simplify" traffic operations at intersections. By providing appropriate advance information about route choices and destinations, clearly identifying lane assignments for allowed maneuvers, and implementing conspicuous and easily comprehensible sign and signal displays for traffic control, engineers can manage workload during intersection approach and negotiation in a manner that benefits road users of all ages. Likewise, the need for intersection geometrics to unambiguously convey path, direction, and speed is universal, and such “positive guidance” is an explicit goal of the treatments presented in this chapter.

# PROVEN PRACTICES

## 1 Intersecting Angle (Skew)

The HSM (page 10-32) defines skew angle as: "intersection skew angle (in degrees); the absolute value of the difference between 90 degrees and the actual intersection angle.

### A. Unrestricted Right-of-Way

In the design of new facilities or redesign of existing facilities where right-of-way is not restricted, all intersecting roadways should meet at a 90-degree angle (as indicated in Figure 3).

**References:** *Green Book*:1, NCHRP 279:1, TEH:1, NCHRP 500-9:1

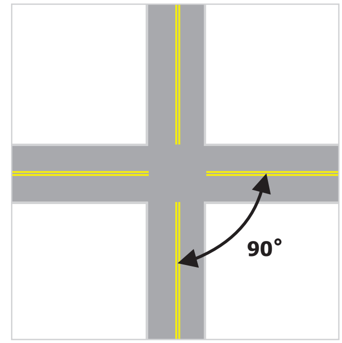


**Figure 3.** Example 90° angle of intersection

### B. Restricted Right-of-Way

In the design of new facilities or redesign of existing facilities where right-of-way is restricted, intersecting roadways should meet at an angle of not less than 75 degrees (as indicated in Figure 4).

**References:** TEH:2

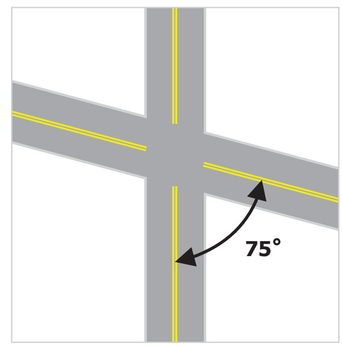


**Figure 4.** Example 75° angle of intersection

### C. Skewed Signalized Intersections

At skewed signalized intersections where the approach leg to the left intersects the driver's approach leg at an angle of less than 75 degrees, prohibit right turn on red (RTOR) (see Figure 5).

**References:** TEH:4, *MUTCD*:2

The rationale and supporting evidence for these treatments begins on page 96 of the *Handbook*.

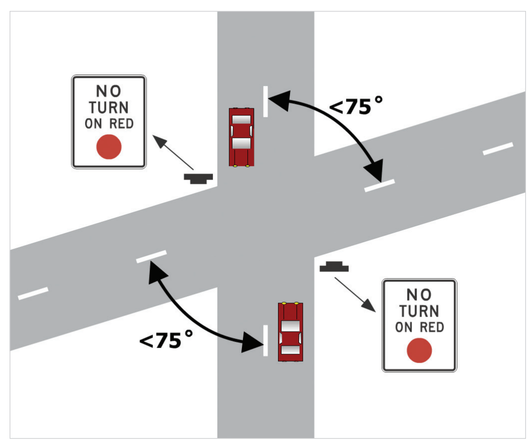


**Figure 5.** Skewed signalized intersection with prohibition of right turn on red

**REFERENCES LEGEND** *See pages 3 and 4 for full description of codes and acronyms of cited design guides.*

1: most conservative
2: preferred among differing guides
3: new application of current practice
4: more specific, detailed or stringent
5: permissible only in accordance with MUTCD section 1A.10, Interpretations, Experimentations, and Changes

# 2 Receiving Lane (Throat) Width

## A. Minimum Width

Wherever practical, a minimum receiving throat width of 16 ft is recommended. The total width may include a travel lane of 11 to 12 ft and a paved shoulder or bicycle lane of 4 to 5 ft as shown in Figure 6.

**References:** NCHRP 279:2, TEH:2

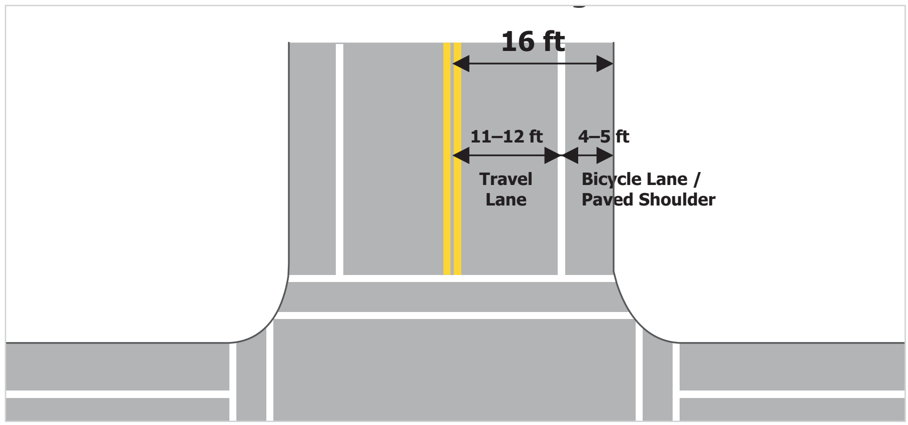


**Figure 6.** Recommended receiving lane width

The rationale and supporting evidence for this treatment begins on page 99 of the *Handbook*.

# 3 Channelization

## A. Left- and Right-Turn Lanes

Raised channelization with sloping curbs (see Figure 7) is recommended over channelization accomplished through the use of pavement markings alone (flush) for left- and right-turn lane treatments at intersections on all roadways with operating speeds of less than 45 mph.

**References:** *Green Book*:4, NCHRP 279:4, TEH:4, *MUTCD*:4, NCHRP 500-9:4

## B. Retroreflective Markings

Where raised channelization is implemented at intersections (see Figure 7) the median and island curb sides and curb horizontal surfaces should be treated with retroreflectorized markings, such as edge lines, painted curbs, or raised

**REFERENCES LEGEND** *See pages 3 and 4 for full description of codes and acronyms of cited design guides.*

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5: permissible only in accordance with MUTCD section 1A.10, Interpretations, Experimentations, and Changes

pavement markers, and be maintained at a minimum luminance contrast level* as follows:

B-1. With overhead lighting, a contrast of at least 2.0.

B-2. Without overhead lighting, a contrast of at least 3.0.

Contrast should be calculated according to this formula:

$$\text{Luminance contrast (C)} = \frac{\text{Luminance}_{\text{stripe}} - \text{Luminance}_{\text{pavement}}}{\text{Luminance}_{\text{pavement}}}$$

** Luminance is the amount of light reflected from an object. This is different from retroreflectivity, which is a property of a material. While increasing retroreflectivity generally results in higher luminance, (often described as brightness)—especially at night—this may vary greatly for the same object or marking depending upon such factors as the location and intensity of the source of illumination, and the angle at which a driver views it.*

**References:** *MUTCD*:4, NCHRP 500-9:4

## C. Acceleration Lane

If right-turn channelization is present at an intersection, an acceleration lane providing for the acceleration characteristics of passenger cars as delineated in AASHTO (2011) specifications is recommended for operating speeds of 45 mph or greater.

**References:** *Green Book*:4

## D. Sloping vs. Vertical Curbs

The use of sloping curbs rather than vertical curbs (see Figure 7) for channelization is recommended, except where the curbs surround a pedestrian refuge area or are being used for access control. Vertical curbs should also not be used for channelization on high-speed (i.e., 45 mph or greater) roadways.

**References:** *Green Book*:4, NCHRP 279:4

## E. Pedestrian Refuge Island

If right-turn channelization is present and pedestrian traffic may be expected based on surrounding land use, it is recommended that an adjacent pedestrian refuge island, conforming to *MUTCD* (2009) and AASHTO (2011) specifications, be provided.

**References:** *Green Book*:1, NCHRP 279:3, *MUTCD*:1

**Figure 7.** Vertical Curb (top), Sloping Curb (bottom)

**REFERENCES LEGEND** *See pages 3 and 4 for full description of codes and acronyms of cited design guides.*

1: most conservative
2: preferred among differing guides
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5: permissible only in accordance with MUTCD section 1A.10, Interpretations, Experimentations, and Changes

### F. Median Channelization

To reduce unexpected midblock conflicts with opposing vehicles, the use of channelized left-turn lanes in combination with continuous raised-curb medians is recommended instead of center, two-way, left-turn lanes (TWLTL) for new construction or reconstruction where average daily traffic volumes exceed 20,000 vehicles per day, or for remediation where there is a demonstrated crash problem, or wherever a need is demonstrated through engineering study.

**References:** *Green Book*:4, NCHRP 279:4

The rationale and supporting evidence for these treatments begins on page 102 of the *Handbook*.

## 4 Intersection Sight Distance

### A. Gap Value

It is recommended that a gap of no less than 8.0 s, plus 0.5 s for each additional lane crossed, be used in intersection sight distance (ISD) calculations to accommodate the slower decision-making and maneuver times of aging drivers for the following cases:

- Cases B1, B2, and B3 – stop-control on the minor road,
- Cases C1 and C2 – yield control on the minor road,
- Case D - signalized with permissive left-turn phases and/or where RTOR is permitted and/or which are placed on flashing operations at night, and
- Case F - left turns from a major roadway.

**Note**: Cases refer to the intersection control cases defined in the AASHTO *Green Book* (2011).

**References:** *Green Book*:1

The rationale and supporting evidence for these treatments begins on page 107 of the *Handbook*.

**REFERENCES LEGEND** *See pages 3 and 4 for full description of codes and acronyms of cited design guides.*

1: most conservative
2: preferred among differing guides
3: new application of current practice
4: more specific, detailed or stringent
5: permissible only in accordance with MUTCD section 1A.10, Interpretations, Experimentations, and Changes

# 5 Offset Left-Turn Lanes

## A. Full Offset – Opposing Cars

Left-turn lanes should be positively offset (as shown in Figure 8) at least 4 ft to the left of the opposing left-turn lane to achieve the desired sight distance for the left-turning driver. This will provide a margin of safety for aging drivers who, as a group, do not position themselves to the far left within the lane and within the intersection before initiating a left turn.

**References:** *Green Book*:1, NCHRP 279:4, TEH:4, NCHRP 500-9:4

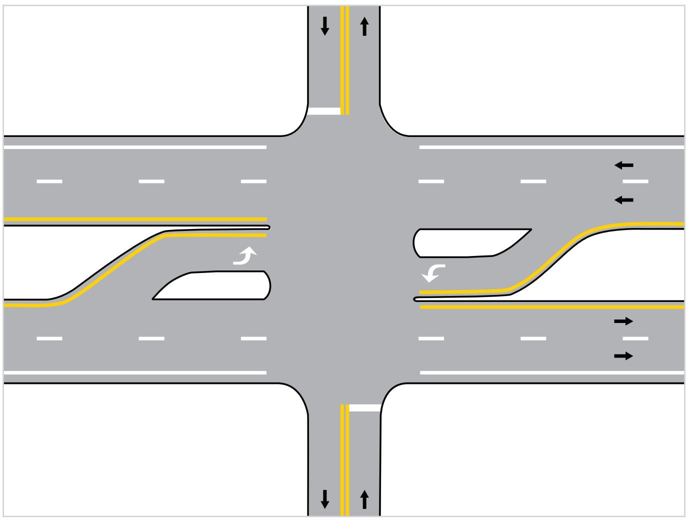

**Figure 8.** Left-turn lanes with positive offset

## B. Full Offset – Opposing Heavy Trucks

At intersections where engineering judgment indicates a high probability of heavy trucks as the opposing left-turning vehicles, the positive offset is recommended to be 5.5 ft to achieve the desired sight distance.

**References:** *Green Book*:4, NCHRP 279:4, TEH:4, NCHRP 500-9:4

## C. Minimum Offset

At locations where the full offset distances cannot be obtained, it is recommended that the minimum offset distances shown in Table 6 be provided to achieve minimum required sight distances according to design speed. It is recommended that the "Opposing Truck" values be used where the opposing left-turn traffic includes a moderate to heavy volume of large trucks.

**References:** *Green Book*:4, NCHRP 279:4, TEH:4, NCHRP 500-9:4

**REFERENCES LEGEND**

*See pages 3 and 4 for full description of codes and acronyms of cited design guides.*

1: most conservative
2: preferred among differing guides
3: new application of current practice
4: more specific, detailed or stringent
5: permissible only in accordance with MUTCD section 1A.10, Interpretations, Experimentations, and Changes

**Table 6.** Minimum offset distances for left-turn lanes.

| Design Speed (mph) | Minimum Offset (ft) | |
|---|---|---|
| | Opposing Car | Opposing Truck |
| ≤ 30 | 0.8 | 3.0 |
| 35 | 1.4 | 3.5 |
| 40 | 1.8 | 3.8 |
| 45 | 2.1 | 4.1 |
| 50 | 2.4 | 4.2 |
| 55 | 2.6 | 4.4 |
| 60 | 2.7 | 4.5 |
| 65 | 2.8 | 4.6 |
| 70 | 2.9 | 4.7 |

*1 ft = 0.305 m*

## D. Signs and Markings

At intersections where the left-turn lane treatment results in channelized offset left-turn lanes (e.g., a parallel or tapered left-turn lane between two medians), the following countermeasures (see Figure 9) are recommended to reduce the potential for wrong-way maneuvers by drivers turning left from a stop-controlled intersecting minor roadway:

D-1. Largest practical sign sizes as specified in the *MUTCD* (2009) for DIVIDED HIGHWAY CROSSING, WRONG WAY, DO NOT ENTER, KEEP RIGHT, and ONE WAY signs.

**References:** TEH:4, *MUTCD*:3, NCHRP 500-9:4

D-2. For the signs listed above, use prismatic retroreflective sheeting, to provide increased sign conspicuity and legibility for older drivers. Ensure these signs are replaced before they meet the minimum sign retroreflectivity levels, which includes white on red signs having a contrast ratio of at least 3:1.

**References:** *MUTCD*:1, NCHRP:4

D-3. Retroreflective lane-use arrows.

**References:** *MUTCD*:1, NCHRP 500-9:4

D-4. Retroreflective pavement marking extensions of the center line that scribe a path through the turn, except where extensions for opposing movements cross.

**References:** *MUTCD*:3, NCHRP 500-9:4

**REFERENCES LEGEND**

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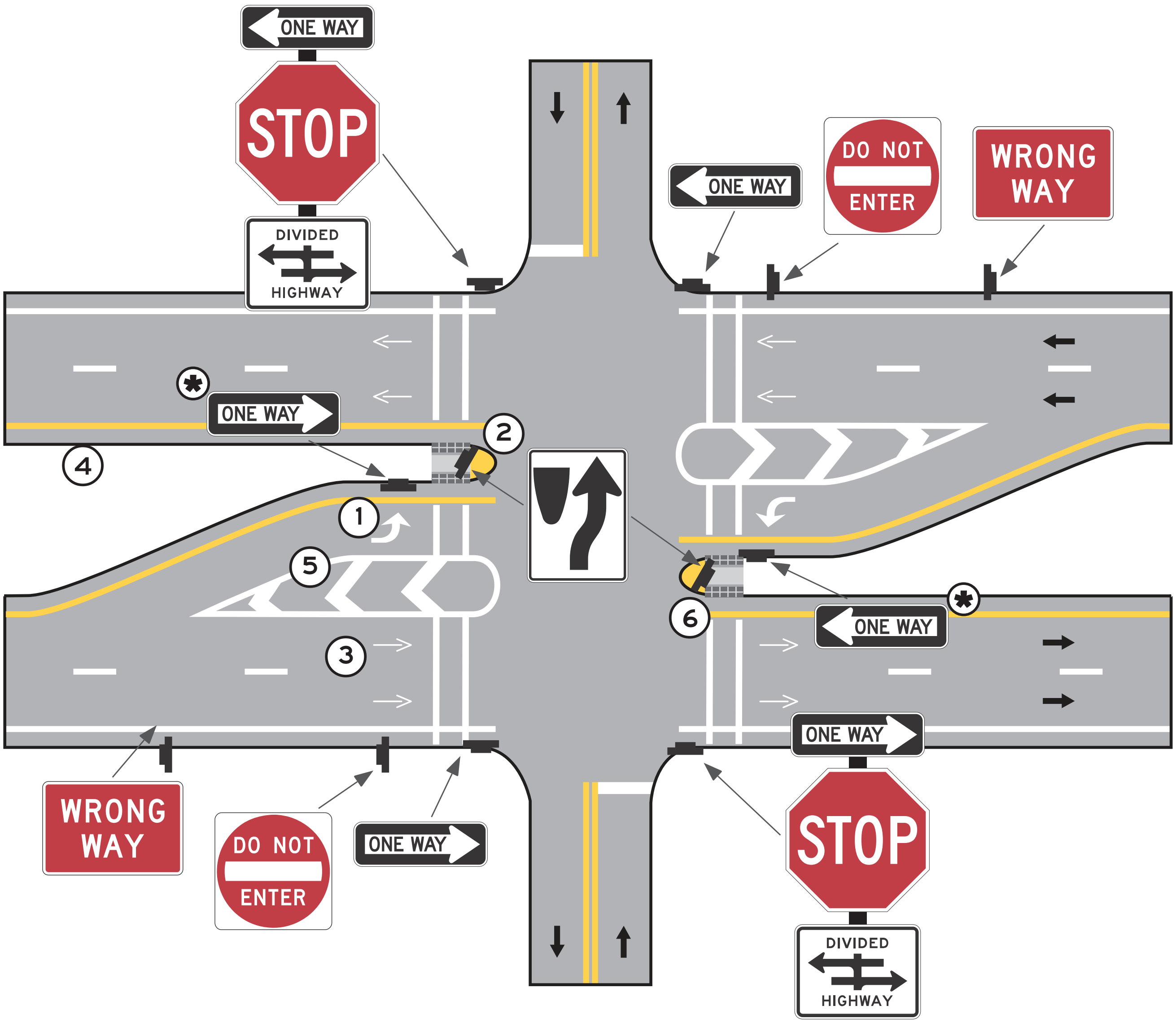


1 Left-Turn Arrow (Lane-use pavement marking)

2 Median Nose Delineation

3 Wrong-Way Arrow Pavement Marking

4 Raised Channelization

5 Channelization Accomplished Using Retroreflective Pavement Markings

6 Raised Crossing Island for Pedestrians

✱ Optional Signs (For medians less than 30ft wide)

**Figure 9.** Recommended signs and markings for intersections with channelized offset left-turn lanes

REFERENCES LEGEND *See pages 3 and 4 for full description of codes and acronyms of cited design guides.*

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D-5. Placement of 23.5-ft- long retroreflective wrong-way arrows in the through lanes at locations determined to have a special need, as specified in the *MUTCD* (2009), Sections 3B.19 and 2E-50.

**References:** *MUTCD*:3, NCHRP 500-9:4

D-6. Delineation of median noses using retroreflective treatments to increase their visibility and improve driver understanding of the intersection design and function.

**References:** *Green Book*:1, *MUTCD*:2, NCHRP 500-9:4

### E. Pedestrian Accommodations

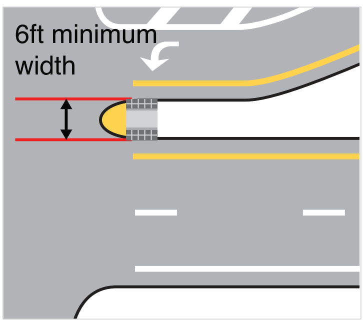


**Figure 10.** Pedestrian Crossing Island (or Refuge Area)

At intersections where there are high pedestrian volumes, and the offset left-turn treatment results in a crossing width that would require a pedestrian walking at 3.0 ft/s to cross in two stages, the following is recommended to create a pedestrian crossing island (or refuge area), as shown in Figure 10:

E-1. Flush (painted) channelization is used to separate the left-turn lane and adjacent through lanes.

E-2. Raised channelization with a vertical curb and a minimum width of 6 ft is used to separate the left-turn lane from opposing travel lanes. While a 6-ft width is the minimum, there are advantages to providing wider islands where possible. Sloped curbs should be used instead of vertical curbs for channelization on high-speed (i.e., 45 mph or greater) roadways.

**References:** *Green Book*:1, *MUTCD*:2

The rationale and supporting evidence for these treatments begins on page 122 of the *Handbook*.

## 6 Delineation of Edge Lines and Curbs

### A. Visibility

A minimum in-service luminance contrast level between the marked edge of the roadway and the road surface should be maintained as follows:

A-1. At intersections with overhead lighting, a contrast of 2.0 or higher.

A-2. At intersections without overhead lighting, a contrast of 3.0 or higher.

**REFERENCES LEGEND** *See pages 3 and 4 for full description of codes and acronyms of cited design guides.*

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Contrast should be calculated according to this formula:

$$\text{Luminance contrast (C)} = \frac{\text{Luminance}_{\text{stripe}} - \text{Luminance}_{\text{pavement}}}{\text{Luminance}_{\text{pavement}}}$$

* *Luminance is the amount of light reflected from an object. This is different from retroreflectivity, which is a property of a material. While increasing retroreflectivity generally results in higher luminance, (often described as brightness)—especially at night—this may vary greatly for the same object or marking depending upon such factors as the location and intensity of the source of illumination, and the angle at which a driver views it.*

**References:** *MUTCD*:4, RLH:4

### B. Intersection Curbs

Curbs at intersections (including median islands and other raised channelization) should be delineated on their vertical face and at least a portion of the top surface, in addition to the provision of a marked edge line on the road surface (see Figure 11).

The use of a Keep Right (R4-7 Series) or a Double Arrow (W12-1) sign with the addition of a low-mounted Type 1 Object Marker (OM1-1) near the median and channelizing island noses, respectively, could also be helpful to aging road users. These signs are optional and can be used if they are warranted. Since markings primarily supplement signing, this treatment should be placed in addition to the signing available for these locations.


**Figure 11.** Raised median island with yellow marking on the vertical face and top surface

**References:** *Green Book*:1, *MUTCD*:1

The rationale and supporting evidence for these treatments begins on page 129 of the *Handbook*.

## 7 Curb Radius

### A. Simple Radius

Where roadways intersect at 90 degrees and are joined with a simple radius curve, a corner curb radius in the range of 25 ft to 30 ft is recommended to: (a) facilitate vehicle turning movements, (b) moderate the speed of turning vehicles, and (c) avoid unnecessary lengthening of pedestrian crossing distances (see Simple Curve in Figure 12).

**References:** AASHTO:1, NCHRP 279:1

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### B. Accommodation of Heavy Vehicles

When it is necessary to accommodate turning movements by large trucks, the use of offsets, tapers, and compound curves is recommended in place of larger simple radii (e.g., 75 ft or more) to minimize pedestrian crossing distances (see Figure 12).

**References:** AASHTO:1, NCHRP 279:4, TEH:4

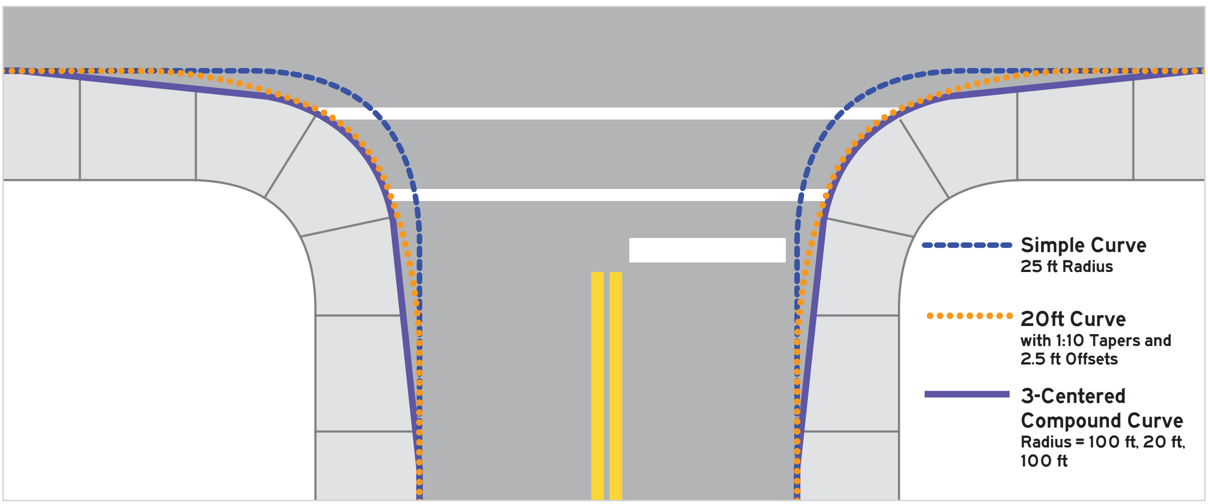


**Figure 12.** Comparison of curb radii

The rationale and supporting evidence for these treatments begins on page 132 of the *Handbook*.

## 8 Left-Turn Traffic Control for Signalized Intersections

### A. Protected-Only Left-Turn Phasing

The use of protected-only left-turn operations is recommended for all left-turning movements, whenever appropriate. In particular, protected-only left-turn phasing should be considered where minimum intersection sight distance requirements are not achieved through the use of offset left-turn lanes (see Design Element 5) or other geometric design features, or where a pattern of permissive left-turn crashes occurs.

**References:** *Green Book*:4, TEH:1, *MUTCD*:1

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### B. Permissive Left-Turn Signing

If circular green is used as the permissive indication of a protected/permissive left-turn, consistent use of the *MUTCD* R10-12 sign, (LEFT TURN YIELD ON GREEN ●) is recommended, with overhead placement preferred at the intersection adjacent to the left-turn signal face (see Figure 13).

**References:** TEH:4, *MUTCD*:1

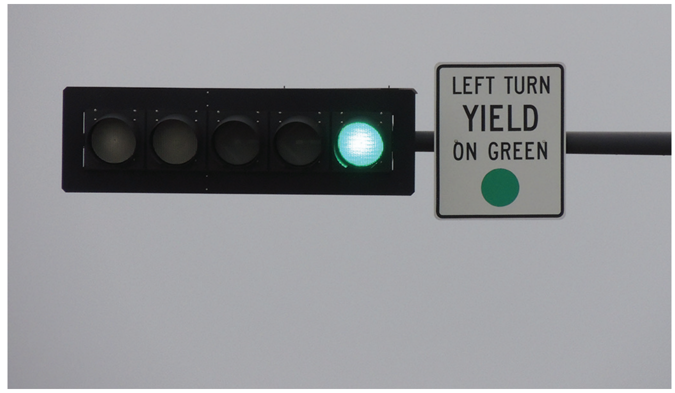


**Figure 13.** MUTCD R10-12 sign adjacent to left-turn signal face

### C. Advance Signing

Where practical, an additional R10-12 sign (i.e., in addition to the R10-12 sign adjacent to the signal face) should be placed in advance of the intersection to advise left-turning drivers of permissive signal operation. The sign should be displayed at a 3-s preview distance before the intersection, or at the beginning of the left-turn lane, as per engineering judgment, accompanied by an AT SIGNAL (R10-31P) supplemental plaque as shown in Figure 14. [See time-speed-distance table on page 5.]


**Figure 14.** (*MUTCD* R10-31P)

**References:** AASHTO:3, *MUTCD*:1, NCHRP 500-9:4

### D. Lead versus Lag Phasing

A leading protected left-turn phase is recommended wherever protected left-turn signal operation is implemented (as opposed to a lagging protected left-turn phase).

**References:** TEH:2, *MUTCD*:2

The rationale and supporting evidence for these treatments begins on page 135 of the *Handbook*.

## 9 Right-Turn Traffic Control for Signalized Intersections

### A Turn Prohibition

At signalized intersections where a right turn on red is prohibited, a supplemental NO TURN ON RED sign, using the *MUTCD* R10-11 design as shown in Figure 15, should be placed at a location on either the near or opposite side of the intersection where, per engineering judgment, it will be most conspicuous. This supplemental NO TURN ON RED sign is in


**Figure 15.** (*MUTCD* R10-11)

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addition to the *MUTCD* recommended practice of installing an R10-11 series sign near the appropriate signal head.

**References:** TEH:4, *MUTCD*: 1

### B. Skewed Signalized Intersections

At skewed signalized intersections where the approach leg to the left intersects the driver's approach leg at an angle of less than 75 degrees (as illustrated in Figure 16), prohibit right turn on red (RTOR).

**References:** TEH:4, *MUTCD*:1

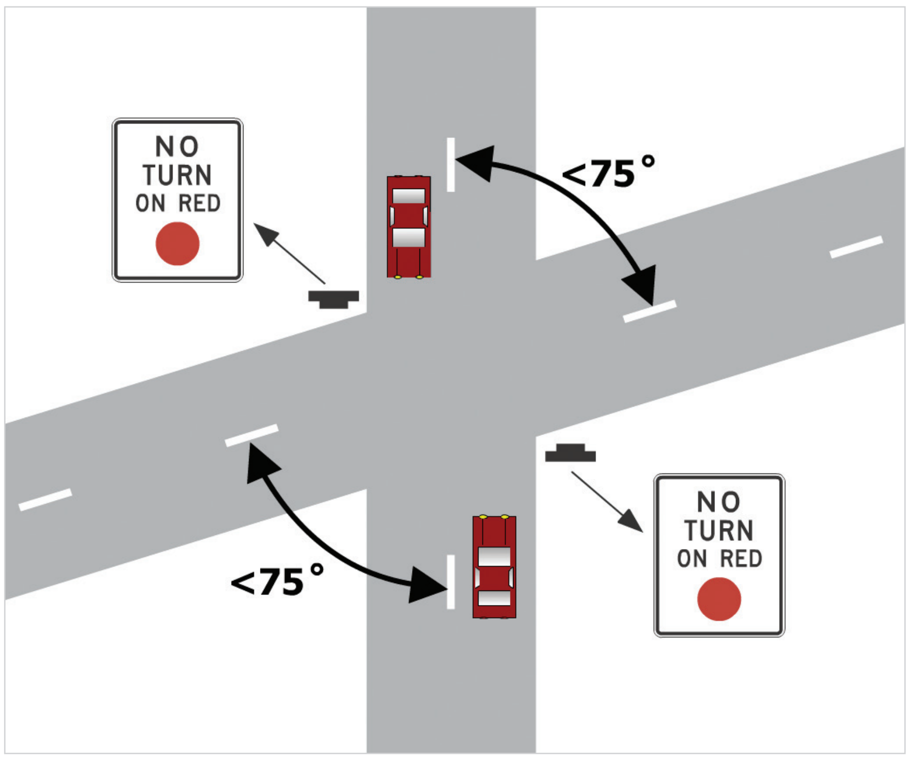


**Figure 16.** Skewed signalized intersection with prohibition of right turn on red

### C. Pedestrian Protection

The posting of *MUTCD* standard R10-15 signs, Turning Vehicles Yield to Pedestrians (shown in Figure 17) is recommended wherever engineering judgment indicates a clear potential for right-turning vehicles to come into conflict with crossing pedestrians. (Note that a yellow background color may be used instead of fluorescent yellow-green for this sign.)

**References:** *MUTCD*:1


**Figure 17.** (*MUTCD* R10-15)

The rationale and supporting evidence for these treatments begins on page 148 of the *Handbook*.

**REFERENCES LEGEND**

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# 10 Street Name Signs

## A. Letter Heights and Sign Border

To accommodate the reduction in visual acuity associated with increasing age, minimum letter heights of 6 in for uppercase letters and 4.5 in for lowercase letters are recommended for use on ground-mounted street-name signs (*MUTCD* D3-1, as shown in Figure 18) on all roads where the posted speed limit is at or below 25 mph. On all roads where the posted speed limit is greater than 25 mph, letter heights of 8 in for uppercase letters and 6 in for lowercase letters should be used.


**Figure 18.** (*MUTCD* D3-1)

The use of overhead-mounted street-name signs is recommended at major intersections as a supplement to ground-mounted street-name signs. Minimum letter heights of 12 in for uppercase letters and 9 in for lowercase letters are recommended by the *MUTCD.*

In the design of street-name signs, the use of larger letter heights may require a larger sign panel. The border may be eliminated on street-name signs if necessary to minimize sign panel size while accommodating the larger letter size.

**References:** *MUTCD*:1, NCHRP 500-9:4

## B. Advance Street-Name Plaque

Wherever an advance intersection warning sign is installed (*MUTCD* W2 series) it should be accompanied by an advance street name plaque (W16-8P or W16-8aP) using minimum letter heights of 6 in for uppercase letters and 4.5 in for lowercase letters (see Figure 19). Where an advance traffic control sign (*MUTCD* W3 series) is installed on a multi-lane approach, an advance street name plaque (W16-8P or W16-8aP), using the same minimum letter heights described above, should be considered.


**Figure 19.** Intersection Warning W2-1 Sign and W16-8P Supplemental Advance Street Name Plaque

**References:** *MUTCD*:2, NCHRP 500-9:4

## C. Advance Street-Name Sign

In the absence of an advance intersection warning sign or advance traffic control sign (with accompanying advance street-name plaque), the use of advance street-name signs (*MUTCD* D3-2) for major intersections is recommended, with turn bays to provide adequate preparation time for any lane change and/or turning maneuvers (see Figure 20).

**References:** *MUTCD*:1, NCHRP 500-9:1

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## D. Directional Street-Name Sign

When different street names are used for different directions of travel on a crossroad, the names should be separated and accompanied by directional arrows on both advance and intersection street-name signs, as shown in Figure 20.

**References:** *MUTCD*:1

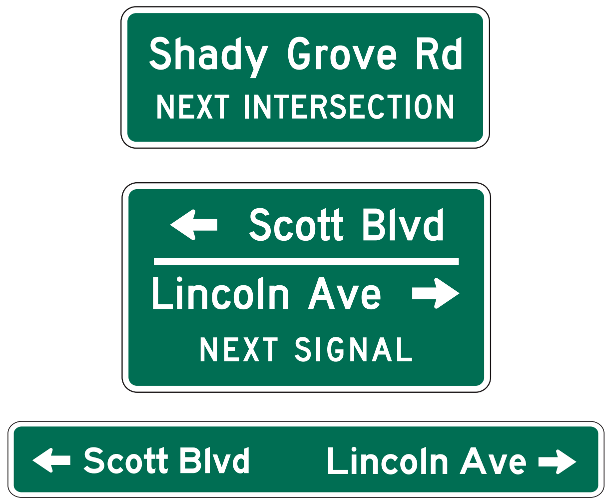


**Figure 20.** (*MUTCD* D3-2)

## E. Retroreflectivity

For ground-mounted street-name signs installed at intersections in areas of intensive land use, complex design features, and heavy traffic, prismatic retroreflective sheeting that provides for high retroreflectance should be used to provide increased sign conspicuity and legibility for aging drivers. The sheeting should be replaced well before it reaches the minimum levels designated in the current MUTCD (Section 2A.08 in the 2009 MUTCD).

**References:** *MUTCD*:1

The rationale and supporting evidence for these treatments begins on page 152 of the *Handbook*.

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# 11 Stop and Yield Signs

Treatments to improve the safe use of intersections by aging drivers, where the need for stop control or yield control has already been determined, include the following:

**A. Sign Size**

The use of standard size (30-in for single lane applications, 36-in for multi-lane applications) STOP (R1-1) and standard size (36-in for single lane applications, 48-in for multi-lane applications, 60-in for freeway applications) YIELD (R1-2) signs, as a minimum, is required by the 2009 *MUTCD* wherever these devices are implemented, with the option of using larger R1-1 (36-in for single lane applications, or 48-in in any location) signs where engineering judgment indicates that greater emphasis or visibility is required.

**References:** *MUTCD*:1

**B. Retroreflectivity**

A minimum sign background (red area) retroreflectivity level (i.e., coefficient of retroreflection [RA]) for STOP (R1-1) and YIELD (R1-2) signs is as follows:

B-1. 12 cd/lux/$m^2$ for roads with operating speeds lower than 40 mph.

B-2. 24 cd/lux/$m^2$ for roads with operating speeds of 40 mph or higher.

Signs with an RA below these levels should be replaced.

**References:** TEH:4, *MUTCD*:1

**C. Supplemental Warning Sign**

The use of a 30-in x 18-in supplemental warning sign panel (*MUTCD* W4-4P) as illustrated in Figure 21, mounted below the STOP (R1-1) sign, is recommended for two-way stop-controlled intersection sites selected on the basis of crash experience, where the sight triangle is restricted, and wherever a conversion from four-way stop to two-way stop operations is implemented.


**Figure 21.** (*MUTCD* W4-4P)

**References:** *MUTCD*:1

**D. Location of Stop Ahead Sign**

A STOP AHEAD sign (*MUTCD* W3-1, as shown in Figure 22) should be used where the distance at which the STOP sign is visible is less than the AASHTO stopping sight distance (SSD) at the operating speed, plus an added preview

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**Figure 22.** (*MUTCD* W3-1)

distance of at least 2.5 s. [See time-speed-distance table on page 5.]

**References:** *Green Book*:4, TEH:4, *MUTCD*:1, NCHRP 500-9:4

**E. Transverse Treatments and Supplemental Pavement Markings**

Utilize supplemental pavement markings on approaches to stop-controlled or yield-controlled intersections where engineering judgment indicates a special need due to sight restrictions, high approach speeds, or a history of ran-stop-sign crashes. "STOP AHEAD" pavement markings to supplement STOP AHEAD signs and triangular pavement markings to supplement YIELD AHEAD signs are described in MUTCD Section 3B.20 and Figure 32. Transverse pavement striping or rumble strips may also be considered where high approach speeds are a concern.

**References:** TEH:4, NCHRP 500-9:3

The rationale and supporting evidence for these treatments begins on page 160 of the *Handbook*.

## 12 Lane Assignment on Intersection Approach

**A. Lane-Use Control Signs**

The consistent overhead placement of lane-use control signs (*MUTCD* R3-5 and R3-6 series) at intersections on a signal mast arm or span wire is recommended, as illustrated in Figure 23.

**References:** *MUTCD*:1

**B. Advance Signs and Markings**

The consistent posting of lane-use control signs (*MUTCD* R3 series) plus application of lane-use arrow pavement markings at a preview distance of at least 5 s (at operating speed) in advance of a signalized intersection is recommended, regardless of the specific lighting, channelization, or delineation treatments implemented at the intersection. [See time-speed-distance table on page 5.] R3-5 and R3-6 series signs should be mounted overhead wherever practical.

**References:** *MUTCD*:4

The rationale and supporting evidence for these treatments begins on page 170 of the *Handbook*.

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**Figure 23.** Mast-arm mounted lane-use control signs

# 13 Traffic Signals

## A. Visibility

To ensure visibility and conspicuity of the traffic signal, the following is recommended:

A-1. A maintained performance level of 200 cd for peak intensity for both 8-in and 12-in signals.

A-2. Use of 12-in signals in all cases except the few limited situations in which the *MUTCD* allows the use of 8-in signals.

**References:** *MUTCD*:1

## B. All-Red Clearance Interval

To accommodate age differences in perception-reaction time, an all-red clearance interval should be consistently implemented, with length determined according to the Institute of Transportation Engineers (2013) expressions given below:

B-1. Where pedestrian traffic is prohibited, or no pedestrian crossing facilities are provided, use:

$$r = \frac{W + L}{1.47V}$$

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B-2. Where pedestrian crossing facilities are provided, use:

$$r = \frac{P + L}{1.47V}$$

where:

r = length of red clearance interval, to the nearest 0.1 s.

W = width of intersection (ft), measured from the near-side stop line to the far edge of the conflicting traffic lane along the actual vehicle path.

P = width of intersection (ft), measured from the near-side stop line to the far side of the farthest conflicting pedestrian crosswalk along the actual vehicle path.

L = length of vehicle (recommended as 20 ft)

V = approach speed of the vehicle (mph)

**References:** *MUTCD*:2

## C. Backplates

Backplates with retroreflective borders should be considered as part of efforts to systemically improve safety performance at signalized intersections. Use backplates with traffic signals on all roads with operating speeds of 40 mph or higher. The use of backplates with signals is also recommended on roads with operating speeds lower than 40 mph where engineering judgment indicates a need due to the potential for sun glare problems, site history, or other variables. Yellow retroreflective borders, shown in Figure 24, may be used as an option to improve visibility of the illuminated face of the signal. The yellow retroreflective strip should have a minimum width of 1 inch and a maximum width of 3 inches and be placed along the perimeter of the face of a signal backplate to project a rectangular appearance at night. The yellow retroreflective strip should have a minimum width of 1 inch and a maximum width of 3 inches and be placed along the perimeter of the face of a signal backplate to project a rectangular appearance at night.

**References:** *MUTCD*:4

The rationale and supporting evidence for these treatments begins on page 173 of the *Handbook*.

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**Figure 24.** Yellow retroreflective backplates

# 14 Intersection Lighting

## A. Fixed Installations

Wherever feasible, fixed lighting installations are recommended as follows:

A-1. Where the potential for wrong-way movements is indicated through crash experience or engineering judgment.

A-2. Where twilight or nighttime pedestrian volumes are high.

A-3. Where shifting lane alignment, turn-only lane assignment, or a pavement-width transition forces a path-following adjustment at or near the intersection.

**References:** *Green Book*:4, RLH:4

## B. Maintenance

Regular cleaning of lamp lenses, and lamp replacement when output has degraded by 20 percent or more of peak performance (based on hours of service and manufacturer's specifications), are recommended for all fixed lighting installations at intersections.

**References:** RLH:4

The rationale and supporting evidence for these treatments begins on page 181 of the *Handbook*.

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# 15 Pedestrian Crossings

## A. Walking Speed

To accommodate the aging pedestrian who typically has a shorter stride, slower gait, and delayed "start-up" time before leaving from a position further back from the curb at signalized crossings, the joint application of the following practices is recommended:

A-1. Use a walking speed of 3.0 ft/s to calculate total crossing time (WALK interval plus pedestrian clearance interval).

A-2. Measure crossing distance from a location 6 ft back from the curb or travel lane edge to the far side of the travel way being crossed.

**References:** *Green Book*:2, NCHRP 279:2, *MUTCD*:1

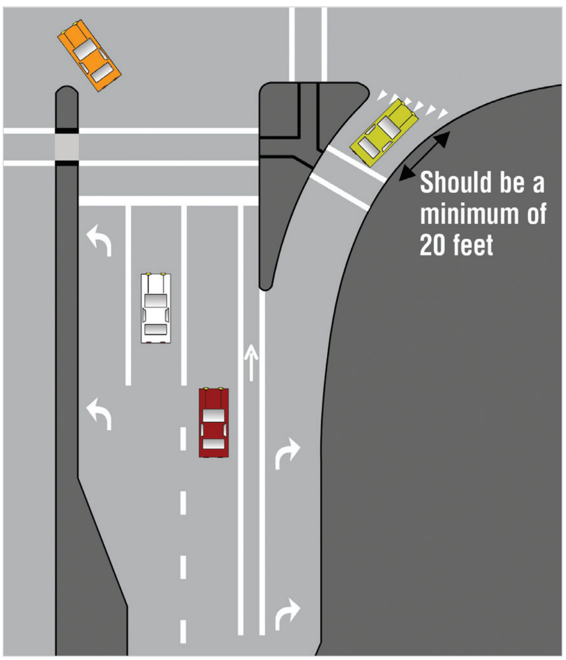


**Figure 25.** Pedestrian crossing at channelized right-turn lane

## B. Channelized Right-Turn Lane

For pedestrian crossings where the right-turn lane is channelized, it is recommended that:

B-1. An adjacent pedestrian refuge island conforming to *MUTCD* (2009) and AASHTO (2011) specifications be provided.

B-2. If a crosswalk is within the channelized area, it should be located approximately one car length from the yield line for the intersection (see Figure 25), which will allow drivers on the approach leg to look for and yield to pedestrians before reaching the intersecting roadway and scanning for gaps in traffic.

**References:** *Green Book*:4, NCHRP 279:4, TEH:4, *MUTCD*:2

## C. Educational Signs

Where engineering judgment deems there to be a need to improve understanding of pedestrian signals, it is recommended that educational signs be posted near the crosswalk as follows:

C-1. For single stage crossings, use *MUTCD* R10-3b, R10-3c, R10-3e, R10-3f, R10-3g, or R10-3i as shown in Figure 26.

**References:** *MUTCD*: 2

**REFERENCES LEGEND**

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C-2. For two-stage crossings using a median refuge island, use *MUTCD* R10-3d or R10-3h (see Figure 26) on the corners of the intersection and the placards defined above on the median refuge island.

**References:** *MUTCD*: 2

## D. Turning Vehicles Yield to Pedestrians Sign

The posting of the *MUTCD* R10-15 sign (see Figure 27) is recommended wherever engineering judgment indicates a clear potential for right-turning

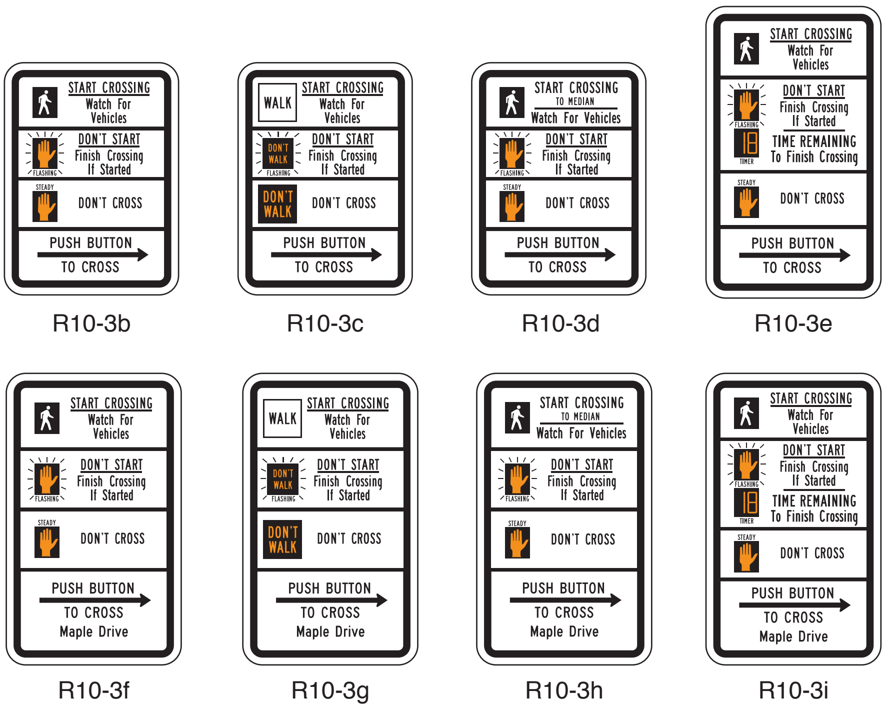


**Figure 26.** (*MUTCD* R10-3 Series)

vehicles to come into conflict with crossing pedestrians.

**References:** *MUTCD*:1

## E. Leading Pedestrian Interval

At intersections with high turning-vehicle volumes and no turn on red (NTOR) control for traffic moving parallel to a marked crosswalk, a leading pedestrian interval (LPI), timed to allow slower walkers to cross at least one moving lane of traffic is recommended to reduce conflicts between pedestrians and turning vehicles. The length of the LPI, which should be at least 3 s, may be

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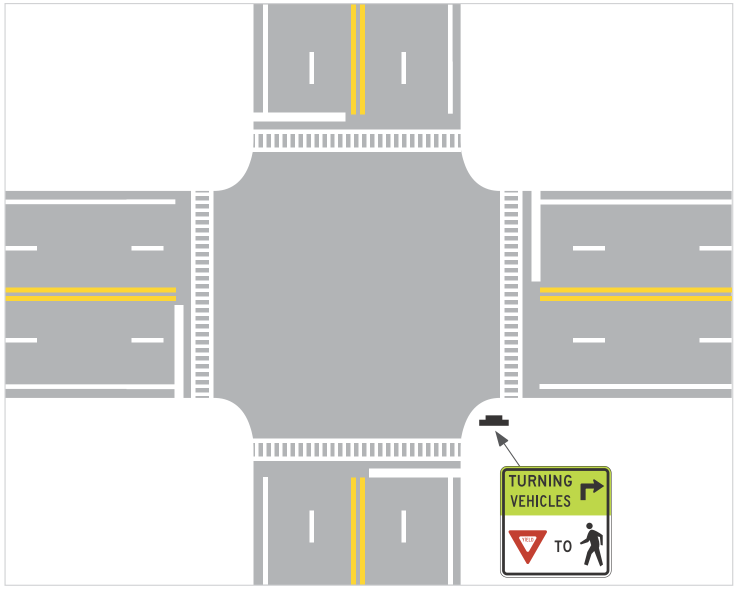


**Figure 27.** Recommended placement of MUTCD R10-15 sign

calculated using the formula:

$$LPI = (ML + PL + 6.0)/3.0$$

where:

LPI = seconds between onset of the WALK signal for pedestrians and the green indicator for vehicles.

ML = width of moving lane in ft

PL = width of parking lane (if any) in ft

6.0 = distance in ft back from the edge of the curb to the assumed starting location for pedestrians

3.0 = walking speed in ft/s

**References:** *MUTCD*:1

**Figure 28.** Countdown pedestrian signal

## F. Countdown Signal

Countdown pedestrian signals (see Figure 28) should be installed at all signalized intersections where pedestrian signals are warranted. The 2009 *MUTCD* requires the use of countdown pedestrian signals when the pedestrian change interval is greater than 7s.

**References:** *MUTCD*: 1

The rationale and supporting evidence for these treatments begins on page 185 of the *Handbook*.

**REFERENCES LEGEND** *See pages 3 and 4 for full description of codes and acronyms of cited design guides.*

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# 16 Roundabouts

There are features of roundabout intersections that can benefit aging drivers and be a beneficial treatment over a traditional stop- or signal-controlled intersection if properly designed to meet the needs of that location. When properly designed, roundabouts are low-speed intersections, which provide benefits to aging drivers and pedestrians alike. In addition, roundabouts effectively eliminate severe right-angle crashes. Any crashes that do occur are typically low-angle (i.e., sideswipe) crashes at reduced speeds. The low-speed features associated with roundabouts eliminate the problems associated with making unprotected left turns at intersections. It is therefore recommended that roundabouts be considered as part of the engineering study in the design of new intersections and the redesign of existing intersections.

Treatments for preferred practices when a State or local highway authority has determined through engineering study to install a modern roundabout during construction or reconstruction of an intersection include the following (see Figure 29):

**A. Number of Lanes**

Unless required by operational needs, it is recommended that roundabout installations be limited to one-lane entrances and exits and one lane of circulating traffic.

**References:** NCHRP 672:1

**B. Pedestrian Crossings**

Pedestrian crossings at single-lane roundabouts should be set back a minimum of 25 ft from the yield lines and include a crossing island of at least 6 ft in width.

**References:** NCHRP 672:1

**C. Splitter Islands**

To control for wrong-way movements, calm traffic, and provide a pedestrian refuge for all roundabout categories, raised splitter islands should be used, as opposed to pavement markings, to delineate the channelization. The pedestrian crosswalk area should be designed at street level (crosswalk cut through a splitter island).

**References:** NCHRP 672:1

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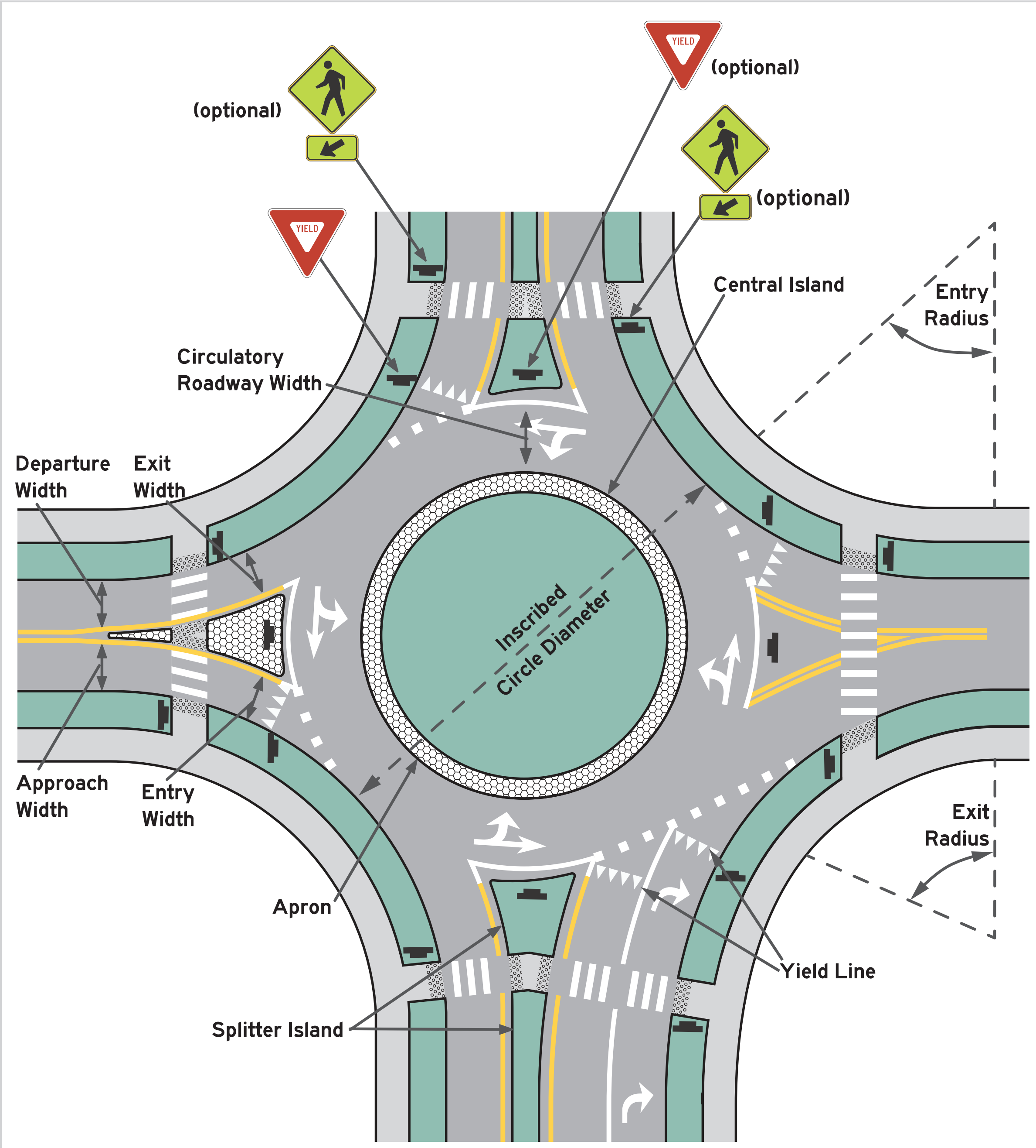


**Figure 29.** Key geometric design elements and traffic control devices for roundabouts

REFERENCES LEGEND

*See pages 3 and 4 for full description of codes and acronyms of cited design guides.*

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### D. Conspicuity

To enhance the conspicuity of roundabouts in all categories, the sides and tops of curbs on the splitter islands and the central island should be treated with retroreflective markings, and be maintained at a minimum luminance contrast level* as follows:

D-1. At roundabouts with overhead lighting, a contrast of 2.0 or higher.

D-2. At roundabouts without overhead lighting, a contrast of 3.0 or higher.

Contrast should be calculated according to this formula:

$$\text{Luminance contrast (C)} = \frac{\text{Luminance}_{\text{stripe}} - \text{Luminance}_{\text{pavement}}}{\text{Luminance}_{\text{pavement}}}$$

* *Luminance is the amount of light reflected from an object. This is different from retroreflectivity, which is a property of a material. While increasing retroreflectivity generally results in higher luminance, (often described as brightness)—especially at night—this may vary greatly for the same object or marking depending upon such factors as the location and intensity of the source of illumination, and the angle at which a driver views it.*

**References:** NCHRP 672:4

### E. Advance Warning Sign

The use of an advance roundabout warning sign (W2-6), as shown in Figure 30, is recommended on all approaches to a roundabout.

**References:** *MUTCD*:1

### F. Directional Signs

The use of a Roundabout Directional Arrow sign (R6-4 series) is recommended to direct traffic counter-clockwise around the central island. This sign display should be placed on the central island in direct view of a driver's entry point, as shown in Figure 31, (if different than at the centerline of the approaching roadway).

**References:** *MUTCD*:1

**Figure 30.** (*MUTCD* W2-6)

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### G. Roundabout Circulation Plaque

The Roundabout Circulation Plaque (R6-5P) should be placed immediately below the R1-2 Yield sign on both sides of the road at each entrance to a roundabout (see Figure 32).

**References:** *MUTCD*:5

The rationale and supporting evidence for these treatments begins on page 197 of the *Handbook*.

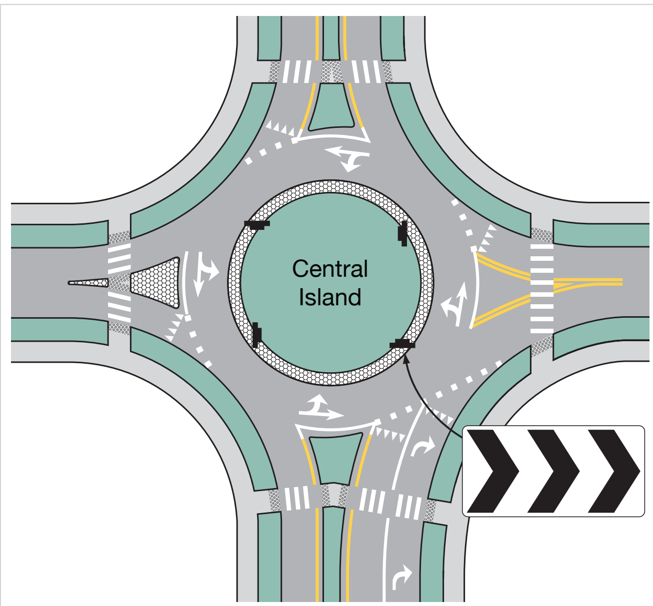
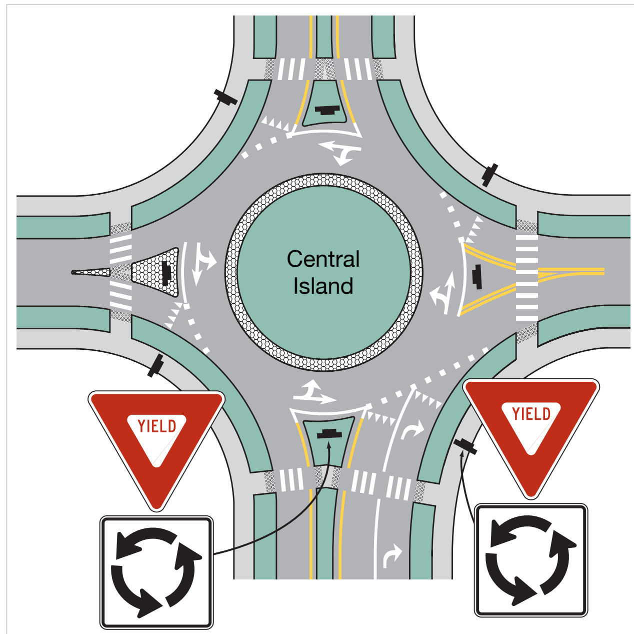



**Figure 31.** Roundabout directional arrow sign




(Optional)

**Figure 32.** Placement of Roundabout Circulation Plaques

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# PROMISING PRACTICES

These are treatments being utilized by transportation agencies that should benefit aging road users as determined by a subjective assessment by staff participating on the development of this Handbook. Current trends indicate these practices have a positive impact on aging road user safety.

## 17 Right-Turn Channelization Design

Right-turn channelization with tighter turning radii to reduce turning speeds to approximately 17 to 18 mph, decrease pedestrian crossing distances, and optimize the right-turning motorists' line of sight should be considered during design, as shown in the Preferred example on the right of Figure 33. Designs such as those on the left of Figure 33 are potentially problematic as drivers have to turn their heads farther to see oncoming traffic. The short curve radius should be between 25 and 40 ft, and the long curve radius should be between 150 and 275 ft. Traffic control devices at the end of the channelization should be visible to vehicles entering the channelized lane.

**References:** NCHRP 674:1

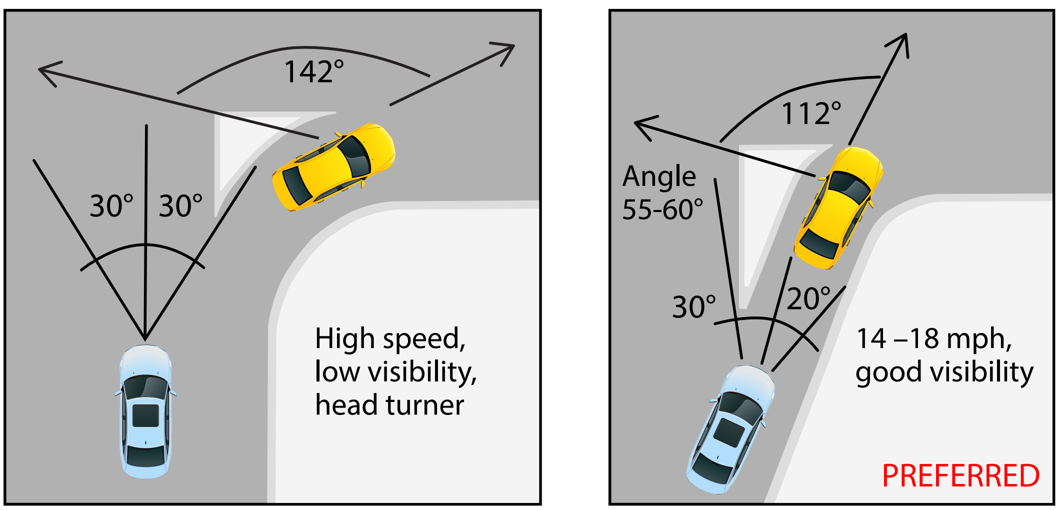


**Figure 33.** Right-Turn Channelization Design

The rationale and supporting evidence for these treatments can be found beginning on page 215 of this *Handbook*.

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# 18 Combination Lane-Use/Destination Overhead Guide Signs


**Figure 34.** Combination Lane Use/Destination Guide Sign (*MUTCD* D15-1)

At intersections where complex design features or heavy traffic is present, and specific guidance advising roadway users which lane is necessary for their intended destination, combination lane use/destination signs (D15-1) should be used. These signs are typically used as overhead combination lane use destination guide signs and are described in Section 2D.33 of the 2009 *MUTCD* (see Figure 34).

References: *MUTCD*:1

The rationale and supporting evidence for these treatments can be found beginning on page 215 of this *Handbook*.

# 19 Signal Head Visibility

Place all required signal heads overhead and centered over each lane instead of placing them on pedestal poles (see Figure 35). Supplemental signal heads may be placed on pedestal posts as needed. Do not place a signal head that displays a circular green indication over or directly in front of a left-turn lane. Instead, place a shared signal face over the lane line between the left-turn and through lane, or slightly to the right of it, or place a separate signal face over the center of the left turn lane that uses a flashing yellow arrow as the permissive indication.


**Figure 35.** Example Of One Signal Head Per Lane

References: *MUTCD*: 1

The rationale and supporting evidence for these treatments can be found beginning on page 216 of this *Handbook*.

**REFERENCES LEGEND** *See pages 3 and 4 for full description of codes and acronyms of cited design guides.*

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# 20 High-Visibility Crosswalks

To allow drivers to more easily see pedestrians in a marked crosswalk, high-visibility crosswalk marking patterns should be utilized. Two examples of such markings include white diagonal lines at a 45 degree angle to the crosswalk or the "ladder" crosswalk design shown in Figure 36.

**References:** *MUTCD*: 1

The rationale and supporting evidence for these treatments can be found beginning on page 216 of this *Handbook*.

**Figure 36.** High-Visibility ("Ladder") Crosswalk

# 21 Supplemental Pavement Marking for Stop and Yield Signs

Utilize "STOP AHEAD" word pavement markings to supplement stop ahead signs (W3-1) and "YIELD AHEAD" word pavement markings or yield ahead triangle symbol pavement markings to supplement yield ahead signs (W3-2). See Section 3B.20 of the 2009 *MUTCD* and Figure 37.

**References:** *MUTCD*: 1

The rationale and supporting evidence for these treatments can be found beginning on page 217 of this *Handbook*.

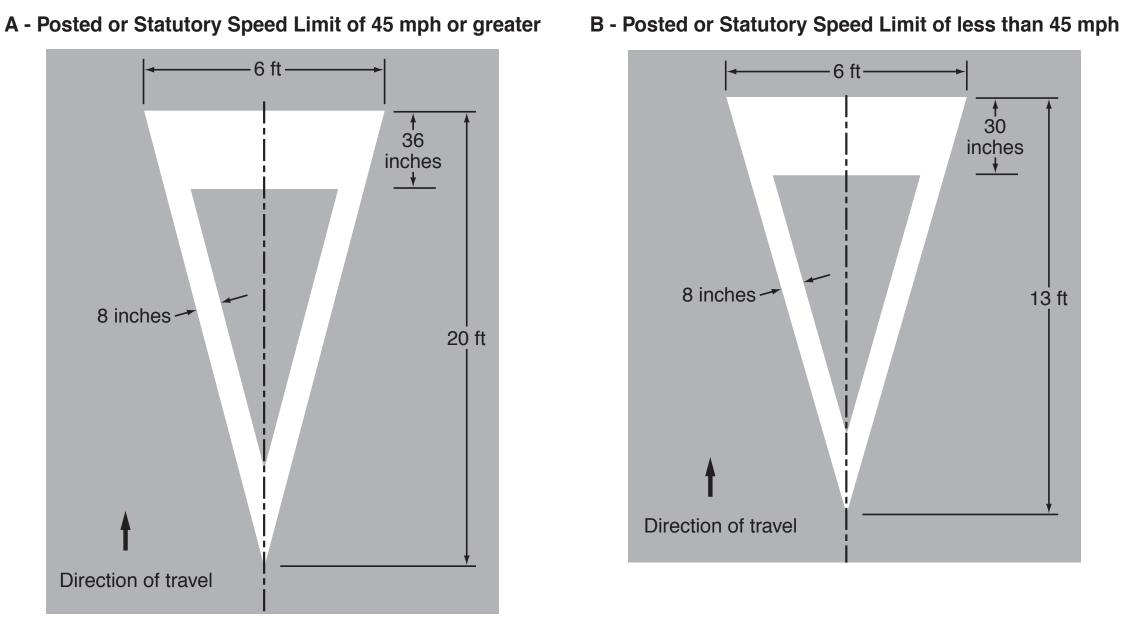


**Figure 37.** Yield Ahead Triangle Symbols

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# 22 Reduced Left-Turn-Conflict Intersections

A class of innovative intersection designs accommodate left-turns in unique ways, which greatly reduce, if not eliminate, unprotected left-turns at the intersection. Designs such as the median U-turn intersection (see Figure 38) and restricted-crossing U-turn (RCUT) intersection (see Figure 39) have features that minimize the operational delay and potential for crashes due to left turns. Other intersection designs that are increasingly common include the displaced left-turn (DLT) intersection and the diverging diamond interchange (DDI). These innovative intersection designs should be considered for suitability during the engineering study for new and reconstructed intersections.

The rationale and supporting evidence for these treatments can be found beginning on page 218 of this *Handbook*.

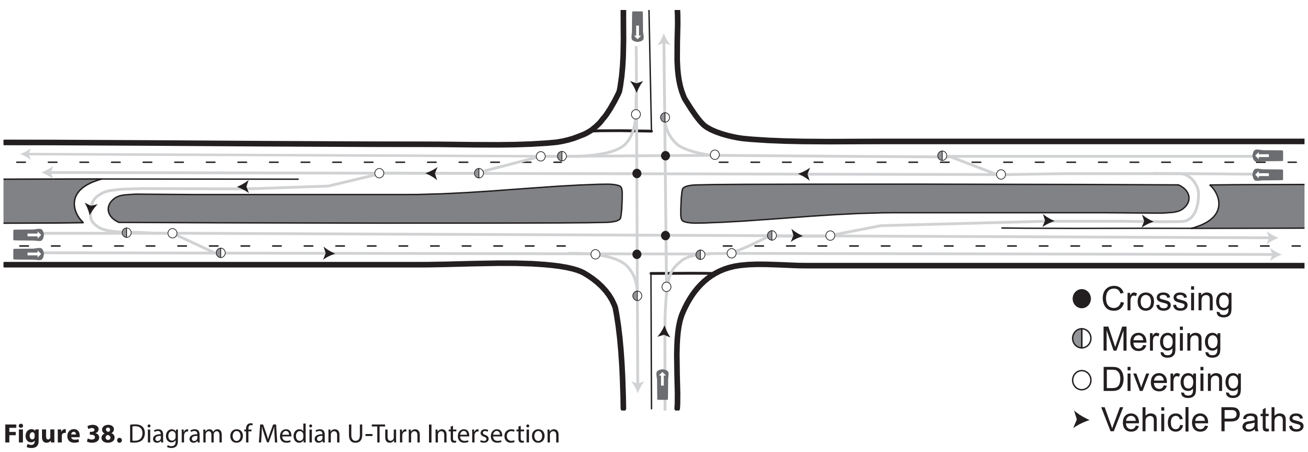


**Figure 38.** Diagram of Median U-Turn Intersection

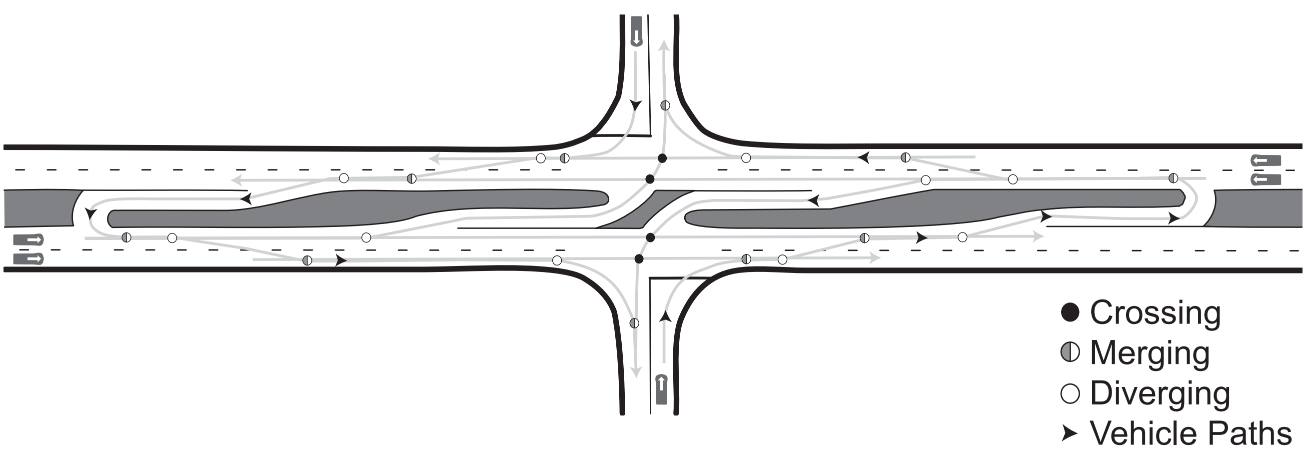


**Figure 39.** Diagram of Restricted Crossing U-Turn Intersection

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# 23 Accessible Pedestrian Signal (APS) Treatments

**A. Pushbutton-Activated Extended Pedestrian Crossing Phase**

At crosswalks frequently used by aging pedestrians, consider inclusion of pushbutton-activated extension of the pedestrian crossing phase, using the required signage described by the MUTCD, as shown in Figure 40.

**B. Passive Pedestrian Detection**

Use of passive pedestrian detection to help aging pedestrians who have difficulty using the pushbutton or to detect pedestrians within the crosswalk that may need more time to complete the crossing maneuver. Passive pedestrian detection uses sensors to detect the presence of pedestrians and register a pedestrian call with the signal system; as a result, the pedestrian does not have to push a button to request a WALK signal or extended crossing time.

The rationale and supporting evidence for these treatments can be found beginning on page 219 of this *Handbook*.

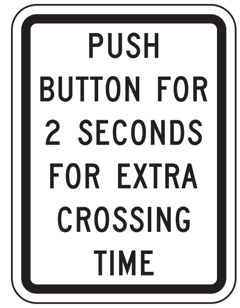


**Figure 40.** (MUTCD R10-32P)

# 24 Flashing Yellow Arrow

The flashing yellow arrow (see Figure 41) is the recommended signal indication for permissive left-turn movements at signalized intersections.

The rationale and supporting evidence for these treatments begins on page 220 of the *Handbook*.

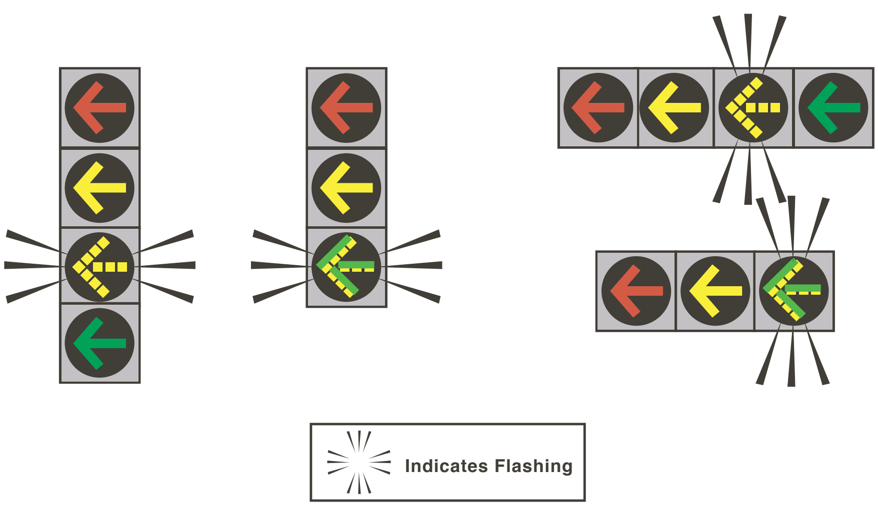


**Figure 41.** Typical arrangements of signal faces with flashing yellow arrow indications for permissive left-turn movements

REFERENCES LEGEND

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# CHAPTER 3
# Interchanges

This section of the *Handbook* provides treatments for highway design elements in six areas to enhance the performance of aging drivers at interchanges. Also, after the last design element, two promising practice treatments are presented. Drawings are for illustrative purposes only; they are not to scale and should not be used for design purposes.

## Proven Practices

25. Exit Signs and Markings
26. Freeway Entrance Traffic Control Devices
27. Delineation
28. Acceleration/Deceleration Lane Design
29. Interchange Lighting
30. Restricted or Prohibited Movements

## Promising Practices

31. Route Shield Markings at Major Freeway Junctions
32. Wrong-Way Driving Countermeasures

Overall, freeways are characterized by the highest safety level (lowest fatality rates) when compared with other types of highways in rural and urban areas (AAA Foundation for Traffic Safety, 1995). At the same time, freeway interchanges have design features that have been shown to result in safety and operational issues. Taylor and McGee (1973) reported that erratic maneuvers are a common occurrence at freeway exit ramps, and that the number of crashes there is four times greater than at any other freeway location. Two decades later, Lunenfeld (1993) reiterated that most freeway crashes and directional uncertainty occur in the vicinity of interchanges.

Distinct patterns in the occurrence of freeway interchange crashes emerge in studies that look specifically at driver age. Staplin and Lyles (1991) conducted a statewide (Michigan) analysis of the crash involvement ratios and types of violations for drivers in four age groups: age 76 and older; ages 56 to 75; ages 27 to 55; and age 26 and younger. Using induced-exposure methods to gauge crash involvement levels, this analysis showed that drivers over age 75 were overrepresented as the driver at fault in merging and weaving crashes near interchange ramps. With respect to violation types, the older driver groups were cited most frequently for failing to yield and for improper use of lanes. Similarly, Harkey, Huang, and Zegeer's study (1996) of the pre-crash maneuvers and contributing factors in aging driver freeway crashes indicated that aging drivers were much more likely than younger drivers to be merging or changing lanes, or passing/overtaking prior to a crash, and that aging drivers' failure to yield was the most common contributing factor. These data raise concerns about the use of freeway interchanges by aging drivers. Broader demographic and societal changes suggest that the dramatic growth in aging driver freeway travel between 1977 and 1988 reported by Lerner and Ratté (1991) will continue and even accelerate in the years ahead.

Age differences in interchange crashes and violations may be understood in terms of driving task demands and age-related diminished driver capabilities. The exit gore area is a transitional area that requires a major change in tracking. A driver (especially in an unfamiliar location) must process a large amount of directional information during a short period of time and at high speeds, while maintaining or modifying his/her position within the traffic stream. When drivers must perform guidance and navigation tasks in close proximity, the chances increase that they will become overloaded and commit errors (Lunenfeld, 1993). Erratic maneuvers resulting from driver indecisiveness in such situations include encroaching on the gore area, and even backing up on the ramp or the through lane. When weaving actions are required, the information-processing task demands for both entry and exit maneuvers are further magnified.

On a population basis, the age-related diminished capabilities that contribute most to aging drivers' difficulties at freeway interchanges include losses in vision and information-processing ability, and decreased physical flexibility in the neck and upper body. Specifically, aging adults show declines in static and dynamic acuity, increased sensitivity to glare, poor night vision, and reduced contrast sensitivity (McFarland, et al., 1960; Weymouth, 1960; Richards, 1972; Pitts, 1982; Sekuler, Kline, and Dismukes, 1982; Owsley, Sekuler, and Siemsen, 1983). These sensory losses are compounded by the following perceptual and cognitive deficits, the first two of which are recognized as being especially critical to safety: reduction in the ability to rapidly localize the most relevant stimuli in a driving scene; reduction in the ability to efficiently switch attention between multiple targets; reduction in working memory capacity; and reduction in processing speed (Avolio, Kroeck, and Panek, 1985; Plude and Hoyer, 1985; Ponds, Brouwer, and van Wolffelaar, 1988; Brouwer, et al., 1990; Brouwer, et al., 1991). The most important physical losses are reduced range of motion (head and neck), which impairs visual search, and slowed response time to execute a vehicle control movement, especially when a sequence of movements—such as braking, steering, and accelerating to weave and then exit a freeway—is required (Smith and Sethi, 1975; Goggin, Stelmach, and Amrhein, 1989; Goggin and Stelmach, 1990; Hunter-Zaworski, 1990; Staplin, Lococo, and Sim, 1990; Ostrow, Shaffron, and McPherson, 1992).

One result of these age-related diminished capabilities is demonstrated by a driver who waits when merging and entering freeways at on-ramps until he/she is alongside traffic, then relies on mirror views of overtaking vehicles on the mainline to begin searching for an acceptable gap (McKnight and Stewart, 1990). Exclusive use of mirrors to check for gaps, and slowing or stopping to look for a gap, increase the likelihood of crashes and have a negative effect on traffic flow. Malfetti and Winter (1987), in a critical incident study of merging and yielding problems, reported that aging drivers on freeway acceleration lanes merged so slowly that traffic was disrupted, or they stopped completely at the end of the ramp instead of attempting to approach the speed of the traffic flow before entering the mainline. In a survey of 692 aging drivers, 25 percent reported that they stop on a freeway entrance ramp before merging onto the highway, and 17 percent indicated that they have trouble finding a large enough gap in which to merge onto the mainline (Knoblauch, Nitzburg, and Seifert, 1997). Thirty-four percent of the respondents ages 50 to 72, and 26 percent of the respondents ages 73 to 97, responded that they wish entrance lanes were longer. In Lerner and Ratté's research (1991), aging drivers in focus group discussions commented that they experienced difficulty maintaining vehicle headway because of slower reaction times, difficulty reading signs, fatigue, mobility limitations, a tendency to panic or become disoriented, and loss of daring or confidence. Merging onto the freeway was the most difficult maneuver discussed. Needed improvements identified by these aging drivers included the elimination of weaving sections and short merge areas, which would facilitate the negotiation of on-ramps at interchanges. Improvements identified to ease the exit process included better graphics, greater use of sign panels listing several upcoming exits, and other methods to improve advance signing for freeway exits.

The intersection of interchange entrance and exit ramps with surface streets often creates an environment that is unfriendly and sometimes unsafe for pedestrians. Motorists often have a low yield rate at these locations and are traveling at moderately high speeds. These factors place vulnerable pedestrians, including aging pedestrians, in a compromised state when crossing at these locations. There has been very little research performed on specific roadway treatments for pedestrians at interchanges. As a result, there are not specific treatments included in this chapter. However, the treatments included in Chapter 2 for intersections may be considered and applied where engineering judgment deems it appropriate to increase driver awareness of pedestrians, slow vehicle speeds, and improve pedestrian mobility.

# PROVEN PRACTICES

## 25 Exit Signs and Markings

### A. Letter Size

The calculation of letter size requirements for signs at interchanges and on their approaches based on an assumption of a minimum specific ratio of 1 inch of letter height per 30 feet of legibility distance is recommended for new or reconstructed installations and for sign replacement.

**References:** TEH:4, *MUTCD*:1

### B. Mixed-Case Lettering

To increase the reading distance of all highway destination signs, it is required by the 2009 *MUTCD* that mixed-case lettering be used for destination and street names.

**References:** *MUTCD*:1

### C. Overhead Arrow-per-Lane Sign

The *MUTCD* recommends Overhead Arrow-per-Lane guide signs to be used on all new or reconstructed freeways and expressways as described in *MUTCD* Sections 2E.20 and 2E.21, whereby the number of arrow shafts appearing on the sign matches the number of lanes on the roadway at the location of the sign (see Figure 42).

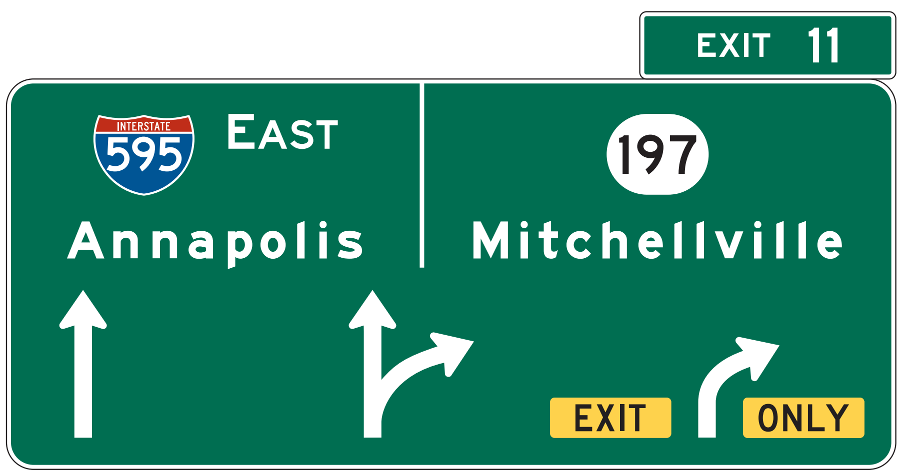


**Figure 42.** Example Overhead Arrow-per-Lane Sign

**REFERENCES LEGEND** *See pages 3 and 4 for full description of codes and acronyms of cited design guides.*

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Freeway and expressway splits or multi-lane exit interchanges that contain an interior option lane in which traffic can either leave the route or remain on the route, or choose either destination at a split, from the same lane should use overhead arrow-per-lane guide signs rather than diagrammatic guide sign designs. Overhead arrow-per-lane guide signs have been shown to be superior to either conventional guide signs or diagrammatic guide signs because they convey positive direction about which destination and direction each approach lane serves, particularly for the option lane, which is otherwise difficult to clearly sign.

**References:** *MUTCD*:1

### D. Retroreflective Sheeting

Microprismatic retroreflective sheeting should be used on overhead and ground-mounted guide signs (in place of Type III sheeting). The use of Clearview® font, in conjunction with retroreflective sheeting, should be considered because it may further enhance positive contrast legends if used appropriately.

**References:** *MUTCD*:4, *MUTCD*:5

The rationale and supporting evidence for these treatments can be found beginning on page 224 of this *Handbook*.

**REFERENCES LEGEND** *See pages 3 and 4 for full description of codes and acronyms of cited design guides.*

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# 26 Freeway Entrance Traffic Control Devices

## A. Guide Sign


**Figure 43.** (MUTCD D13-3)

A 48-in x 30-in guide sign panel with the legend Freeway Entrance (see Figure 43), using a minimum letter height of 8 in, should be consistently used in situations where freeway entrance and exit ramps are adjacent to one another (such as at a partial cloverleaf interchange) and placed as described in Section 2D.46 and shown in Figure 2D-14 of the *MUTCD*.

**References:** *MUTCD*:1

## B. Adjacent Entrance/Exit Ramps

Where adjacent entrance and exit ramps intersect with a crossroad, the use of a median separator, either painted or preferably raised, is recommended, with the nose of the separator delineated with yellow retroreflectorized markings and extending as close to the crossroad as practical without obstructing the turning path of vehicles (see Figure 44). Where engineering judgment determines the need for the median nose to be set back from the intersection, the setback distance should be treated by a 12-in or wider yellow stripe. In addition, a KEEP RIGHT (R4-7) sign should be posted on the median separator nose, if it is raised.

**References:** *MUTCD*:4

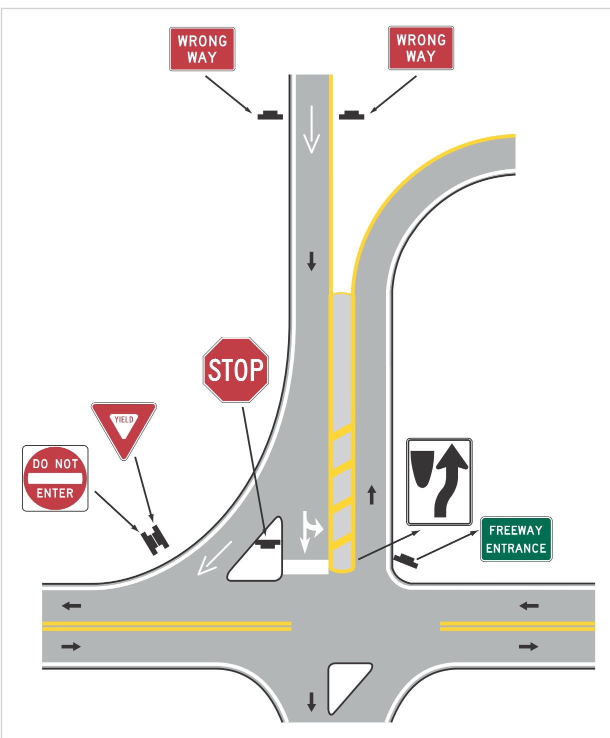


**Figure 44.** Recommended signs and markings for adjacent entrance/exit ramps at a crossroad intersection

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### C. Diagrammatic Entrance Sign

For diagrammatic guide signs depicting lane use for entry to a freeway from an urban multilane arterial, maximum visibility is achieved through overhead sign placement. Where this is not feasible, two advance ground-mounted diagrammatic guide signs should be used, one placed at 0.5 mi and the second placed at 0.25 mi in advance of the interchange (see Figure 45).

**References:** *MUTCD*:**4**

The rationale and supporting evidence for these treatments can be found beginning on page 235 of this *Handbook*.


**Figure 45.** Advance ground-mounted diagrammatic sign

# 27 Delineation

### A. Delineators/Raised Pavement Markers

Delineation in the vicinity of the exit gore at non-illuminated and partially illuminated interchanges should include, as a minimum, raised pavement markers and retroreflective post-mounted delineators as shown in Figure 46.

**References:** *Green Book*:4, *MUTCD*:4

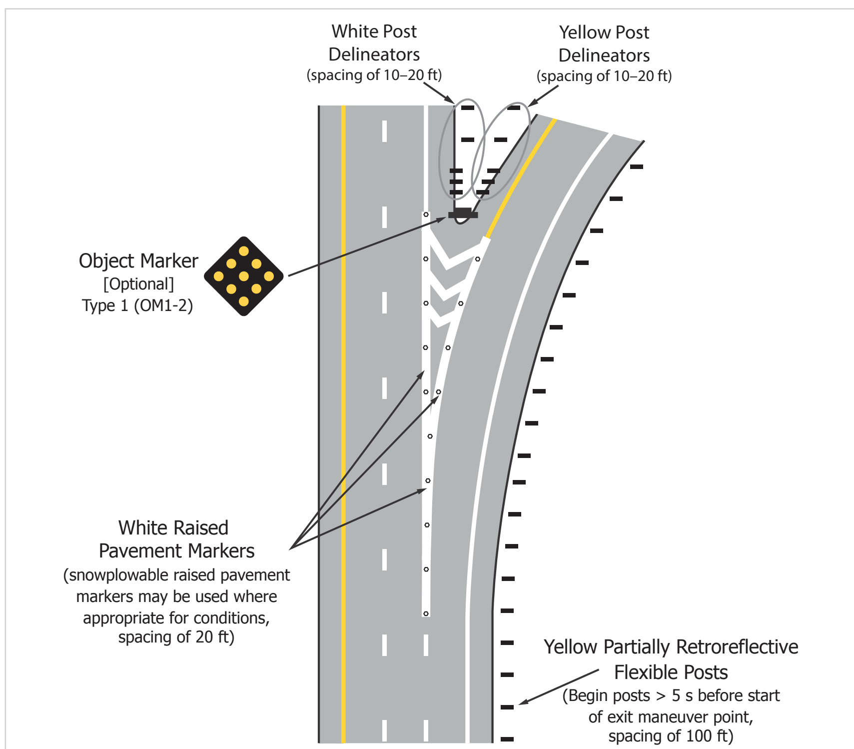


**Figure 46.** Recommended raised pavement markers and post-mounted delineators at an exit gore

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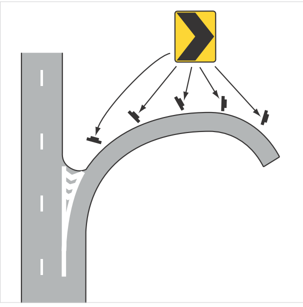

**Figure 47.** Placement of chevrons on the controlling curve of an exit ramp

**B. Object Marker**

Where engineering judgment has identified a hazardous gore area (e.g., containing a ditch) or other special visibility need, the minimum treatments described above should be supplemented by adding Type 1 object markers to the exit gore sign post as illustrated in Figure 46.

**References:** *Green Book*:4, TEH:3, *MUTCD*:1

**C. Chevrons/Post-Mounted Delineators**

Post-mounted delineators and/or chevrons should be applied to delineate the controlling curvature on exit ramps, as illustrated in Figure 47.

**References:** *MUTCD*:3

The rationale and supporting evidence for these treatments can be found beginning on page 238 of this *Handbook*.

## 28 Acceleration/Deceleration Lane Design

**A. Entrance Ramp Geometry**

A parallel (rather than a taper) design for entrance ramp geometry is recommended, as shown in Figure 48. AASHTO recognizes the operational and safety benefits of long acceleration lanes provided by parallel type entrances. A long acceleration lane provides more time for merging drivers to find an opening in the through-traffic stream. A parallel style entrance lane length of at least 1,200 ft, plus a taper, is desirable.

**References:** *Green Book*:1

**B. Location of Exit Ramps**

The AASHTO (2011) decision sight distance values should be consistently applied in locating ramp exits downstream from sight-restricting vertical or horizontal curvature on the mainline (instead of locating ramps based on stopping sight distance formulas).

**References:** *Green Book*:2

The rationale and supporting evidence for these treatments can be found beginning on page 243 of this *Handbook*.

**REFERENCES LEGEND** *See pages 3 and 4 for full description of codes and acronyms of cited design guides.*

1: most conservative
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3: new application of current practice
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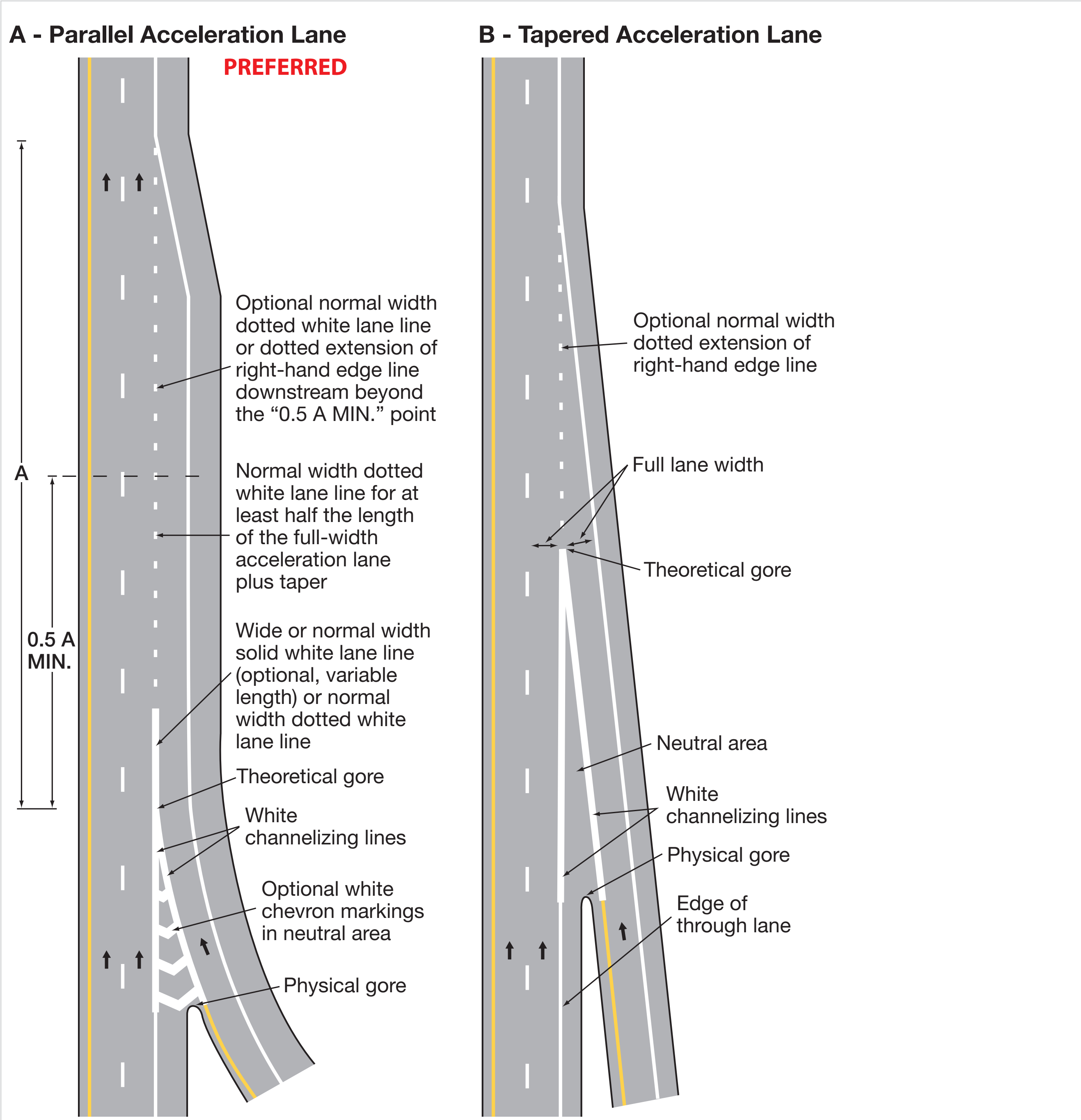


**Figure 48.** Recommended markings for acceleration lanes from entrance ramps onto freeways

**Legend**

- ➞ Direction of travel
- **A** Length of acceleration lane plus taper

**REFERENCES LEGEND** *See pages 3 and 4 for full description of codes and acronyms of cited design guides.*

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# 29 Interchange Lighting

## A. Complete versus Partial Lighting

Complete interchange lighting (CIL) is the preferred practice, but where a CIL system is not feasible to implement, a partial interchange lighting (PIL) system comprised of two high-mast installations (e.g., 60- to 150-ft- high structures with 3 to 12 luminaires per structure) per ramp is recommended, with one fixture located on the inner ramp curve near the gore, and one fixture located on the outer curve of the ramp, midway through the controlling curvature.

**References:** *Green Book*:4, RLH:4

The rationale and supporting evidence for this treatment can be found beginning on page 248 of this *Handbook*.

# 30 Restricted or Prohibited Movements

## A. Signing Practices

To meet overriding concerns for enhanced conspicuity of signing for prohibited movements, the following countermeasures should be used where DO NOT ENTER (R5-1) and WRONG WAY (R5-1a) signs are used:

A-1. For enhanced conspicuity of DO NOT ENTER (R5-1) and WRONG WAY (R5-1a) signs placed on freeway ramps, use larger than minimum *MUTCD* sizes for freeway applications with corresponding increases in letter size.

**References:** *MUTCD*:4

A-2. To provide increased sign conspicuity and legibility for aging drivers, use retroreflective fluorescent red sheeting materials that provide for high retroreflectance overall.

**References:** *MUTCD*:1

A-3. Where engineering judgment indicates an exaggerated risk of wrong-way movement crashes, both the R5-1 and R5-1a signs should be installed on both sides of the ramp, placed in accordance with the *MUTCD* (see Figure 49).

**References:** *MUTCD*:4

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A-4. Where all other engineering options have been tried or considered, lowering sign height to maximize brightness under low-beam headlight illumination is recommended by mounting the signs 36 in above the pavement (measured from the road surface to the bottom of the sign), or the lowest value above 36 in that is practical when the presence of snow, vegetation, or other obstructions is taken into consideration.

**References:** *MUTCD*: 2

## B. Pavement Markings

B-1. The application of 23.5-ft long wrong-way arrow pavement markings near the terminus on all exit ramps is recommended (see Figure 49).

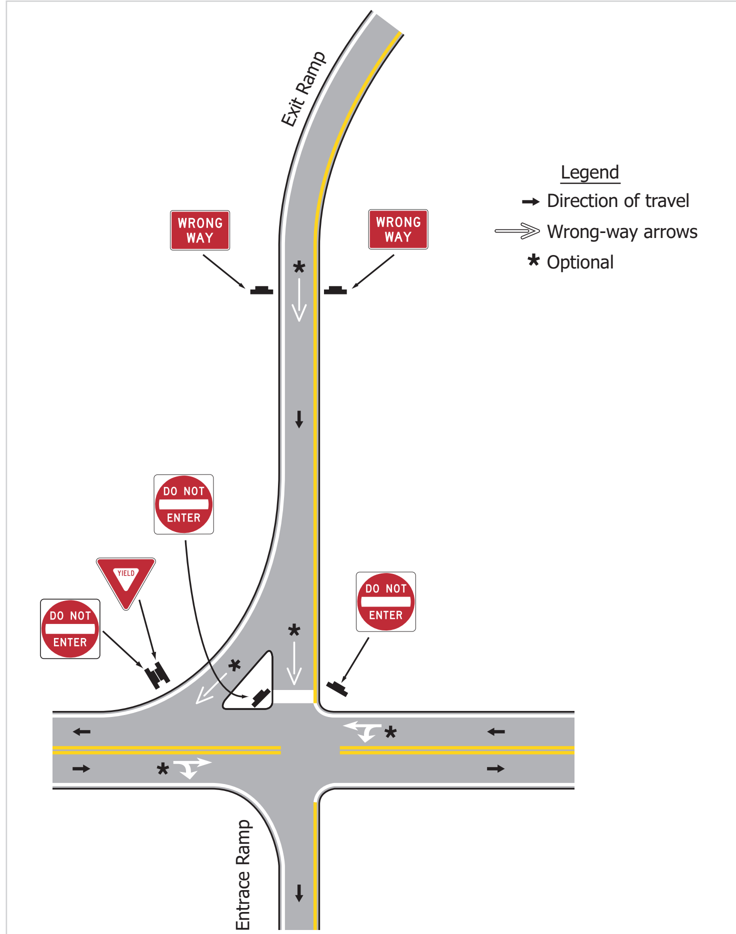


**Figure 49.** Recommended signing for restricted movements on an exit ramp

B-2. Where engineering judgment indicates a need for increased conspicuity, wrong-way arrow pavement markings should be supplemented with red/white bidirectional retroreflective raised pavement markers.

**References:** *MUTCD*:3

The rationale and supporting evidence for these treatments can be found beginning on page 252 of this *Handbook*.

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# PROMISING PRACTICES

These are treatments being utilized by transportation agencies that should benefit aging road users as determined by a subjective assessment by staff participating on the development of this Handbook. Current trends indicate these practices have a positive impact on aging road user safety.

## 31 Advance Pavement (Route Shield) Markings at Major Freeway Junctions

At major freeway interchanges and route splits, route shield markings should be used in the lanes approaching the split to guide drivers to the correct approach lane (see Figure 50). The placement of this type of marking should be just prior to the location of the advance guide signs.

**References:** *MUTCD*:1


**Figure 50.** Route Shield Markings At Freeway Junctions

The rationale and supporting evidence for these treatments can be found beginning on page 257 of this *Handbook*.

**REFERENCES LEGEND**

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# 32 Wrong-Way Driving Countermeasures

The NTSB's FARS analysis determined that drivers over the age of 70 are over-represented in fatal wrong-way crashes (NTSB, 2013). Additional treatments to counter wrong-way driving by aging drivers (e.g., improved lighting, channelization, signs and markings in addition to those in Treatment 30) should be considered where exit ramps intersect with surface streets. Road owners could employ the use of a Road Safety Audit (RSA) to examine the performance of the interchange and determine appropriate countermeasures to employ. A Wrong-Way Driving (WWD) Prompt list is available to focus specific attention on wrong-way driving issues and contributing factors. The prompt list has been developed in a similar framework to the broader RSA prompt lists contained in Chapter 8 of the FHWA RSA Guidelines document. The prompts are only an aid to the RSA team and they are not intended to cover all conditions or circumstances an RSA team may encounter. The American Traffic Safety Services Association also provides a publication that describes promising practices in wrong-way driving countermeasures (ATSSA, 2012); a review of that document should be included during the consideration of potential WWD treatments to implement.

**References:** *MUTCD*:4

The rationale and supporting evidence for these treatments can be found beginning on page 257 of this *Handbook*.

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# CHAPTER 4
# Roadway Segments

This section of the *Handbook* provides treatments to enhance the performance of aging drivers for the following design elements associated with roadway segments. Also, after the last element, six promising practice treatments are provided. Drawings are for illustrative purposes only; they are not to scale and should not be used for design purposes.

### Proven Practices

33. Horizontal Curves
34. Vertical Curves
35. Passing Zones
36. Lane Control Devices

### Promising Practices

37. Lane Drop Markings
38. Contrast Markings on Concrete Pavement
39. Utilize Highly Retroreflective Marking Material
40. Curve Warning Markings
41. Road Diets
42. High Friction Surface Treatments

Crashes on horizontal curves have been recognized as a considerable safety problem for many years. Crash studies indicate that roadway curves experience a higher crash rate than tangents, with rates ranging from one-and-a-half to four times higher than tangents (Glennon, Neuman, and Leisch, 1985; Zegeer, et al., 1990; Neuman, 1992). Lerner and Sedney (1988) reported anecdotal evidence that horizontal curves present problems for aging drivers. Also, analyses of crash data in Michigan found that aging drivers were involved in crashes on horizontal curves as a result of driving too fast for the curve or, more significantly, because they were surprised by the curve alignment (Lyles, et al., 1997). In reviewing literature on driver behavior on rural road curves, Johnston (1982) reported that horizontal curves that are less than 1960 ft in radius on two-lane rural roads, and those requiring a substantial reduction in speed from that prevailing on the preceding tangent section, were disproportionately represented among crash sites.

Successful curve negotiation depends on the choice of appropriate approach speed and adequate lateral positioning through the curve. Many studies have shown that loss-of-control crashes result from an inability to maintain a lateral position through the curve because of excessive speed, with inadequate deceleration in the approach zone. These problems, in turn, stem from a combination of factors, including poor anticipation of vehicle control requirements, induced by the driver's prior speed, and inadequate perception of the demands of the curve.

Many studies report a relationship between horizontal curvature (and the degree of curvature) and the total percentage of crashes by geometric design feature on the highways. The reasons for these crashes are related to the following inadequate driving behaviors:

- Deficient skills in negotiating curves, especially those of more than 3 degrees (Eckhardt and Flanagan, 1956).
- Exceeding the design speed on the curve (Messer, Mounce, and Brackett, 1981).
- Exceeding the design of the vehicle path (Glennon and Weaver, 1971; Good, 1978).
- Failure to maintain appropriate lateral position in the curve (McDonald and Ellis, 1975).
- Incorrect anticipatory behavior of curve speed and alignment when approaching the curve (Messer et al., 1981; Johnston, 1982).
- Inadequate appreciation of the degree of hazard associated with a given curve (Johnston, 1982).

With respect to vertical curves, design policy is based on the need to provide drivers with adequate stopping sight distance (SSD). That is, enough sight distance must exist to permit drivers to see an obstacle soon enough to stop for it under some set of reasonable worst-case conditions. The parameters that determine sight distance on crest vertical curves include the change of grade, the length of the curve, the height above the ground of the driver's eye, and the height of the obstacle to be seen. SSD is determined by the driver's reaction time, design speed, and deceleration rate. Current practice assumes an obstacle height of 2.0 ft and controlled braking rather than locked-wheel braking (AASHTO, 2004). Minimum lengths of crest vertical curves are based on sight distance and driver comfort. These criteria do not currently include adjustments for age-related effects in driving performance measures, which would suggest an even more conservative approach. At the same time, the general lack of empirical data demonstrating benefits for limited sight-distance countermeasures has led some to propose liberalization of model criteria, such as obstacle height (Neuman, 1989; Fambro, Fitzpatrick, and Koppa, 1997).

Standards and criteria for sight distance, horizontal and vertical alignment, and associated traffic control devices are based on the following driver performance characteristics: detection and recognition time, perception-reaction time, decision and response time, time to perform brake and accelerator movements, maneuver time, and (if applicable) time to shift gears. However, these values have typically been based on driving performance (or surrogate driving measures) of the entire driving population, or have been formulated from research biased toward younger (college age) as opposed to aging driver groups. The models underlying these design standards and criteria therefore have not, as a rule, included variations to account for slower reaction time or other performance deficits consistently demonstrated in research on aging driver response capabilities. In particular, diminished visual performance (reduced acuity and contrast sensitivity), physical capability (reduced strength to perform control movements and sensitivity to lateral force), cognitive performance (attentional deficits and declines in choice reaction time in response to unpredictable stimuli), and perceptual abilities (reduced accuracy of processing speed-distance information as required for gap judgments) combine to make the task of negotiating the highway design elements addressed in this section more difficult and less forgiving for aging drivers.

With the increasing need to provide more capacity on freeways and urban arterials, more jurisdictions are moving to the use of reversible lanes to accommodate peak-period traffic flows. The control of wrong-way movements on these facilities may be accomplished through the use of lane control signals (LCS), which provide real-time information to motorists about which lanes are open (green downward arrow), which are closed (red X) and which lanes are about to be closed (yellow X) either because of an incident downstream or because the lane is a reversible lane. Drivers should vacate lanes designated with a yellow X and should not enter lanes designated with a red X. Safe and effective responses to these indications by aging drivers hinge upon visual target detection and recognition processes that decline with advancing age.

# PROVEN PRACTICES

## 33 Horizontal Curves

### A. Edge Lines

White edge lines on horizontal curves (see Figure 51) are to be maintained at the following in-service contrast levels:

A-1. On highways without median separation of opposing directions of traffic, the recommended minimum in-service contrast level for edgelines on horizontal curves is 5.0.

A-2. On highways where median barriers effectively block the drivers' view of oncoming headlights or where median width exceeds 50 ft, the recommended minimum in-service contrast level for edgelines on horizontal curves is 3.75.

Contrast should be calculated according to this formula:

$$\text{Luminance contrast (C)} = \frac{\text{Luminance}_{\text{stripe}} - \text{Luminance}_{\text{pavement}}}{\text{Luminance}_{\text{pavement}}}$$

* *Luminance is the amount of light reflected from an object. This is different from retroreflectivity, which is a property of a material. While increasing retroreflectivity generally results in higher luminance, (often described as brightness)—especially at night—this may vary greatly for the same object or marking depending upon such factors as the location and intensity of the source of illumination, and the angle at which a driver views it.*

**References:** *MUTCD*: 4

**Figure 51.** White edge lines, centerline RPMs, and chevrons on a horizontal curve

**REFERENCES LEGEND**

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## B. Retroreflective Pavement Markers

The use of retroreflective raised pavement markers (RPMs) is recommended to improve the visibility of surface delineation treatments on horizontal curves in the following situations where demands on motorists for path maintenance and vehicle guidance are increased:

B-1. For curves with radii greater than 1640 ft and less than 3280 ft, it is recommended that standard centerline markings be supplemented with RPMs installed at standard spacing (i.e., 40 ft apart), and that they be applied for a distance of 5 s of driving time (at 85th percentile speed) on the approach to the curve and continued throughout the length of the curve. [See time-speed-distance table on page 5.] The Highway Safety Manual cites a negative effect on roadway crashes for some drivers when RPM's are installed on curves with radii less than 1640 feet.

B-2. Where engineering judgment indicates that nighttime wet pavement visibility for surface delineation treatments is a priority for safe operations, regardless of curve radius, the use of RPMs is recommended.

**References:** *MUTCD*: 4

## C. Post-Mounted Delineators

In addition to the installation of chevron alignment signs (W1-8) as specified in the *MUTCD*, roadside post-mounted delineators should be installed on horizontal curves with approximate uniform spacing as shown in Table 7.

**References:** *MUTCD*: 2

**Table 7.** Recommended spacing for post-mounted delineators.

| Radius of Curve (Feet) | Approximate Spacing (Feet) |
|---|---|
| < 600 | 40 |
| 700 | 75 |
| 800 | 80 |
| 900 | 85 |
| > 1000 | 90 |

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Note: Spacing for curves greater than 600 ft based on the following formula from the *MUTCD* (Table 3D-1):

$$\textbf{English: } S = 3(R\text{-}50)^{0.5}$$

Where:

S = approximate spacing on curve (ft)
R = radius (ft)

### D. Pavement Width

On two-lane rural roads, the combined (lane plus shoulder) paved width in one direction should be at least 18 ft throughout the length of the curve for a horizontal curve with a radius less than 1900 ft.

**References:** *Green Book*: 4

The rationale and supporting evidence for this treatment can be found beginning on page 260 of this *Handbook*.

## 34 Vertical Curves

### A. Perception-Reaction Time

To accommodate the exaggerated decline among aging drivers in response to unexpected hazards, strict adherence to a perception-reaction time (PRT) of at least 2.5 sec for a roadway hazard obscured by the vertical curvature should be used in the design of new and reconstructed facilities.

**References:** *Green Book*: 1

### B. Passive Warning Sign

Where a need has been determined for installation or replacement of a device to warn motorists that sight distance is restricted by a crest vertical curve, use the 30-in x 30-in HILL BLOCKS VIEW sign (*MUTCD* W7-6) with an Advisory Speed plaque (*MUTCD* W13-1P) as shown in Figure 52.

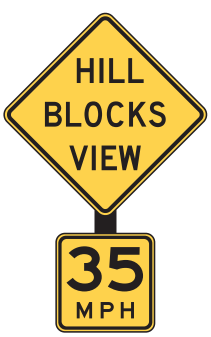

**Figure 52.** (*MUTCD* W7-6 and W13-1P)

**References:** *MUTCD*: 2

### C. Active Warning Sign

If a signalized intersection is obscured by vertical curvature in a manner that the signal becomes visible at a preview distance of 8 s or less (at operating speed), then it is recommended that, in addition to the standard advance signal warning sign (*MUTCD* W3-3), a BE PREPARED TO STOP warning sign (*MUTCD* W3-4) and WHEN FLASHING plaque (*MUTCD* W16-13)

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be used along with a warning beacon interconnected with the traffic signal controller (see Figure 53). The yellow warning beacon should be activated at a sufficient interval prior to the onset of the yellow signal phase and sustained after the onset of the green signal phase to take into account the end of queues experienced during peak traffic conditions, as determined through engineering study. [See time-speed-distance table on page 5.]

**References:** *MUTCD*: 2

The rationale and supporting evidence for these treatments can be found beginning on page 272 of this *Handbook*.


**Figure 53.** (*MUTCD* W3-4 and W16-13)

# 35 Passing Zones

## A. Passing Sight Distance

To accommodate age-related difficulties in judging gaps and longer decision-making and reaction times exhibited by aging drivers, use the most conservative minimum required passing sight distance (PSD) values from the 2009 MUTCD, Table 3B-1. See Table 8.

**References:** *Green Book*: 2, TEH: 2, MUTCD: 1

**Table 8.** Minimum passing sight distances for no-passing zone markings.

| 85th-Percentile or Posted or Minimum Passing | Statutory Speed Limit Sight Distance |
|---|---|
| 25 mph | 450 feet |
| 30 mph | 500 feet |
| 35 mph | 550 feet |
| 40 mph | 600 feet |
| 45 mph | 700 feet |
| 50 mph | 800 feet |
| 55 mph | 900 feet |
| 60 mph | 1,000 feet |
| 65 mph | 1,100 feet |
| 70 mph | 1,200 feet |

## B. Pennant

Use of the MUTCD oversized (48-in x 64-in x 64-in) NO PASSING ZONE pennant (W14-3), or the standard size (36 in x 48 in x 48 in) using fluorescent yellow retroreflective sheeting, is recommended as a high-conspicuity supplement to conventional centerline pavement markings at the beginning of no passing zones (see Figure 54).

**References:** MUTCD: 1, MUTCD: 3


**Figure 54.** (MUTCD W14-3)

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### C. Passing Lanes

To the extent feasible for new or reconstructed two-lane facilities, the implementation of passing/overtaking lanes (in each direction) at intervals of no more than 3.1 mi is recommended.

**References:** *Green Book*: 4, TEH: 4

The rationale and supporting evidence for these treatments can be found beginning on page 277 of this *Handbook*.

## 36 Lane Control Devices

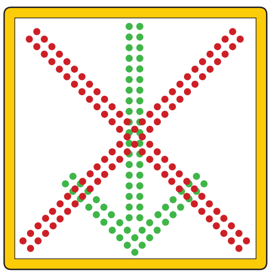

**Figure 55.** Lane Control Signal (adapted from Ullman et al. 1996)

### A. Pixel Specifications

To increase the legibility distance of overhead lane-control signal indications for prohibited movements (red X), use a double-stroke arrangement of pixels that are small (approximating 0.15 in diameter) and closely spaced (approximating 0.70 in center-to-center), as shown in Figure 55.

**References:** *MUTCD*: 4

The rationale and supporting evidence for these treatments can be found beginning on page 281 of this *Handbook*.

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# PROMISING PRACTICES

These are treatments being utilized by transportation agencies that should benefit aging road users as determined by a subjective assessment by staff participating on the development of this Handbook. Current trends indicate these practices have a positive impact on aging road user safety.

## 37 Lane Drop Markings

To provide additional guidance where a through lane becomes a mandatory turn lane at an intersection or becomes a mandatory exit lane at an interchange, a "dotted" lane line should be used to separate the continuing through lane from the mandatory turn or mandatory exit lane, as described in Section 3B.04 of the 2009 *MUTCD* and as shown in Figure 56.

**References:** *MUTCD*:1


**Figure 56.** Dotted Lane Line Markings at Freeway Lane Drop

The rationale and supporting evidence for these treatments can be found beginning on page 284 of this *Handbook*.

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# 38 Contrast Markings on Concrete Pavement

Contrast markings should be used wherever the pavement color is light to increase visibility of pavement markings (see *MUTCD* Section 3A.05 and Figure 57).

**References:** *MUTCD*:1

The rationale and supporting evidence for these treatments can be found beginning on page 284 of this *Handbook*.

**Figure 57.** Contrast Markings on Light Colored Pavement

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# 39 Utilize Highly Retroreflective Marking Material

To maintain visibility under adverse driving conditions, use highly retroreflective marking material.

**References:** *MUTCD*:4

The rationale and supporting evidence for these treatments can be found beginning on page 285 of this *Handbook*.

# 40 Curve Warning Markings

Curve warning pavement markings, such as shown in Figure 58, should be considered as a supplement to curve warning signs at horizontal curves identified as a safety problem.

**References:** TEH: 4, FHWA:2, *MUTCD*:5

The rationale and supporting evidence for these treatments can be found beginning on page 285 of this *Handbook*.


**Figure 58.** Curve Warning Markings (*MUTCD*:5)

**REFERENCES LEGEND** *See pages 3 and 4 for full description of codes and acronyms of cited design guides.*

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# 41 Road Diets

The classic roadway reconfiguration commonly referred to as a "road diet" involves converting an undivided four-lane roadway into three lanes made up of two through lanes and a center two-way left turn lane. An example of a completed road diet is shown in Figure 59. When performing an evaluation or road safety audit of a roadway segment that may be redesigned or reconstructed, a road diet should be included among the options to be considered.

**References:** HCM:1

The rationale and supporting evidence for these treatments can be found beginning on page 286 of this *Handbook*.

# 42 High Friction Surface Treatments

High friction surface treatments (HFST) are the site-specific application of very high quality polish-resistant, abrasion-resistant aggregates bonded to the pavement surface using a polymer binder that restores and maintains pavement friction where the need for a safer pavement surface is the greatest.

HFSTs are recommended on horizontal and vertical curves (such as the example shown in Figure 60), at intersections, at on and off-ramps, on bridge decks, locations prone to frequent rain, snow, or ice, or where additional side friction is beneficial.

**References:** *Green Book*:1

The rationale and supporting evidence for these treatments can be found beginning on page 287 of this *Handbook*.

**Figure 59.** Example of Road Diet

**Figure 60.** High Friction Surface Treatment on a Horizontal Curve

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# CHAPTER 5
# Construction/Work Zones

This section of the *Handbook* provides treatments to enhance the performance of aging drivers as they approach and travel through construction/work zones, keyed to five specific design elements. Also, after the last element, two promising practices treatments are provided. Drawings are for illustrative purposes only; they are not to scale and should not be used for design purposes.

## Proven Practices

43. Signing and Advance Warning
44. Portable Changeable (Variable) Message Signs
45. Channelization (Path Guidance)
46. Delineation of Crossovers/Alternate Travel Paths
47. Temporary Pavement Markings

## Promising Practices

48. Increased Letter Height for Temporary Work Zone Signs
49. Work Zone Road Safety Audit (WZRSA)

Highway construction and maintenance zones deserve special consideration with respect to aging driver needs because of their strong potential to violate driver expectancy. Alexander and Lunenfeld (1986) properly emphasized that driver expectancy is a key factor affecting the safety and efficiency of all aspects of the driving task. Consequently, it is understandable that crash analyses consistently show that more crashes occur on highway segments containing construction zones than on the same highway segments before the zones were implemented (Juergens, 1972; Graham, Paulsen, and Glennon, 1977; Lisle, 1978; Nemeth and Migletz, 1978; Paulsen, Harwood, and Glennon, 1978; Garber and Woo, 1990; Hawkins, Kacir, and Ogden, 1992).

Work-zone traffic control must provide adequate notice to motorists that describes the condition ahead, the location, and the required driver response. Once drivers reach a work zone, pavement markings, signing, and channelization must be conspicuous and unambiguous in providing guidance through the area. The National Transportation Safety Board (NTSB, 1992) stated that the *MUTCD* guidelines concerning signing and other work-zone safety features provide more than adequate warning for a vigilant driver, but may be inadequate for an inattentive or otherwise impaired driver. It is within this context that functional deficits associated with normal aging, as described below, may place aging drivers at greater risk when negotiating work zones.

In a crash analysis at 20 case-study work-zone locations, among the most frequently listed contributing factors were driver attention errors and failure to yield the right-of-way (Pigman and Agent, 1990). Aging drivers are most likely to demonstrate these deficits. Research on selective attention has documented that aging adults respond much more slowly to stimuli that are unexpected (Hoyer and Familant, 1987), suggesting that aging adults could be particularly disadvantaged by changes in roadway geometry and operations such as those found in construction zones. There is also research indicating that aging adults are more likely to respond to new traffic patterns in an "automatized" fashion, resulting in more frequent driver error (Fisk, McGee, and Giambra, 1988). To respond in situations that require decisions among multiple and/or unfamiliar alternatives, with unexpected path-following cues, drivers' actions are described by *complex reaction times* that are longer than reaction times in simple situations with expected cues. In Mihal and Barrett's analysis (1976) relating simple, choice, and complex reaction time to crash involvement, only an increase in complex reaction time was associated with crashes. The relationship with driver age was most striking: the correlation between complex reaction time and crash involvement increased from $r = 0.27$ for the total analysis sample (all ages) to $r = 0.52$ when only aging adults were included. Such data suggest that in situations where there is increased complexity in the information to be processed by drivers—such as in work zones—the most relevant information must be communicated in a dramatic manner to ensure that it receives a high priority by aging individuals.

Compounding their exaggerated difficulties in allocating attention to the most relevant aspects of novel driving situations, diminished visual capabilities among aging drivers are well documented (McFarland, Domey, Warren, and Ward, 1960; Weymouth, 1960; Richards, 1972; Pitts, 1982; Sekuler, Kline, and Dismukes, 1982; Owsley, Sekuler, and Siemsen, 1983; Wood and Troutbeck, 1994). Deficits in static and dynamic acuity and contrast sensitivity, particularly under low-luminance conditions, make it more difficult for them to detect and read traffic signs, to read variable message signs, and to detect pavement markings and downstream channelization devices. Olson (1988) determined that for a traffic sign to be noticed at night in a visually complex environment, its reflectivity must be increased by a factor of 10 to achieve the same level of conspicuity as in a low-complexity environment. Mace (1988) asserted that the minimum required visibility distance—the distance from a traffic sign required by drivers in order to detect the sign, understand the situation, make a decision, and complete a vehicle maneuver before reaching a sign—is increased significantly for aging drivers due to their poorer visual acuity and contrast sensitivity, coupled with inadequate sign luminance and legend size. Other age-related deficits cited by Mace (1988) include lowered driver alertness, slower detection time in complex roadway scenes due to distraction from irrelevant stimuli, increased time to understand unclear messages such as symbols, and slower decision making.

In a mail survey of 1,329 AARP members ages 50 to 97, conducted to identify aging driver freeway needs and capabilities, 21 percent of the respondents indicated that they have problems with accurately judging distances in construction zones (Knoblauch, Nitzburg, and Seifert, 1997). These drivers reported additional problems in negotiating work zones, including congestion/traffic; lack of adequate warning; narrow lanes; lane closures and lane shifts; and difficulty staying in their lane.

## PROVEN PRACTICES

# 43 Signing and Advance Warning

### A. Flashing Yellow Arrow Panel

At construction/maintenance work zones on high-speed roadways (where the posted speed limit is 45 mph or greater) and divided highways, the consistent use of a flashing arrow panel located at the taper for each lane closure is recommended as shown in Figure 61.

**References:** MUTCD:4

### B. Lane Closure Advance Signing

In implementing advance signing for lane closures as per MUTCD Part 6, it is recommended that:

A supplemental (portable) changeable message sign (CMS) displaying the one-page (phase) message LEFT (RIGHT, CENTER) LANE CLOSED should be placed 0.5 to 1.0 mile upstream of the lane closure taper (see Figure 62).

**OR**

Redundant static signs should be used, with a minimum letter height of 8 in and fluorescent orange retroreflective sheeting, where both the first upstream sign (e.g., W20-1) and the second sign (e.g., W20-5) encountered by the driver are equipped with flashing warning lights throughout the entire time period of the lane closure (see Figure 63).

**References:** TEH:4, MUTCD:4

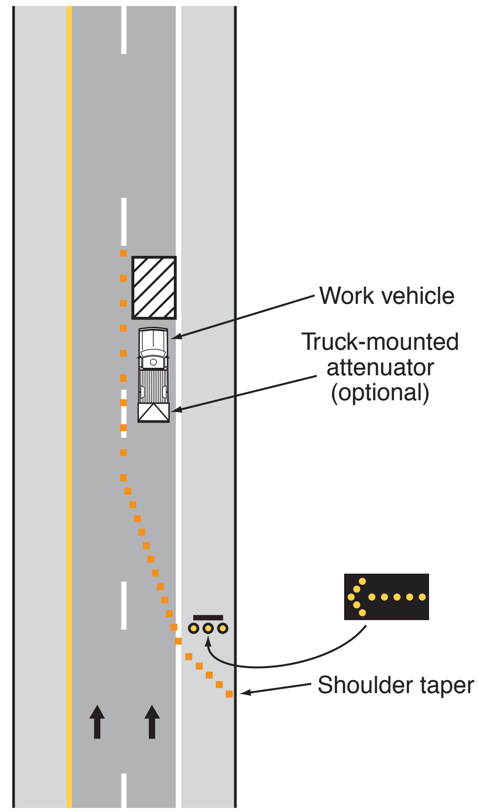


**Figure 61.** Flashing arrow panel at lane closure taper

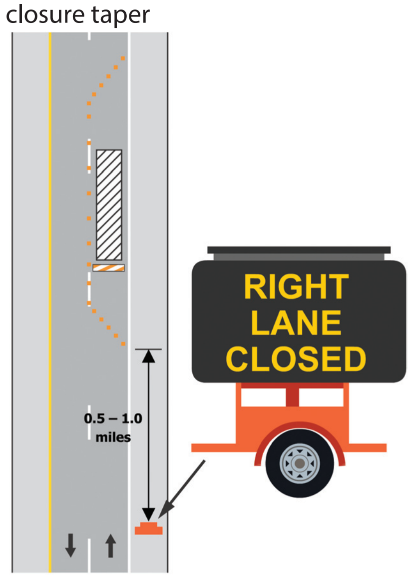


**Figure 62.** Changeable message sign upstream of lane closure taper

**REFERENCES LEGEND** *See pages 3 and 4 for full description of codes and acronyms of cited design guides.*

1: most conservative
2: preferred among differing guides
3: new application of current practice
4: more specific, detailed or stringent
5: permissible only in accordance with MUTCD section 1A.10, Interpretations, Experimentations, and Changes

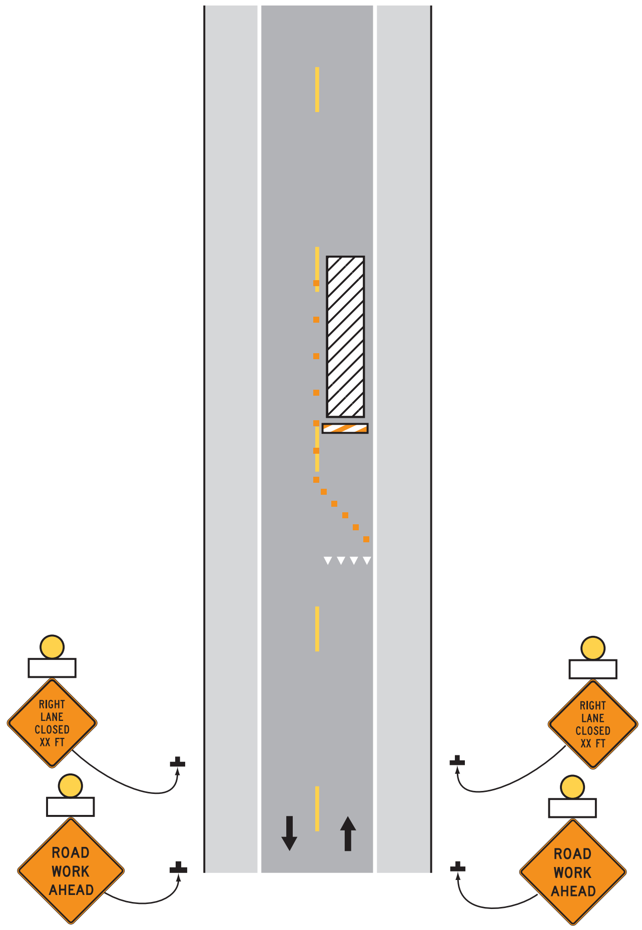


**Figure 63.** Redundant static signs upstream of lane closure taper

### C. Sign Sheeting

To increase the legibility distance of ground-mounted work-zone signs, the use of fluorescent orange is recommended over the use of beaded high-intensity orange sheeting.

**References:** MUTCD:1, NCHRP 500-9:4

### D. Legibility Distance

A minimum specific ratio of 1 inch of letter height per 30 feet of legibility distance should be used.

**References:** TEH:4, *MUTCD*:1

The rationale and supporting evidence for these treatments can be found beginning on page 290 of this *Handbook*.

**REFERENCES LEGEND**

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# 44 Portable Changeable (Variable) Message Signs

## A. Number of Phases

The *MUTCD* requires that no more than two phases be used on a changeable message sign (CMS). If a message cannot be conveyed in two phases, multiple CMSs and/or a supplemental highway advisory radio message should be used; alternatively, the action statement only may be presented on a single page/phase.

**References:** TEH:2, *MUTCD*:4

## B. Display Time

Each phase of a CMS message should be displayed for a minimum of 3 s.

**References:** *MUTCD*:1

## C. Units of Information

C-1. It is recommended that no more than one unit of information be displayed on a single line on a CMS, and no more than three units should be displayed for any single phase. A unit of information is one or more words that answers a specific question (e.g., What happened? Where? What is the effect on traffic? What should the driver do?).

**References:** *MUTCD*:4

C-2. For CMS messages split into two phases, a total of no more than four unique units of information should be presented.

**References:** TEH:4, *MUTCD*:4

## D. Sign Content

When a CMS is used to display a message in two phases, the problem and location statements should be displayed during phase 1 and the effect or action statement during phase 2, as illustrated in Figure 64.

If legibility distance restrictions rule out a two-phase display, the use of abbreviations [as specified in the *MUTCD* (FHWA, 2007)] plus elimination of the problem statement is the recommended strategy to allow for the presentation of the entire message in one phase, as illustrated in Figure 65.

**References:** TEH:4, *MUTCD*:4



**Figure 64.** Phase 1 (Top) and Phase 2 (Bottom)


**Figure 65.** Use of approved abbreviation in one-phase message

**REFERENCES LEGEND** *See pages 3 and 4 for full description of codes and acronyms of cited design guides.*

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### E. Legibility

For superior legibility:

E-1. Only single-stroke lettering should be used for displays of alphanumeric characters on portable CMSs with the conventional 5- x 7-pixel matrix; double-stroke lettering should be avoided.

**References:** *MUTCD*:4

E-2 As new portable CMSs are procured by a highway agency, the performance specifications of such devices should include a minimum character width-to-height ratio of 0.7 (complete character) and a maximum stroke width-to-height ratio of 0.13.

**References:** *MUTCD*:4

### F. Sign Height

Portable changeable message signs should be elevated to a height sufficient to be seen across multiple lanes of (same-direction) traffic by approaching passenger car drivers.

**References:** *MUTCD*:4

The rationale and supporting evidence for these treatments can be found beginning on page 300 of this *Handbook*.

## 45 Channelization (Path Guidance)

### A. Device Dimensions

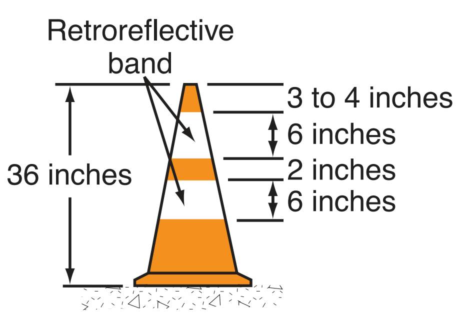


**Figure 66.** Traffic cone for nighttime work zone operations

The following minimum dimensions or properties for channelizing devices used in highway work zones are recommended to accommodate the needs of aging drivers:

A-1 Traffic cones—36 in high, with two bands of retroreflective material totaling at least 12 in wide for nighttime operations. (see Figure 66)

**References:** *MUTCD*:4

A-2 Tubular markers—42 in high, with a single band of retroreflective material at least 12 in wide for nighttime operations.

**References:** *MUTCD*:4

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A-3 Vertical (striped) panels—12 in wide.

**References:** *MUTCD*:1

A-4 Barricades—12-in x 36-in minimum dimension.

**References:** *MUTCD*:2

A-5 Drums—18 in x 36 in, with high-brightness sheeting for the orange and white retroreflective stripes (as per *MUTCD* guidelines).

**References:** *MUTCD*:4

**B. Device Spacing**

Channelizing devices through work zones (in non-crossover applications) should be spaced at no more than a distance in feet equal to the speed limit through the work zone in miles per hour (e.g., in 40-mph work zone, channelizing devices should be spaced no farther apart than 40 ft). Where engineering judgment indicates a special need for speed reduction where there is horizontal curvature or through the taper for a lane closure, spacing of channelizing devices at a distance in feet equal to no more than half of the speed limit in miles per hour is recommended (e.g., in a 40-mph zone, space the devices no farther apart than 20 ft).

**References:** *MUTCD*:4

**C. Reflectors**

The use of side reflectors with cube-corner lenses or reflectors (facing the driver) mounted on top of concrete safety-shaped barriers and related temporary channelizing barriers is recommended, spaced (in feet) at no more than the construction zone speed limit (in miles per hour) through a work zone.

**References:** *MUTCD*:4

The rationale and supporting evidence for these treatments can be found beginning on page 313 of this *Handbook*.

**REFERENCES LEGEND** *See pages 3 and 4 for full description of codes and acronyms of cited design guides.*

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# 46 Delineation of Crossovers/ Alternate Travel Paths

## A. Positive Barriers

Use positive barriers in transition zones and positive separation (channelization) between opposing two-lane traffic throughout a crossover, for intermediate- and long-term-duration work zones, for all roadway classes except residential.

**References:** *MUTCD*:1

## B. Device Spacing

A maximum spacing (in feet) of one-half the construction zone speed limit (in miles per hour) for channelizing devices (other than concrete barriers) is recommended in transition areas, and through the length of the crossover, and in the termination area downstream (where operations as existed prior to the crossover resume).

**References:** *MUTCD*:4

## C. Reflectors

Use side reflectors with cube-corner lenses spaced (in feet) at no more than the construction zone speed limit (in miles per hour) on concrete channelizing barriers in crossovers (or alternately, the use of retroreflective sheeting on plastic glare-control louvers [paddles] placed in crossovers).

**References:** *MUTCD*:4

## D. Screens

It is recommended for construction/work zones on high-volume roadways that glare-control screens be mounted on top of temporary traffic barriers that separate two-way motor vehicle traffic, when used in transition and crossover areas, at a spacing of not more than 24 in.

**References:** *MUTCD*:4

The rationale and supporting evidence for these treatments can be found beginning on page 318 of this *Handbook*.

**REFERENCES LEGEND**

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# 47 Temporary Pavement Markings

## A. Raised Pavement Markers

Where temporary pavement markings shorter than the 10-ft standard length are implemented, it is recommended that a raised pavement marker be placed at the center of the gap between successive markings.

**References:** *MUTCD*:2

The rationale and supporting evidence for this treatment can be found beginning on page 323 of this *Handbook*.

**REFERENCES LEGEND** *See pages 3 and 4 for full description of codes and acronyms of cited design guides.*

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# PROMISING PRACTICES

These are treatments being utilized by transportation agencies that should benefit aging road users as determined by a subjective assessment by staff participating on the development of this Handbook. Current trends indicate these practices have a positive impact on aging road user safety.


**Figure 67.** Temporary work zone sign with increased letter height

## 48 Increased Letter Height for Temporary Work Zone Signs

It is recommended that some "action" words on temporary work zone signs on portable sign stands have a minimum letter height of 8 in. (see Figure 67)

**References:** *MUTCD*:4

The rationale and supporting evidence for these treatments can be found beginning on page 328 of this *Handbook*.

## 49 Work Zone Road Safety Audit (WZRSA)

The Work Zone Road Safety Audit Guidelines and Prompt Lists provide a process for individuals or agencies performing formal work zone safety examinations to improve the safety of workers and all roadway users, including the aging population. This document includes guidance on conducting Road Safety Audits (RSA) at all phases of work zone planning, design and deployment, and considerations for each project phase. The guidelines and prompt lists explain the importance of the Work Zone RSA and navigate the practitioner through the RSA process.

**References:** *MUTCD*:4

The rationale and supporting evidence for these treatments can be found beginning on page 329 of this *Handbook*.

**REFERENCES LEGEND**

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# CHAPTER 6
# Highway-Rail Grade Crossing

This section of the *Handbook* provides treatments to enhance the performance of aging drivers at highway-rail grade crossing, keyed to two specific proven practices:

### Proven Practices

50. Passive Traffic Control Devices
51. Lighting

There are no promising practice treatments for this element.  Drawings are for illustrative purposes only; they are not to scale and should not be used for design purposes.

According to the Federal Railroad Administration (FRA, 2014), there were 1,967 highway-rail grade crossing crashes in 2012, resulting in 233 fatalities and 941 injuries. An FRA report found 55 percent of such incidents in 2012 occurred during the day, 29 percent occurred at night, and 16 percent occurred during dusk/dawn. Fifty-six percent of the crashes in 2012 occurred at crossings with passive controls. In a U. S. Department of Transportation Office of Inspector General report (June 2004), driver error was cited as the probable cause of the crash in 94 percent of vehicle crashes at highway grade crossings for the previous ten years.

Klein, Morgan, and Weiner (1994) analyzed Fatality Analysis Reporting System (FARS) data from 1975 to 1992 to determine the characteristics of drivers involved in fatal crashes at highway-rail grade crossings, and the circumstances under which such crashes occurred. This analysis indicated that drivers ages 25 to 34 are involved in the highest percentage (almost 25 percent) of all fatal rail crossing crashes, followed by drivers ages 16 to 20 (approximately 18 percent).  Drivers in these age groups also show the highest involvement in all fatal crashes and all fatal intersection crashes, based on crash frequency data uncorrected for exposure.  By contrast, drivers ages 65 to 74 were involved in 6.5 percent of fatal railroad crossing crashes and drivers ages 74 and older account for almost 5 percent of the railroad crossing fatalities.  Again, these data do not reflect level of exposure.  However, the data show that the percentage of drivers ages 65 to 74 who are involved in fatal rail crossing crashes is slightly more than the percentage of drivers in this age group who are involved in all fatal crashes (4.6 percent) and about the same as those involved in fatal intersection crashes (6.2 percent), which is the maneuver category for which aging drivers are most at risk.  Notably, the proportion of aging drivers involved in highway-rail grade crossing crashes at night is higher than the proportion of aging drivers in vehicle-involved crashes at night, suggesting special problems associated with the use of these facilities under reduced visibility conditions.

There are several age-related diminished capabilities that may make the task of safely negotiating highway-rail grade crossing more difficult for aging drivers.  Well-documented losses in visual acuity and contrast sensitivity with advancing age (Burg, 1967; Ball and Owsley, 1991; Ball, et al., 1993; Decina and Staplin, 1993) may delay substantially the detection of critical elements such as the standard crossbuck or warning symbol during a motorist's approach to a crossing, and may preclude detection of a train actually present at the crossing until impact is imminent, especially at night. While the analyses of Klein et al. (1994) paint a compelling picture of young males engaging in intentionally risky behavior as a significant component of the crash problem at rail crossings, the technical literature suggests that willful noncompliance with traffic control devices by aging drivers at these sites will not be a major problem—if they (visually) detect and comprehend the advisory, warning, and regulatory information conveyed by these devices in time to respond safely.

Expectancy also plays a role in where and when drivers look for trains, and consequently, train detection (Raslear, 1995). A driver who is familiar with a crossing and rarely or never encounters a train during the time period he or she uses the crossing is more likely to miss seeing a train than either the driver who is unfamiliar with the crossing and therefore has no expectations about train frequency, or the driver who is familiar with the crossing and frequently encounters trains during the time period that he or she crosses the tracks. Drivers who don't expect trains do not look for them. As a consequence, per train, crash rates are higher for crossings with the lowest frequency of trains (Raslear, 1995). Enhancing the conspicuity and comprehension of design elements at passive crossings, plus the use of signing that orients drivers' attention toward trains and advises drivers on the appropriate action to be taken, are thus top priorities.

Comprehension of highway-rail crossing traffic control devices and performance of related information-processing tasks may be expected to pose disproportionate difficulty for aging drivers. Although the crossbuck sign is a regulatory sign that serves as an implied YIELD sign, researchers consistently report that drivers do not understand the message it is intended to convey (Bridwell, et al., 1993; Fambro, et al., 1997).

Furthermore, assuming that a driver has been properly alerted to the need to search for an approaching train by design elements upstream and at the crossing, has slowed, and has begun to actively scan the tracks in each direction, the perception-reaction time (PRT) for a decision either to stop or to proceed, plus the subsequent execution of a brake or accelerator response, draw upon abilities found to slow significantly among the elderly (Staplin and Fisk, 1991; Goggin, Stelmach, and Amrhein, 1989; Stelmach, Goggin, and Amrhein, 1988). Whereas AASHTO (2011) uses a PRT of 2.5 s for calculating the sight triangle at passive grade crossings, over two decades ago, Gordon, McGee, and Hooper (1984) recommended that a full second be added to this design value to accommodate the 85th percentile driver. With the ever-increasing number and percentage of aging drivers, the need to refocus attention on this issue is urgent.

Additional insight is provided by Leibowitz (1985), who showed that inaccurate judgments of train speed and distance may make drivers' decisions to cross hazardous, due to perceptual illusions. Most drivers are not aware of the effects of the illusions of perspective, train size, and velocity (e.g., the bigger the object, the slower it appears to be moving), and this results in unsafe crossing decisions. Kinnan (1993) states that, in most cases, the driver believes the decision to cross is a rational one; most motorists seriously underestimate the risk because they can't properly gauge the speed of the train or its distance from the crossing. This problem will only be exacerbated by the age-related decline in the ability to integrate speed and distance information, as reported by Staplin, Lococo, and Sim (1993) for the judgment of gaps at intersections.

Finally, age-related hearing loss may contribute to a failure to detect a train approaching a crossing. According to government statistics (DHHS, 1994), approximately 30 to 35 percent of people ages 65 to 75 have a hearing loss, increasing to 40 percent for persons over the age of 75. Janke (1994) reported that totally deaf males have more crashes than their non-deaf counterparts, and drivers who wear hearing aids have an increased risk of crashing compared to drivers who do not wear them (excluding individuals who formerly wore hearing aids then discarded them, who had an even worse driving record). Thus, auditory train signals may not be completely effective as a secondary warning system for visually impaired drivers or drivers who neglect to properly scan at rail crossings if they are also hearing impaired. At the same time, data show that audible warnings can help reduce nighttime crashes, as evidenced by the 195 percent increase in collisions in Florida as a result of a nighttime whistle ban between 10:00 p.m. and 6:00 a.m. (Kinnan, 1993). Raslear's (1995) crash prediction model indicates that the use of the train whistle reduces the field of visual search from 180° to 10°, which, in turn, reduces the visual search time by a factor of 18. By decreasing visual search time, the train whistle decreases the probability of a crash.

Though few studies have directly measured the effectiveness of countermeasures for aging drivers in this arena, sufficient data exist to explain performance errors among the population at large to support highway-rail grade crossing design element treatments for passive crossing control devices that offer the greatest promise to improve safety for aging road users.

## PROVEN PRACTICES

# 50 Passive Traffic Control Devices

**A. Post-Mounted Delineators**

For rural passive grade crossings that are not illuminated, it is recommended that the approach be delineated with post-mounted delineators spaced 50 ft or closer together on the right shoulder, from the location of the Railroad Advance Warning sign (W10-1) to the crossbuck, and extending an equal distance beyond the crossbuck (as illustrated in Figure 68).

**References:** RRX:4

The rationale and supporting evidence for these treatments can be found beginning on page 332 of this *Handbook*.

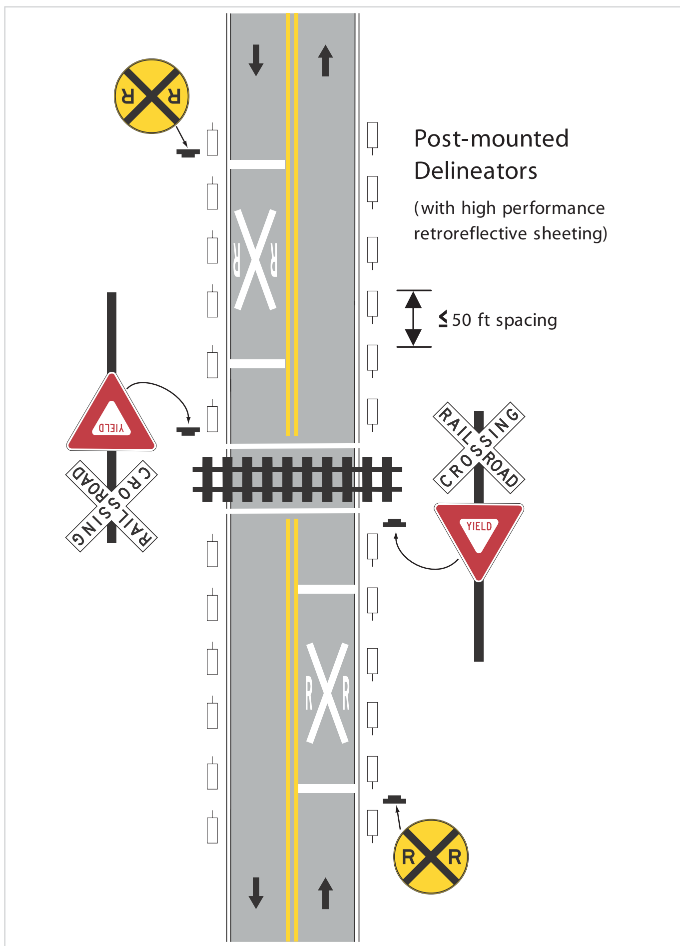


**Figure 68.** Recommended placement of post-mounted delineators

**REFERENCES LEGEND** *See pages 3 and 4 for full description of codes and acronyms of cited design guides.*

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# 51 Lighting

## A. Luminaire Type/Alignment

Illumination at a crossing may be effective in reducing nighttime collisions. Illuminating most crossings is technically feasible because more than 90 percent of all crossings have commercial power available. Illumination may be effective under the following conditions:

- Nighttime train operations.
- Low train speeds.
- Blockage of crossings for long periods at night.
- Collision history indicating that motorists often fail to detect trains or traffic control devices at night.
- Horizontal and/or vertical alignment of highway approach such that vehicle headlight beam does not fall on the train until the vehicle has passed the safe stopping distance.
- Long dark trains, such as unit coal trains.
- Restricted sight or stopping distance in rural areas.
- Humped crossings where oncoming vehicle headlights are visible under trains.
- Low ambient light levels.
- A highly reliable source of power.

Luminaires may provide a low-cost alternative to active traffic control devices on industrial or mine tracks where switching operations are carried out at night.

Luminaire supports should be placed in accordance with the principles in the Roadside Design Guide and NCHRP Report 350. If they are placed in the clear zone on a high-speed road, they should be breakaway.

**References:** RLH:4, RRX:4, MUTCD:4

The rationale and supporting evidence for these treatments can be found beginning on page 343 of this *Handbook*.

**REFERENCES LEGEND** *See pages 3 and 4 for full description of codes and acronyms of cited design guides.*

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# PART II

# Rationale and Supporting Evidence

## Overview

This section of the *Handbook* is organized in terms of the same category of highway features as the treatments:

Chapter 7 – Intersections,

Chapter 8 – Interchanges,

Chapter 9 – Roadway Segments,

Chapter 10 – Construction/Work Zones, and

Chapter 11 – Highway-Rail Grade Crossings.

Within each of these five chapters (category), subsections are organized in terms of design elements with unique geometric, operational, and/or traffic control characteristics, also consistent with the treatments. Also, the rationale for the additional "Promising Practices" treatments included under Intersections, Interchanges, Roadway Segments and Construction/Work Zones is presented at the end of their respective chapters.

At the beginning of each subsection within a class of highway features, reference material for a particular design element is introduced using a cross-reference table. This table relates the discussion in that subsection—as well as the associated treatments, presented earlier—to entries in standard reference manuals consulted by practitioners in this area. Principal among these reference manuals are the following:

- *Manual on Uniform Traffic Control Devices*, Editions 2009 and 2003. (Note to reader: if the discussion refers to *MUTCD* material found in the revisions to 2003 published in 2007, the citation will be *MUTCD* 2003a.)
- *A Policy on Geometric Design of Highways and Streets* [the *Green Book*], 2011);
- *Traffic Engineering Handbook* (TEH, 2009).

Other standard references with more restricted applicability, which also appear in the cross-reference tables for selected design elements, include the following:

- *Intersection Channelization Design Guide*, NCHRP Report No. 279, (Neuman, 1985).

- *Roundabouts: An Informational Guide*, Second Edition, NCHRP Report 672, (Rodegerdts, et al., 2010).
- *Roundabouts: An Informational Guide* (FHWA, 2000).
- *Roadway Lighting Handbook* (FHWA, 1978).
- *Railroad-Highway Grade Crossing Handbook* (FHWA, 2007).
- *Highway Capacity Manual* (TRB, 2010).
- *A Guide for Reducing Collisions Involving Older Drivers*, NCHRP Report No. 500-Volume 9, (Potts et al, 2004).

Material in this part of the *Handbook* represents, to as great an extent as possible at the time of its development, the results of empirical work with aging driver or pedestrian samples for investigations with the specific highway features of interest. Naturalistic and controlled field studies were given precedence, augmented by laboratory simulations employing traffic stimuli and relevant situational cues. Crash data are cited as appropriate. In addition, some citations reference studies showing effects of design changes, where the predicted impact on (aging) driver performance is tied logically to the results of research on age-related differences in detection, comprehension, response selection, maneuver execution, or other capability needed to safely negotiate the design element.

# CHAPTER 7
# Intersections

The following discussion presents the rationale and supporting evidence for *Handbook* treatments pertaining to these 24 proven and promising practices:

## Proven Practices

1. Intersecting Angle (Skew)
2. Receiving Lane (Throat) Width
3. Channelization
4. Intersection Sight Distance
5. Offset Left-Turn Lanes
6. Delineation of Edge Lines and Curbs
7. Curb Radius
8. Left-Turn Traffic Control for Signalized Intersections
9. Right-Turn Traffic Control for Signalized Intersections
10. Street Name Signs
11. Stop and Yield Signs
12. Lane Assignment on Intersection Approach
13. Traffic Signals
14. Intersection Lighting
15. Pedestrian Crossings
16. Roundabouts

## Promising Practices

17. Improved Design for Right-Turn Channelization
18. Combination Lane-Use/Destination Overhead Guide Signs
19. Signal Head Visibilty
20. High-Visibility Crosswalks
21. Supplemental Pavement Markings for Stop and Yield Signs
22. Reduced Left-Turn Conflict Intersections
23. Accessible Pedestrian Signal (APS) Treatments
24. Flashing Yellow Arrow

# PROVEN PRACTICES

## 1 Intersecting Angle (Skew)

There is broad agreement that right-angle intersections are the preferred design. Decreasing the angle of the intersection makes detection of and judgments about potential conflicting vehicles on crossing roadways much more difficult. In addition, the amount of time required to maneuver through the intersection increases, for both vehicles and pedestrians, due to the increased pavement area. However, there is some inconsistency among reference sources concerning the degree of skew that can be safely designed into an intersection. The *Green Book* states that although a right-angle crossing normally is desired, an angle of 60 degrees provides most of the benefits that are obtained with a right-angle intersection. Subsequently, factors to adjust intersection sight distances for skewness are suggested for use only when angles are less than 60 degrees (AASHTO, 2011). However, another source on subdivision street design states that: "Skewed intersections should be avoided, and in no case should the angle be less than 75 degrees" (Institute of Transportation Engineers [TEH], 1984). *The Traffic Engineering Handbook* (TEH, 1999) states that: "Crossing roadways should intersect at 90 degrees if possible, and not less than 75 degrees." It further states that: "Intersections with

**Table 9.** Cross-References of Related Entries for Intersecting Angle (Skew).

| Applications in Standard Reference Manuals | | | | |
|---|---|---|---|---|
| *MUTCD* (2009) | AASHTO *Green Book* (2011) | NCHRP 500-Volume 9 (2004) | NCHRP 279 Intersection Channelization Design Guide (1985) | Traffic Engineering Handbook (2009) |
| Sections 2B.54, 4D.06, 4D.09, 4D.12, 4D.13 | Pg. 5-9, Final Paragraph<br>Pg. 9-5, 3rd bullet item<br>Pg. 9-10, Final Paragraph<br>Pgs. 9-19, 9-20, Sect. 9.3.3 *Multileg Intersections*<br>Pgs. 9-25 through 9-27, Sect. 9.4.2 *Alignment*<br>Pgs. 9-57 through 9-63, Tables 9-15 and 9-16<br>Pg. 9-82, Sect. on *Oblique-Angle Turns*<br>Pgs. 9-97 through 9-99, Sects. on *Divisional Islands, Refuge Islands, & Island Size and Designation*<br>Pg. 9-98 Figure 9-37<br>Pg. 9-112, Sect. on *Oblique-Angle Turns with Corner Islands*<br>Pgs. 9-113 through 9-114 Table 9-18<br>Pg. 9-54, Sect. 9.5.4 *Effect of Skew*<br>Pg. 9-55, Figure 9-22<br>Pgs. 9-151 through 9-153, Sect. 9.8.5 *Effect of Skew*<br>Pg. 9-152 through 9-153, Table 9-28 | Pgs. V-25-V-26, Sect. on *Strategy*<br>3.1 B10: *Reduce Intersection Skew Angle* | Pg. 19, Top fig.<br>Pg. 21, Item 5<br>Pg. 25, Para. 2<br>Pg. 30, Para. 1 & top three figs.<br>Pg. 31, Para. 3 & bottom left fig.<br>Pgs. 42-44, Sect. on *Angle of Intersection*<br>Pg. 45, Fig. 4-5<br>Pg. 71, Top two figs.<br>Pgs. 100-105, Intersct. Nos. 7 -9<br>Pgs. 148-149, Intersct. No. 35 | Pg. 243, 5th Principle<br>Pg. 243, Sect. on *Alignment Design* |

severe skew angles (e.g., 60 degrees or less) often experience operational or safety problems. Reconstruction of such locations or institution of more positive traffic control such as signalization is often necessary." With regard to intersection design issues on two-lane rural highways, TEH (1999) states that: "Skew angles in excess of 75 degrees often create special problems at stop-controlled rural intersections. The angle complicates the vision triangle for the stopped vehicle; increases the time to cross the through road; and results in a larger, more potentially confusing intersection."

Skewed intersections pose particular problems for aging drivers. Many aging drivers experience a decline in head and neck mobility, which accompanies advancing age and may contribute to the slowing of psychomotor responses. Joint flexibility, an essential component of driving skill, has been estimated to decline by approximately 25 percent in aging adults due to arthritis, calcification of cartilage, and joint deterioration (Smith and Sethi, 1975). A restricted range of motion reduces an aging driver's ability to effectively scan to the rear and sides of his or her vehicle to observe blind spots, and similarly may be expected to hinder the timely recognition of conflicts during turning and merging maneuvers at intersections (Ostrow, Shaffron, and McPherson, 1992). For aging drivers, diminished physical capabilities may affect their performance at intersections designed with acute angles by requiring them to turn their heads further than would be required at a right-angle intersection. This obviously creates more of a problem in determining appropriate gaps. For aging pedestrians, the longer exposure time within the intersection becomes a major concern.

Isler, Parsonson, and Hansson (1997) measured the maximum head rotation of 20 drivers in each of four age groups: less than age 30; ages 40 to 59; ages 60 to 69; and age 70 and older, as well as their horizontal peripheral visual field. The oldest subjects exhibited an average decrement of approximately one-third of head range of movement compared with the youngest group of subjects. The mean maximum head movement (in one direction) was 86 degrees for the youngest drivers, 72 degrees for drivers ages 40 to 59, 67 degrees for drivers ages 60 to 69, and 59 degrees for drivers age 70+. In addition, the percentage of drivers with less than 30 degrees of horizontal peripheral vision increased with increases in age, from 15 percent of the younger driver sample to 65 percent of the drivers age 70+. Three of the oldest drivers had less than 50 degrees of head movement and two of these drivers also had less than 20 degrees of horizontal peripheral vision.

In a survey of aging drivers conducted by Yee (1985), 35 percent of the respondents reported problems with arthritis and 21 percent indicated difficulty in turning their heads to scan rearward while driving. Excluding vision/visibility problems associated with nighttime operations, difficulty with head turning placed first among all concerns mentioned by aging drivers participating in a focus group conducted by Staplin, Harkey, Lococo, and Tarawneh (1997) to examine problems in the use of intersections where the approach leg meets the main road at a skewed angle, and/or where channelized right-turn lanes require an exaggerated degree of head/neck rotation to check for traffic conflicts before merging. Comments about this geometry centered around the difficulty aging drivers experience turning their heads at angles less than 90 degrees to view traffic on the intersecting roadway, and several participants reported an increasing reliance on outside rearview mirrors when negotiating highly skewed angles. However, they reported that the outside mirror is of no help when the roads meet at the middle angles (e.g., 40 to 55 degrees) and a driver is not flexible enough to physically turn to look for traffic.

In an observational field study conducted as a part of the same project, Staplin et al. (1997) found that approximately 30 percent of young/middle-aged drivers (ages 25–45) and young-old drivers (ages 65–74) used their mirrors in addition to making head checks before performing a right-turn-on-red (RTOR) maneuver at a skewed intersection (a channelized right-turn lane at a 65-degree skew). By comparison, none of the drivers age 75 and older used their mirrors; instead, they relied solely on information obtained from head/neck checks. In this same study, it was found that the likelihood of a driver making an RTOR maneuver is reduced by intersection skew angles that make it more difficult for the driver to view conflicting traffic.

The practical consequences of restricted head and neck movement on driving performance at T-intersections were investigated by Hunter-Zaworski (1990), using a simulator to present videorecorded scenes of intersections with various levels of traffic volume and sight distance in a 180-degree field of view from the driver's perspective. Drivers in two subject groups, ages 30–50 and 60–80, depressed a brake pedal to watch a video presentation (on three screens), then released the pedal when it was judged safe to make a left turn; half of each age group had a restricted range of neck movement as determined by goniometric measures of maximum (static) head-turn angle. Aside from demonstrating that skewed intersections are hazardous for any driver with a neck movement impairment, this study found that maneuver decision time increased with both age and level of impairment. Thus, the younger drivers in this study were able to compensate for their impairments, but aging drivers both with and without impairments were unable to make compensations in their (simulated) intersection response selections.

Older and younger driver performance was compared at 10 intersections (5 improved and 5 unimproved) to test the effectiveness of FHWA's recommendations for intersection design to accommodate aging road users (Classen et al., 2007). Thirty-nine drivers ages 25 to 45 and 32 drivers ages 65 to 85 drove an instrumented vehicle on urban and residential streets in Gainesville, FL, accompanied by a front-seat driving evaluator who recorded behavioral errors. The course took approximately 1 hour to complete, and included driving through 5 sets of improved and unimproved intersections. One set of intersections included roadways that met at a 90-degree angle (improved) and roadways that met at an angle less than 75 degrees (unimproved). Both kinematic data (vehicle control responses during the turn phase including longitudinal and lateral accelerations, yaw, and speed) and behavioral data (driving errors including vehicle position, lane maintenance, speed, yielding, signaling, visual scanning, adjustment to stimuli/traffic signs, and left-turn gap acceptance) were recorded. With the exception of speed during the turn, kinematic measures showed significantly better performance associated with the improved intersection, and there were significantly fewer behavioral errors with the improved design. The improved design was associated with lesser side forces, indicating improved lateral stability, and fewer deviations from the idealized curved path during the turn, indicating greater vehicle stability. There were no significant differences between age groups for either the kinematics measures or the behavioral measure.

These research findings reinforce the desirability of providing a 90-degree intersection geometry and support the TEH (1984) recommendation establishing a 75-degree minimum as a practice to accommodate age-related performance deficits, benefiting both older as well as younger drivers.

# 2 Receiving Lane (Throat) Width

Lane widths are addressed in the Intersection Channelization Design Guide (Neuman, 1985). A recommendation for (left) turning lanes, which also applies to receiving lanes, is that "12-ft widths are desirable, (although) lesser widths may function effectively and safely. Absolute minimum widths of 9 ft should be used only in unusual circumstances, and only on low-speed streets with minor truck volumes." Similarly, the TEH (1984) guidelines suggest a minimum lane width of 11 ft and specify 12 ft as desirable. These guidelines suggest that wider lanes be avoided due to the resulting increase in pedestrian crossing distances. However, the TEH guidelines provide a range of lane widths at intersections from 9 ft to 14 ft, where the wider lanes would be used to accommodate larger turning vehicles, which have turning paths that sweep a path from 13.6 ft for a single-unit truck or bus up to 20.6 ft for a semitrailer. Thus, wider (12-ft) lanes used to accommodate (right) turning trucks also are expected to benefit (left) turning drivers. Further increases in lane width for accommodation of heavy vehicles may result in unacceptable increases in (aging) pedestrian crossing times, however.

Results of field observation studies conducted by Firestine, Hughes, and Natelson (1989) found that trucks turning on urban roads encroached into other lanes on streets with widths of less than 12 ft. They noted that on rural roads, lanes wider than 12 ft or 13 ft allowed oncoming vehicles on the cross street to move further right to avoid trucks, and shoulders wider than 4 ft allowed oncoming vehicles a greater margin of safety. Lane widths are addressed in the Intersection Channelization Design Guide (Neuman, 1985). A recommendation for (left) turning lanes, which also applies to receiving lanes, is that "12-ft widths are desirable, (although) lesser widths may function effectively and safely. Absolute minimum widths of 9 ft should be used only in unusual circumstances, and only on low-speed streets with minor truck volumes."

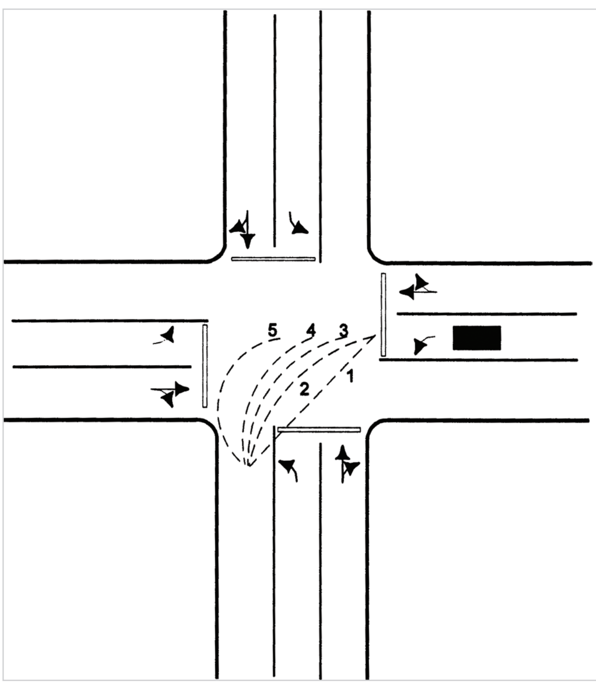
**Table 10.** Cross-References of Related Entries for Receiving Lane (Throat) Width.

| Applications in Standard Reference Manuals | | |
|---|---|---|
| **AASHTO** *Green Book* **(2011)** | **NCHRP 279 Intersection Channelization Design Guide (1985)** | **Traffic Engineering Handbook (2009)** |
| Pgs. 3-97 through 3-106, Sect. 3.3.11 *Widths for Turning Roadways at Intersections*<br>Pg. 9-55, Section 9.6.1 *Types of Turning Roadways*, Para. 1<br>Pg. 9-97, Final Two Paragraphs<br>Pg. 9-98, Figure 9-37 | Pg. 10, Table 2-4<br>Pg. 57, Para. 5, 1st Bullet<br>Pg. 58, Fig. 4-20<br>Pg. 63, Sect. on Lane Widths<br>Pg. 69, Sect. on *Width of Roadways*<br>Pg. 73, Fig. 4-29<br>Pg. 107, Fig. c<br>Pg. 113, Fig. a<br>Pg. 115, Figs. d- e<br>Pg. 120, Item 3<br>Pg. 122, Item 2<br>Pg. 125, Intersct. No. 19 | Pg. 381, Para. 2 |

Design recommendations for lane width at intersections follow from consideration of vehicle maneuver requirements and their demands on drivers. Positioning a vehicle within the lane in preparation for turning has long been recognized as a critical task (McKnight and Adams, 1970). Swinging too wide to lengthen the turning radius and minimize rotation of the steering wheel ("buttonhook turn") while turning left or right is a common practice of drivers who lack strength (including aging drivers) or are physically limited (McKnight and Stewart, 1990).

Two factors can compromise the ability of aging drivers to remain within the boundaries of their assigned lane during a left turn. One factor is the diminishing ability to share attention (i.e., to assimilate and concurrently process multiple sources of information from the driving environment). The other factor involves the ability to turn the steering wheel sharply enough, given the speed at which they are traveling, to remain within the boundaries of their lanes. Some aging drivers seek to increase their turning radii by initiating the turn early and rounding-off the turn. The result is either to cut across the apex of the turn, conflicting with vehicles approaching from the left, or to intrude upon a far lane in completing the turn.

In an observational field study conducted to determine how aging drivers (age 65 and older) compare with younger drivers during left-turn operations under varying intersection geometries, one variable that showed significant differences in older and younger driver behavior was turning path (Staplin, Harkey, Lococo, and Tarawneh, 1997). Aging drivers encroached into the opposing lane of the cross street (see Figure 69, turning path trajectory number 1) when making the left turn more often than younger drivers at the location where the throat width (equivalent to the lane width) measured 12 ft. Where the throat width measured 23 ft, which consisted of a 12-ft lane and an 11-ft




**Turning Path Descriptors**

| | |
|---|---|
| 1 | Encroach into Opposing Cross-Traffic Stream |
| 2, 3 and 4 | Proper Turning from Different Points within the Intersection |
| 5 | Left Turn from a Position Requiring a Greater-than-90-Degree Turn to Enter the Cross-Street |

**Figure 69.** Turning Path Taken by Left-Turning Vehicles (from Staplin et al., 1997)

shoulder, there was no significant difference in the turning paths. The narrower throat width resulted in higher encroachments by aging drivers, who physically may have more difficulties maneuvering their vehicles through smaller areas.

In a study comparing older and younger driver performance at improved and unimproved intersections to test the effectiveness of FHWA's recommendations for intersection design to accommodate aging road users, Classen et al. (2007) included an intersection where a left-turning vehicle had an extended receiving lane width of at least 12 ft and a forgiving shoulder of 4 ft and an intersection where the receiving lane was less than 12 ft and there was no forgiving shoulder. In this study, 39 drivers ages 25 to 45, and 32 drivers ages 65 to 85 drove an instrumented vehicle on urban and residential streets in Gainesville, FL, accompanied by a front-seat driving evaluator who recorded behavioral errors. The course took approximately 1 hour to complete, and included driving through five sets of improved and unimproved intersections. Both kinematic data (vehicle control responses during the turn phase including longitudinal and lateral accelerations, yaw, and speed) and behavioral data (driving errors including vehicle position, lane maintenance, speed, yielding, signaling, visual scanning, adjustment to stimuli/traffic signs, and left-turn gap acceptance) were recorded. There were significantly fewer behavioral errors with the improved design. The improved design was associated with lesser side forces and fewer deviations from the idealized curved path during the turn, indicating improved lateral control and greater vehicle stability. The increased speed at the improved intersection indicated greater control and confidence during turning. There were no significant differences between age groups for either the kinematics measures or the behavioral measures. The authors concluded that the guidelines for extended receiving lane width at intersections are effective for driver safety, and improve the performance of older as well as younger drivers.

In a retrospective site-based review and crash analysis, that included a detailed investigation of over 400 crashes involving drivers age 65 years and older at 62 sites in Australia, absence of a minimum receiving lane width of 12 ft with a 4 ft shoulder was a contributing factor in 8 percent of the crashes (Oxley, et al., 2006).

These data sources indicate that a 12-ft lane width provides the most reasonable tradeoff between the need to accommodate aging drivers, as well as larger turning vehicles, without penalizing the aging pedestrian in terms of exaggerated crossing distance.

# 3 Channelization

The spatial visual functions of acuity and contrast sensitivity are important in the ability to detect/recognize downstream geometric features such as pavement width transitions, channelized turning lanes, island and median features across the intersection, and any non-reflectorized raised elements at intersections. Visual acuity (the ability to see high-contrast, high-spatial-frequency stimuli, such as black letters on a white eye chart) shows a slow decline beginning at approximately age 40, and marked acceleration at age 60 (Richards, 1972). Approximately 10 percent of men and women between ages 65 and 75 have (best corrected) acuity worse than 20/30, compared with roughly 30 percent over the age of 75 (Kahn, et al., 1977). A driver's response to intersection geometric features is influenced in part by the processing of high-spatial-frequency cues—for example, the characters on upstream advisory signs—but it is the larger, often diffuse edges defining lane and pavement boundaries, curb lines, and raised median barriers that are the targets with the highest priority of detection for safety. Aging persons' sensitivity to visual contrast (the ability to see objects of various shapes and sizes under varying levels of contrast) also declines beginning around age 40, then declines steadily as age increases (Owsley, Sekuler, and Siemsen, 1983). Poor contrast sensitivity has been shown to relate to increased crash involvement for drivers age 66 and older, when incorporated into a battery of vision tests also including visual acuity and horizontal visual field size (Decina and Staplin, 1993).

The effectiveness of channelization from a safety perspective has been documented in several studies. An evaluation of Highway Safety Improvement Program projects showed that channelization produced an average benefit-cost ratio of 4.5 (FHWA, 1996). In this evaluation, roadway improvements consisting of turning lanes and traffic channelization resulted in a 47 percent reduction in fatal crashes, a 26 percent reduction in nonfatal injury crashes, and a 27 percent reduction in combined fatal plus nonfatal injury crashes, at locations where before and after exposure data were available.

One of the advantages of using curbed medians and intersection channelization is that it provides a better indication to motorists of the proper use of travel lanes at intersections. In a set of studies performed by the California Department of Public Works investigating the differences in crash experience with raised channelization versus channelization accomplished through the use of flush pavement markings, the findings were as follows: raised traffic islands are more effective than flush marked islands in reducing frequencies of night crashes, particularly in urban areas; and little difference is noted in the effectiveness of raised versus marked channelizing islands at rural intersections (Neuman, 1985).

One of the most common uses of channelization is for the separation of left-turning vehicles from the through-traffic stream. The safety benefits of left-turn channelization have been documented in several studies. A study by McFarland, et al. (1979) showed that crashes at signalized intersections where a left-turn lane was added, in combination with and without a left-turn signal phase, were reduced by 36 percent and 15 percent, respectively. At non-signalized intersections with marked channelization separating the left-turn lane from the through lane, crashes were reduced for rural, suburban, and urban areas by 50, 30, and 15 percent, respectively. When raised channelization devices

**Table 11.** Cross-references of Related Entries for Channelization.

| Applications in Standard Reference Manuals | | | | | |
|---|---|---|---|---|---|
| *MUTCD* (2009) | AASHTO *Green Book* (2011) | FHWA Lighting Handbook (2012) | NCHRP 500-Volume 9 (2004) | NCHRP 279 Intersection Channelization Design Guide (1985) | Traffic Engineering Handbook (2009) |
| Sections 1A.13, 3B.03, 3B.05, 3B.09, 3B.10, 3B.20, 3B.23, 3C.02, 3C. 03, 3E. 01, 3G.01, 3H.01, 3I.01 through 3I.06, 5G.03 | Pg. 4-35, Para. 4<br>Pg. 7-31, Final two paragraphs<br>Pg. 7-32, Fig. 7-7<br>Pgs. 9-12 through 9-14, Sect. on *Channelized Three-Leg Intersections*<br>Pgs. 9-15 through 9-19, Sect. on *Channelized Four-Leg Intersections*<br>Pgs. 9-95 through 9-112, Sects. on *Channelizing Islands, Divisional Islands, Refuge Islands, Island Size and Designation, Island Delineation and Approach Treatment & Right-Angle Turns With Corner Islands*<br>Pgs. 9-8 through 9-10, Introductory portion of Sect. 9.3 *Types and Examples of Intersections* Pgs. 9-92 through 9-94, Sect. 9.6.2 *Channelization*<br>Pgs. 9-182 through 9-183 Sect. 9.11.7 *Midblock Left Turns on Streets with Flush Medians* | Pg. 71, Para. 1-3<br>Pg. 77, Fig. 47 | Pgs. V-23 through V-25, Sect. on Strategy 3.1 B9: *Replace Painted Channelization with Raised Channelization (P)* | Pg. 1, Paras. 2-3<br>Pg. 21, Fig. 3-1<br>Pg. 24, Bottom fig.<br>Pg. 25, Para. 3<br>Pg. 26, Top fig.<br>Pg. 28, Middle fig.<br>Pg. 32, Middle fig.<br>Pg. 34, Para. 1 & bottom fig.<br>Pg. 35, Bottom left fig.<br>Pg. 38, Middle fig.<br>Pg. 39, Paras. 2-3 & top two figs.<br>Pg. 69, Sect. on *Traffic Islands*<br>Pg. 74, Fig. 4-30<br>Pgs. 75-76, Para. 1 on 1st pg. & Sects. on *Guidelines for Design of Traffic Islands, Guidelines for Selection of Island Type, & Guidelines for Design of Median Islands*<br>Pg. 79, Fig. 4-34<br>Pgs. 94- 95, Intersct. No. 4<br>Pgs. 102-103, Intersct. No. 8<br>Pgs. 106-113, Intersct. Nos. 10-13<br>Pgs. 116-117, Intersct. No. 15<br>Pgs. 132-133, Intersct. No. 22<br>Pgs. 138-139, Intersct. No. 29<br>Pgs. 148-153, Intersct. Nos. 35-37 | Pgs. 243, Sect. on *Principles of Channelization*<br>*Pg. 247, Sect. on Traffic Island Design*<br>Pg. 381, Para. 1 |

were used, the crash reductions were 60, 65, and 70 percent in rural, suburban, and urban areas, respectively. Consistent findings were reported in Hagenauer, et al. (1982).

Important considerations in choosing to implement raised versus marked channelization include operating speed and type of maneuver (i.e., left turn versus right turn). Left-turn channelization separating through and turning lanes may, because of its placement, constitute a hazard when a raised treatment is applied, especially on high-speed facilities. Detection and avoidance of such hazards requires visual and response capabilities known to decline significantly with advancing age.

In this same vein, it was reported in *Transportation Research Circular 382* (Transportation Research Board, 1991) that the aging driver, having poorer vision, slower physical reaction time, lower degree of awareness, and reduced ability to maneuver the vehicle, is more likely to be negatively affected by a raised median than is the average driver; and, because medians are fixed objects, when they are struck they pose a serious threat of loss of control, especially for aging drivers. The typical curbed median offers low to no contrast with the adjacent pavement and is difficult to reflectorize at night. Low-beam headlight limitations coupled with reduced vision of the aging driver compounds the visibility problem. In addition, raised medians and raised corner islands, when used together, often create turning path options at complex intersections that are confusing to the average driver, and disproportionately so for the aging one. Thus, to realize the safety benefits channelization can provide, it is particularly important to ensure the visibility of raised surfaces for (aging) drivers with diminished vision, so these road users can detect the channelizing devices and select their paths accordingly.

Another benefit in the use of channelization is the provision of a refuge for pedestrians. Refuge islands are a design element that can aid aging pedestrians who have slow walking speeds. With respect to the Hagenauer et al. (1982) study cited earlier, Hauer (1988) stated that because channelization in general serves to simplify an otherwise ambiguous and complex situation, the channelization of an existing intersection might enhance both the safety and mobility of aging persons, as well as enhance the safety of other pedestrians and drivers. However, in designing a new intersection, he stated that the presence of islands is unlikely to offset the disadvantage of large intersection size for the pedestrian.

Staplin, et al. (1997) conducted a field study evaluating four right-turn lane geometries to examine the effect of channelized right-turn lanes and the presence of skew on right-turn maneuvers made by drivers of different ages. One hundred subjects divided across three age groups drove their own vehicles around test routes using the local street network in Arlington, VA. The three age groups were ages 25–45, ages 65–74, and age 75 and older. As diagrammed in Figure 70, the four right-turn lane geometries were:

a) A non-channelized 90-degree intersection where drivers had the chance to make a right turn on red (RTOR) around a 40-ft radius. This site served as control geometry to examine how channelized intersections compare with non-channelized intersections.
b) A channelized right-turn lane at a 90-degree intersection with an exclusive use (acceleration) lane on the receiving street. Under this geometric configuration, drivers did not need to stop at the intersection and they were removed from

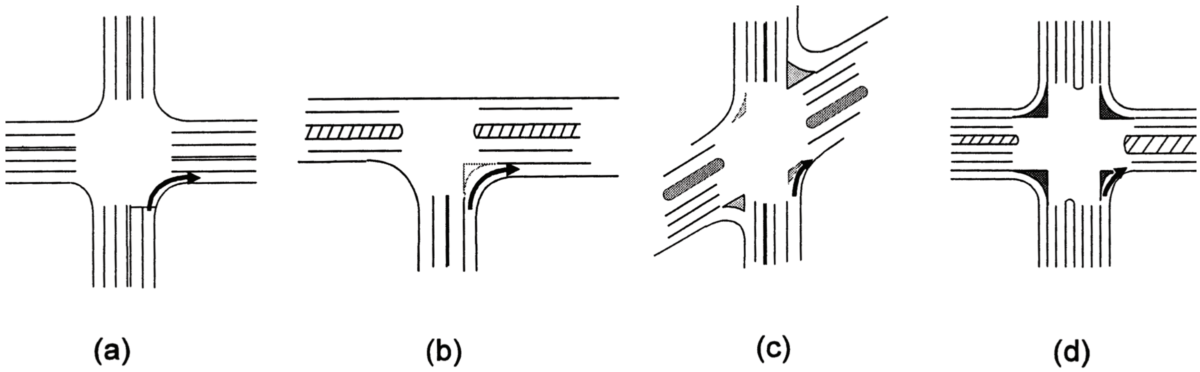



**Figure 70.** Intersection Geometries Examined in a Field Study of Right-Turn Channelization (Staplin et al., 1997)

the conflicting traffic upon entering the cross street. They had the opportunity to accelerate in their own lane on the cross street and then change lanes downstream when they perceived that it was safe to do so.

c) A channelized right-turn lane at a 65-degree skewed intersection without an exclusive use lane on the receiving street.

d) A channelized right-turn lane at a 90-degree intersection without an exclusive use lane on the receiving street. Under this geometry, drivers needed to check the conflicting traffic and complete their turn into a through traffic lane on the cross street.

The right-turn maneuver at all locations was made against two lanes carrying through (conflicting) traffic. The two through lanes were the only ones that had a direct effect on the right-turn maneuver. All intersections were located on major or minor arterials within a growing urban area, where the posted speed limit was 35 mph. All intersections were controlled by traffic signals with yield control on the three channelized intersections.

The results indicated that right-turn channelization affects the speed at which drivers make right turns and the likelihood that they will stop before making a RTOR. Drivers, especially younger drivers (ages 25–45), turned right at speeds 3–5 mph higher on intersection approaches with channelized right-turn lanes than they did on approaches with non-channelized right-turn lanes.

At the non-channelized intersection, 22 percent of drivers age 25–45, 5 percent of the drivers age 65–74, and none of the drivers age 75 and older performed a RTOR without a stop. On approaches with channelized right-turn lanes, drivers age 25–74 were much less likely to stop before making a RTOR. Where an acceleration lane was available, 65 percent of young/middle-aged drivers continued through without a complete stop, compared with 55 percent of drivers age 65–74 and 11 percent of drivers 75 and older. Female drivers age 75 and older always stopped before a RTOR. The increased mobility exhibited by the two younger groups of drivers at the channelized right-turn lane locations was not, however, exhibited by the drivers age 75 and older, who stopped in 19 of the 20 turns executed at the channelized locations. Also, questionnaire results indicated drivers perceived that making a right turn on an approach with a channelized right-turn lane *without an acceleration lane* on the cross street was more difficult than at other locations, and even more difficult than at skewed intersections.

Regarding channelization for mid-block left-turn treatments, Bonneson and McCoy (1997) evaluated the safety and operational effects of three mid-block left-turn treatments: raised curb medians; two-way, left turn-lanes; and undivided cross sections. Traffic flow data were collected during 32 field studies in eight cities in four States, and 3-year crash histories for 189 street segments were obtained from cities in two States. The studies were conducted on urban or suburban arterial segments, and therefore treatments can only be applied to such environments that include the following criteria: traffic volume exceeding 7,000 vehicles per day; speed limit between 30 and 50 mph); spacing of at least 350 ft between signalized intersections; direct access from abutting properties; no angle curb parking (parallel parking is acceptable); located in or near a populated area (e.g., population of 20,000 or more); no more than six through lanes (three in each direction); and arterial length of at least 0.75 mi.

In terms of annual delays to major-street left-turn and through vehicles, the raised-curb treatment has slightly higher delays than the TWLTL treatment at the highest left-turn and through volumes, which results from the greater likelihood of bay overflow for the raised-curb median treatment under high-volume conditions. The undivided cross section has significantly higher delays than the raised-curb treatment for all nonzero combinations of left-turn and through volume.

Looking at crash frequencies as a function of mid-block channelization treatment, the raised curb median treatment is associated with the fewest crashes of all three treatment types. Differences between the crash frequencies for TWLTL treatments vs. undivided cross sections are affected by whether or not parallel parking is allowed on the undivided cross section. When parallel parking is allowed on the undivided cross section, the undivided cross section is associated with significantly more crashes than the TWLTL treatment. However, when parallel parking is not allowed, the TWLTL has about the same crash frequency as the undivided cross section at lower traffic volumes.

In general, at mid-block locations, the raised-curb median treatment was associated with fewer crashes than the undivided cross section and TWLTL, especially for average daily traffic demands greater than 20,000 vehicles per day. Also, a benefit of the raised-curb median is that it provides a pedestrian refuge.

Bonneson and McCoy (1997) provide a set of six tables to use as guidelines in considering the conversion of an undivided cross section to a raised curb median, or to a TWLTL, and conversion from a TWLTL to a raised-curb median treatment. In these tables, it is recommended that the existing treatment remain in place when the benefit-cost ratio (in terms of delay and safety) is less than 1.0, and when the benefit-cost ratio exceeds 2.0, it is recommended that the engineer consider adding the alternative treatment.

Bonneson and McCoy (1997) do not report crash frequencies by driver age for one treatment versus another. However, approximately one-fifth of the aging drivers participating in focus group studies conducted by Staplin, et al. (1997) reported that using center two-way left turn lanes (TWLTL), was confusing, risky, and made them uncomfortable, because at times they came face-to-face with an opposing left-turner, and both drivers were stranded. Also mentioned was the difficulty seeing the pavement markings in poor weather (night, fog, rain) when they are less visible, and particularly when they are snow-covered. Drivers referred to TWLTL's as "suicide lanes." In the same research study, Staplin et al. (1997) reported on a crash analysis that revealed ways in which aging drivers failed to use a TWLTL correctly: a TWLTL was not used for turning at all; and the TWLTL was entered too far in advance of where the turn was to be made.

## 4 Intersection Sight Distance

Because intersections define locations with the highest probability of conflict between vehicles, adequate sight distance is particularly important. Not surprisingly, a number of studies have shown that sight distance problems at intersections usually result in a higher crash rate (Mitchell, 1972; Hanna, Flynn, and Tyler, 1976; David and Norman, 1979). The need for adequate sight distance at an intersection is best illustrated by a quote from the *Green Book*: "The driver of a vehicle approaching an intersection should have an unobstructed view of the entire intersection, including any traffic-control devices, and sufficient lengths along the intersecting highway to permit the driver to anticipate and avoid potential collisions" (AASHTO, 2011, p. 9-28). AASHTO values (for both uncontrolled and stop-controlled intersections) for available sight distance are measured from the driver's eye height (currently 3.5 ft above the roadway surface) to the object to be seen (currently 3.5 ft above the surface of the intersecting road).

**Table 12.** Cross-references of Related Entries for Intersection Sight Distance.

| Applications in Standard Reference Manuals | | | |
|---|---|---|---|
| **AASHTO** *Green Book* **(2011)** | **FHWA Lighting Handbook (2012)** | **NCHRP 279 Intersection Channelization Design Guide (1985)** | **Traffic Engineering Handbook (2009)** |
| Pgs. 3-6 through 3-8, Sect. 3.2.3 *Decision Sight Distance*<br>Pg. 5-21, Para. 6<br>Pg. 5-22, Para. 1<br>Pg. 6-9, Para. 7<br>Pg. 9-25, Para. 2<br>Pg. 9-27, Para. 2<br>Pgs. 9-27 through 9-28, Sect. 9.4.3 *Profile*<br>Pgs. 9-28 through 9-55, Sect. 9.5 *Intersection Sight Distance*<br>Pg. 9-123, Sect. 9.6.7 *Stopping Sight Distance at Intersections for Turning Roadways*<br>Pgs. 9-186 through 9-192, Sect. 9.12.4 *Sight Distance*<br>Pgs. 10-104 through 10-105, Sects. on *Terminal Location and Sight Distance, Ramp Terminal Design, & Distance Between a Free-flow Terminal and Structure* | Pg. 20, Figure 8 | Pg. 1, Item , 1st bullet<br>Pg. 10, Table 2-4<br>Pgs. 13-14, Sect. on *Sight Distance*<br>Pg. 15, Para. 1<br>Pg. 27, Bottom right fig.<br>Pg. 30, 2nd fig. from bottom<br>Pg. 31, Para. 3<br>Pg. 35, Para. 3 & bottom right fig.<br>Pg. 44, Para. 6, item 1<br>Pg. 45, Table 4-2<br>Pg. 63, Para. 3, item 3<br>Pg. 75, Last item 4<br>Pgs. 99-103, Intersct. Nos. 6-8<br>Pgs. 106-111, Intersct. Nos. 10-12 | Pgs. 223-224, Sect. on *Intersection Sight Distance*<br>Pg. 466, Para. 3<br>Pg. 631, Sect. on *Intersection Sight Distance* |

Sight distances at an intersection can be reduced by a number of deficiencies, including physical obstructions too close to the intersection, severe grades, and poor horizontal alignment. The alignment and profile of an intersection have an impact on the sight distance available to the driver and thus affect the ability of the driver to perceive the actions taking place both at the intersection and on its approaches. Since proper perception is the first key to performing a safe maneuver at an intersection, it follows that sight distance should be maximized; this, in turn, means that the horizontal alignment should be straight and the gradients as flat as practical. Horizontal curvature on the approaches to an intersection makes it difficult for drivers to determine appropriate travel paths, because their visual focus is directed along lines tangential to these paths. Kihlberg and Tharp (1968) showed that crash rates increased 35 percent for highway segments with curved intersections over highway segments with straight intersections. Limits for vertical alignment at intersections suggested by AASHTO (2011) and Institute of Transportation Engineers (1984) are 3 and 2 percent, respectively.

Harwood, et al. (1993) stated that the provision of intersection sight distance (ISD) is intended to give drivers an opportunity to obtain the information they need to make decisions about whether to proceed, slow, or stop in situations where potentially conflicting vehicles may be present. They noted that while it is desirable to provide a reasonable margin of safety to accommodate incorrect or delayed driver decisions, there are substantial costs associated with providing sight distances at intersections; therefore, it is important to understand the derivation of ISD requirements and why it is reasonable to expect a safety benefit from tailoring this design parameter to the needs of aging drivers.

Traditionally, the need for—as well as the basis for calculating—sight distance at intersections has rested upon the notion of the sight triangle. As excerpted from NCHRP Report 383, the diagram shown in Figure 71 effectively illustrates how different driver decisions during a (minor) road approach to an intersection (with a major road) depend upon the planned action. The driver's first decision is to either stop or to continue through the intersection (with a turning or a crossing maneuver) according to the type of traffic control information he or she perceives. A red signal or a stop sign results in a "stop" decision; all other types of information are functionally equivalent at this stage of driver decision making, translating into a "yield" decision. That is, drivers' decisions at this stage are dichotomous: (1) slow down and prepare to stop, regardless of traffic on the major road, or (2) based on their view of the major road, either slow down, maintain speed, or accelerate as required to safely complete their intended maneuver. For drivers who are required to stop, their decision to proceed after the stop also is based on a view of traffic on the major road, but at a point much closer to the intersection. The contrasting sight lines and sight triangles defined by the position of a driver who must stop before proceeding at the intersection, versus one who may proceed without stopping, conditional on the intersecting (major) road traffic, are clearly indicated in Figure 71.

For purposes of describing driver decision making, the diagram in Figure 71 may apply to varying aspects of intersection operations in all Cases A through F as per AASHTO (2011) classification. For Case F, however, where a driver is turning left from a major road at an intersection or driveway, the decision process and corresponding sight distance requirements are defined differently. The sight lines in this case are affected by the

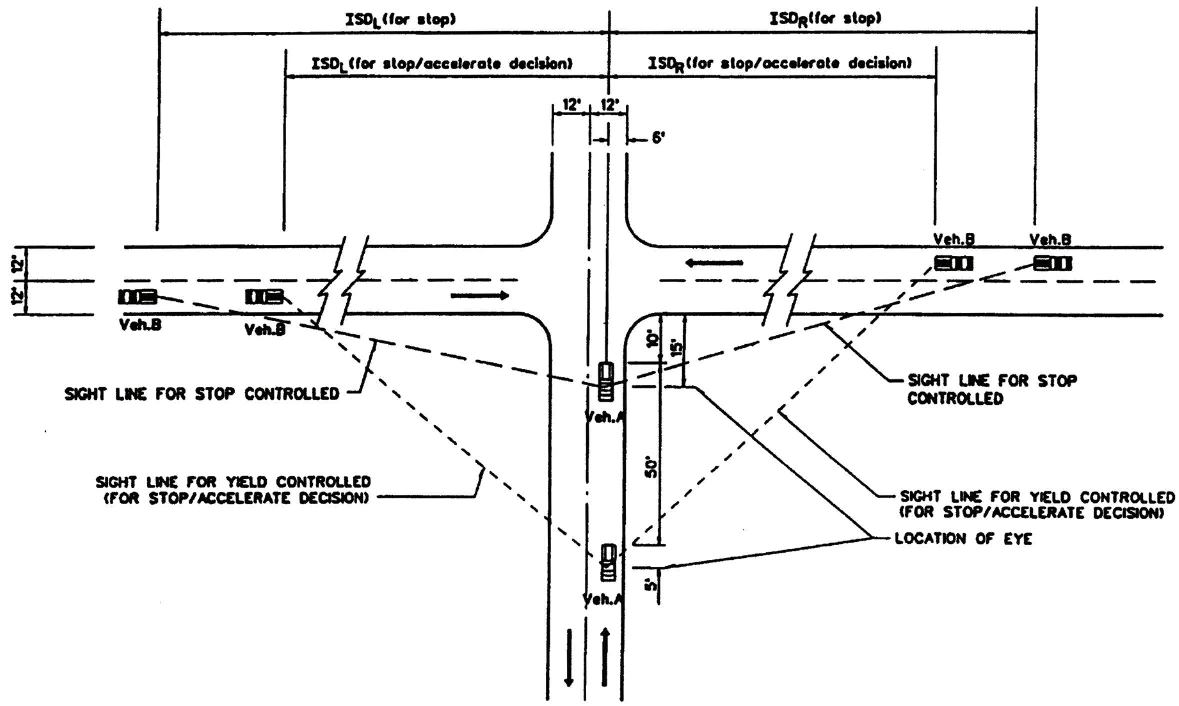



**Figure 71.** Sight Distance for Left and Right Turns for Passenger Car Drivers at Yield-Control Intersections (Harwood et al., 1993)

presence, type (passenger versus heavy vehicle), and location (positioned or un-positioned in the intersection) of opposing left-turning traffic, and by the lateral offset of the opposite left-turn lanes themselves. These relationships are illustrated in Figure 72 from McCoy, Navarro, and Witt (1992).

The rationale for treatments pertaining to intersection sight distance requirements will proceed as follows. First, driver age differences in cognitive and physical capabilities that are relevant to ISD issues will be discussed. Then, research efforts that have attempted to quantify the safety impact of providing adequate sight distance are summarized, plus studies examining the appropriate values for specific components used when calculating sight distance in the AASHTO gap acceptance models. Much of the research cited was conducted on the basis of the PRT models that were included in the *Green Book* prior to 2001. The discussion emphasizes the need for an increased value of PRT, which translates to a need for an increased gap using the current AASHTO models.

Older road users do not necessarily react more slowly to events that are expected, but they take significantly longer to make decisions about the appropriate response than younger road users, and this difference becomes more exaggerated in complex situations. Although the cognitive aspects of safe intersection negotiation depend upon a host of specific functional capabilities, the net result is response slowing. There is general consensus among investigators that older adults tend to process information more slowly than younger adults, and that this slowing transcends the slower reaction times (Anders, Fozard, and Lillyquist, 1972; Eriksen, Hamlin, and Daye, 1973; Waugh, Thomas, and Fozard, 1978; Salthouse and Somberg, 1982; Byrd, 1984). Of course, a conflict must be seen before any cognitive processing of this sort proceeds. Therefore, any decrease in

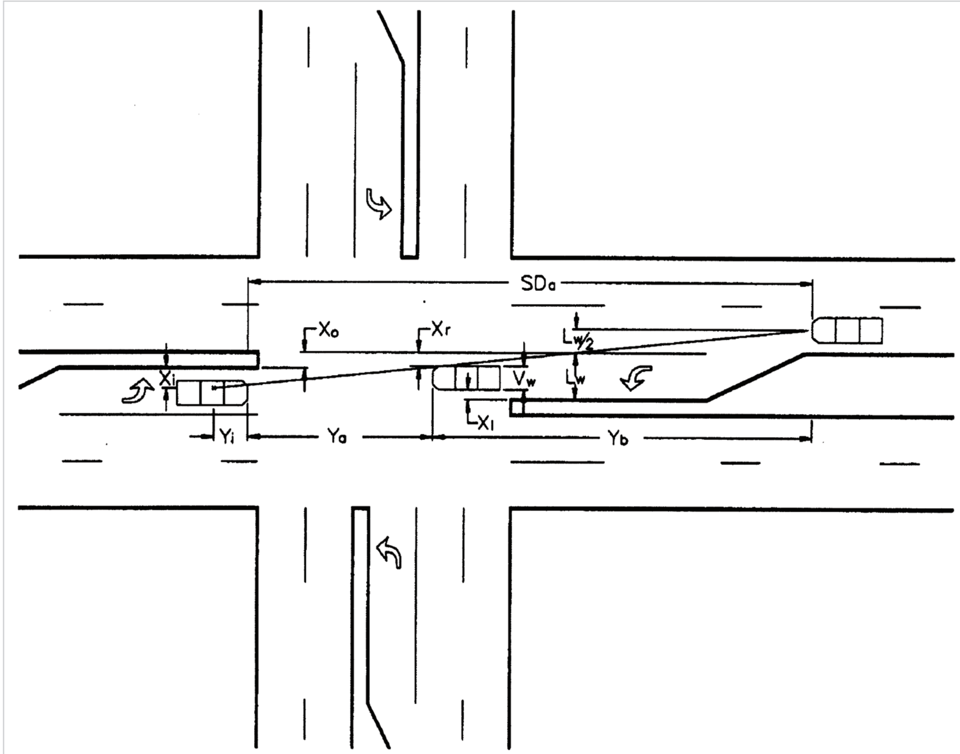



**Figure 72.** Spatial relationships that determine available sight distance (McCoy et al., 1992)

available response time because of sight distance restrictions will pose disproportionate risks to aging drivers. Slower reaction times for older versus younger adults when response uncertainty is increased has been demonstrated by Simon and Pouraghabagher (1978), indicating a disproportionately heightened degree of risk when aging road users are faced with two or more choices of action. Also, research has shown that aging persons have greater difficulty in situations where planned actions must be rapidly altered (Stelmach, Goggin, and Amrhein, 1988). The difficulty aging persons experience in making extensive and repeated head movements further increases the decision and response times of aging drivers at intersections.

David and Norman (1979) quantified the relationship between available sight distance and the expected reduction in crashes at intersections. The results of this study showed that intersections with shorter sight distances generally have higher crash rates. Using these results, predicted crash reduction frequencies related to ISD were derived as shown in Table 13.

Other studies have attempted to show the benefits to be gained from improvements to ISD (Mitchell, 1972; Strate, 1980). Mitchell conducted a before-and-after analysis, with a period of one year on each end, of intersections where a variety of improvements were implemented. The results showed a 67 percent reduction (from 39 to 13) in crashes where obstructions that inhibited sight distance were removed; this was the most effective of the implemented improvements. Strate's analysis examined 34 types of improvements made in Federal Highway Safety Program projects. The results indicated that sight distance improvements were the most cost-effective, producing a benefit-cost ratio of 5.33:1. A report on the FHWA Highway Safety Improvement Programs (1996) indicates that improvements in intersection sight distance have a benefit-cost ratio of 6.1 in

**Table 13.** Expected Reduction in Number of Crashes per Intersection Per Year (David and Norman, 1979).

| AADT* (1000s) | Intersection Sight Distance (ft) | | |
|---|---|---|---|
| | 20-49 | 50-99 | > 100 |
| < 5 | 0.18 | 0.20 | 0.30 |
| 5 – 10 | 1.00 | 1.30 | 1.40 |
| 10 – 15 | 0.87 | 2.26 | 3.46 |
| > 15 | 5.25 | 7.41 | 11.26 |

** Annual average daily traffic entering the intersection*

reducing fatal and injury crashes. In these analyses, fatal crashes were reduced by 56 percent and nonfatal injury crashes by 37 percent after sight distance improvements were implemented.

Collectively, the studies described above indicate a positive relationship between available ISD and a reduction in crashes, though the amount of crash reduction that can be expected by a given increase in sight distance may be expected to vary according to the maneuver scenario and existing traffic control at the intersection. Procedures for determining appropriate ISDs are provided by AASHTO for various levels of intersection control and the maneuvers to be performed. The scenarios defined are as follows:

- Case A: Intersections with No Control. ISD for vehicles approaching intersections with no control, at which vehicles are not required to stop, but may be required to adjust speed.
- Case B: Intersections with Stop Control on the Minor Road.
  - B1: Left Turn from the Minor Road. ISD for a vehicle on a stop-controlled approach on the minor road to accelerate from a stopped position and turn left onto the major road.
  - B2: Right Turn from the Minor Road. ISD for a vehicle on a stop-controlled approach on the minor road to accelerate from a stopped position and turn right onto the major road.
  - B3: Crossing Maneuver from the Minor Road. ISD for a vehicle on a stop-controlled approach on the minor road to accelerate from a stopped position and cross the major road.
- Case C: Intersections with Yield Control. ISD for vehicles on a minor-road approach controlled by a yield sign.
  - C1: Crossing Maneuver from the Minor Road. ISD for a vehicle on a yield-controlled approach on the minor road to cross the major road.
  - C2: Left or Right Turn from the Minor Road. ISD for a vehicle on a yield-controlled approach on the minor road to turn left or right onto the major road.
- Case D: Intersections with Traffic Signal Control. ISD for two-way flashing operations should be determined by Case B guidance.
- Case E: Intersections with All-Way Stop Control. ISD for a vehicle on any approach determined by the location of the first vehicle on all other approaches.

- Case F: Left Turns from the Major Road. ISD for a vehicle making a left-turn across the lanes used by opposing traffic.

Prior to 2001, perception-reaction time (PRT) was a key component in determining ISD in all cases defined according to AASHTO (1994). The discussion of this value is still present in chapters 2 and 3 of the *Green Book* under "Reaction Time" and "Brake Reaction Time," respectively (AASHTO, 2011). Results of several studies (e.g., Normann, 1953; Johansson and Rumar, 1971) are cited, and in conclusion, the 2.5-s value is selected since it was found to be adequate for approximately 90 percent of the overall driver population. Controlled field studies and simulator studies involving aging drivers have confirmed that brake reaction times to unexpected hazards (e.g., a barrel rolling into the road in front of the driver, a vehicle turning in front of a driver who is traveling straight through an intersection) are not significantly different as a function of age, and that virtually all response times are captured by the current 2.5-s AASHTO design parameter for brake perception-response time (Lerner, et al., 1995; Kloeppel, et al., 1995).

With respect to at-grade intersections, the 1994 *Green Book* recommended the following values of PRT for ISD calculations. In Case I, the PRT is assumed to be 2.0 s plus an additional 1.0 s to actuate braking, although the "preferred design" uses stopping sight distance (SSD) as the ISD design value (which incorporates a PRT of 2.5 s). In Case II, SSD is the design value; thus, the PRT is 2.5 s. For all Case III scenarios and Cases IV and V, the PRT is assumed to be 2.0 s. Refer to Table 14 to cross-reference the 1994 vs. 2011 intersection scenarios.

**Table 14.** Cross-Reference for 1994 and 2011 Intersection Sight Distance Cases (AASHTO, 2011; AASHTO, 1994).

| Scenario | AASHTO 2011 Case | 1994 AASHTO Case |
|---|---|---|
| No control | Case A | Case I |
| Stop control on minor road | Case B | Case III |
| Left turn maneuver | B1 | III-B |
| Right turn maneuver | B2 | III-C |
| Crossing maneuver | B3 | III-A |
| Yield control on minor road | Case C | Case II |
| Crossing maneuver | C1 | |
| Left or right turn maneuver | C2 | |
| Traffic signal control | Case D | Case IV |
| All-way stop control | Case E | Not included |
| Left turn from major road | Case F | Case V |

Regarding PRT for Cases III and V, the value of 2.0 s assumed by AASHTO (1994) represents the time necessary for the driver to look in both directions of the roadway, to perceive that there is sufficient time to perform the maneuver safely, and to shift gears, if necessary, prior to starting. This value is based on research performed by Johansson and Rumar (1971). The PRT is defined as the time from the driver's first look for possible oncoming traffic to the instant the car begins to move. Some of these operations are done simultaneously by many drivers, and some operations, such as shifting gears, may be done before searching for intersecting traffic or may not be required with automatic transmissions. AASHTO states that a value of 2.0 s is assumed to represent the time taken by the slower driver.

A critique of these values questioned the basis for reducing the PRT from 2.5 s used in SSD calculations to 2.0 s in the Case III ISD calculations (Alexander, 1989). As noted by the author, "The elements of PRT are: detection, recognition, decision, and action initiation." For SSD, this is the time from object or hazard detection to initiation of the braking maneuver. Time to search for a hazard or object is not included in the SSD computation, and the corresponding PRT value is 2.5 s. Yet, in all Case III scenarios, the PRT has been reduced to 2.0 s and now includes a search component which was not included in the SSD computations. Alexander pointed out that a driver is looking straight ahead when deciding to perform a stopping maneuver and only has to consider what is in his/her forward view. At an intersection, however, the driver must look forward, to the right, and to the left. This obviously takes time, especially for those drivers with lower levels of physical dexterity, e.g., aging drivers. Alexander (1989) proposed the addition of a "search time" variable to the current equations for determining ISD, and use of the PRT value currently employed in the SSD computations (i.e., 2.5 s) for all ISD computations. Neuman (1989) also argued that a PRT of 2.5 s for SSD may not be sufficient in all situations, and can vary from 1.5 s to 5.0 s depending on the physical state of the driver (alert versus fatigued), the complexity of the driving task, and the location and functional class of the highway.

A number of research efforts have been conducted to determine appropriate PRT values for use in ISD computations. Hostetter, et al. (1986) examined the PRT of 124 subjects traversing a 3-hour test circuit which contained scenarios identified above as Cases II, IIIA, IIIB, and IIIC. For the Case II (yield control) scenario, the results showed that in over 90 percent of the trials, subjects reacted in time to meet the SSD criteria established and thus the 2.5-s PRT value was adequate. With respect to Case III scenarios, the PRT was measured from the first head movement after a stop to the application of the accelerator to enter the intersection. The mean and 85th percentile values for all maneuvers combined were 1.82 s and 2.7 s, respectively. The results also showed that the through movement produced a lower value than the mean, while the turning maneuvers produced a higher value. These results led to conclusions that the 2.0-s criteria for Case IIIA be retained and that the PRT value for the Case III turning maneuvers (B and C) be increased from 2.0 to 2.5 s. One other result, which is applicable to the current effort, was that no significant differences were found with respect to age, (i.e., increased PRTs were needed to accommodate all drivers).

Fambro, et al. (1998) found significant differences in mean perception-brake response times as a function of age and gender, with aging drivers and female drivers demonstrating longer response times. They conducted three separate on-road studies to measure driver perception-brake response time to several stopping sight distance situations. Studies were conducted on a closed course as well as on an open roadway. In one study conducted on the closed course, subjects drove an instrumented test vehicle belonging to the Texas Transportation Institute (TTI), and in another closed course study they drove their own vehicles. In the open roadway study, they drove their own vehicles. Seventeen younger drivers (age 24 or under) and 21 older drivers (age 55 or older) participated in trials that required them to brake in response to expected and unexpected events, that included a barrel rolling off of a pickup truck parked next to the roadway, an illuminated LED on the windshield, and a horizontal blockade that deployed ahead of them on the roadway. Across all expected-object, perception-brake response time trials, the mean response time for younger drivers was 0.52 s and the mean response time for older drivers was 0.66 s. For these "expected" trials, the mean perception brake-response time for males was 0.59 s and for females was 0.63 s. For the unexpected-object, perception-brake response trials, longer response times were demonstrated for trials where subjects drove their own vehicles, compared to those in which they drove TTI's vehicle. The study authors suggested that subjects were more relaxed and unsuspecting when driving their own vehicles. The mean response time across studies (controlled and open road, own vehicle and research vehicle) for the unexpected object was 1.1 s; the 95th percentile perception-brake response time was 2.0 s.

Based on this finding, Fambro et al. (1998) concluded that AASHTO's 2.5-s perception-brake reaction time value is appropriate for highway design, when stopping sight distance is the relevant control. However, they note that at locations or for geometric features where something other than stopping sight distance is the relevant control, different perception-reaction times may be appropriate. For example, longer perception-reaction times may be appropriate for intersection or interchange design where more complex decisions and driver speed and/or path correction are required.

Another effort examined the appropriateness of the PRT values currently specified by AASHTO for computing SSD, vehicle clearance interval, sight distance on horizontal curves, and ISD (McGee and Hooper, 1983). With respect to ISD, the results showed the following: for Case I, the driver is not provided with sufficient time or distance to take evasive action if an opposing vehicle is encountered; and for Case II, adequate sight distance to stop before arriving at the intersection is not provided despite the intent of the standard to enable such action. With respect to the PRT values, recommendations include increasing the 2.0-s and 2.5-s values used in Case I and Case II calculations, respectively, to 3.4 s. It was also recommended that the PRT value for Case III scenarios be redefined.

Although there is no consensus from the above studies on the actual values of PRT that should be employed in the ISD computations, there is a very clear concern as to whether the current values are meeting the needs of aging drivers. Since aging drivers tend to take longer in making a decision, especially in complex situations, the need to further evaluate current PRT values is underscored. Slowed visual scanning of traffic on the intersecting roadway by aging drivers has been cited as a cause of near misses of (crossing) crashes at intersections during on-road evaluations. In the practice of coming to a stop, followed by a look to the left, then to the right, and then back to the left again, the aging driver's slowed scanning behavior allows approaching vehicles to have closed the gap by the time a crossing maneuver finally is initiated. The traffic situation has changed when the aging driver actually begins the maneuver, and drivers on the main roadway are often forced to adjust their speed to avoid a collision. Hauer (1988) stated that "the standards and design procedures for intersection sight triangles should be modified because there is reason to believe that when a passenger car is taken as the design vehicle, the sight distance is too short for many aging drivers, who take longer to make decisions, move their heads more slowly, and wish to wait for longer gaps in traffic."

In a retrospective site-based review and crash analysis that included a detailed investigation of over 400 crashes involving drivers age 65 years and older at 62 sites in Australia, Oxley, et al. (2006) identified an insufficient perception-reaction time for intersection sight distance (e.g., a value less than 2.5 s) as a contributing factor in 23 percent of the crashes. This was particularly problematic at intersections controlled by stop and yield signs. The study authors suggest that these findings provide strong support for the argument that longer sight distances at intersections are required to accommodate older drivers, to give them more time to select a safe gap in which to turn across, enter, or cross traffic.

In contrast, research conducted by Lerner, et al. (1995) concluded that, based on older driver performance, no changes to design PRT values were recommended for ISD, SSD, or decision sight distance (DSD), even though the 85th percentile J values exceeded the AASHTO 2.0-s design standard at 7 of the 14 sites. The J value equals the sum of the PRT time and the time to set the vehicle in motion, in seconds. No change was recommended because the experimental design represented a worst-case scenario for visual search and detection (drivers were required to begin their search only after they had stopped at the intersection and looked inside the vehicle to perform a secondary task). Naylor and Graham (1997), in a field study of older and younger drivers waiting to turn left at stop-controlled intersections (Case IIIB), similarly concluded that the current AASHTO value of 2.0 s is adequate for the PRT (J-value) used in calculating intersection sight distance at these sites.

Lerner et al. (1995) conducted an on-road experiment to investigate whether the assumed values for Case III driver PRT used in AASHTO design equations adequately represent the range of actual PRT for aging drivers. Approximately 33 subjects in each of three driver age groups were studied: ages 20–40, ages 65–69, and age 70 and older. Drivers operated their own vehicles on actual roadways, were not informed that their response times were being measured, and were naive as to the purpose of the study (i.e., they were advised that the purpose of the experiment was to judge road quality and how this relates to aspects of driving). The study included 14 data collection sites on a 56-mi route. Results showed that the aging drivers did not have longer PRT than younger drivers, and in fact the 85th percentile PRT closely matched the AASHTO design equation value of 2.0 s. The 90th percentile PRT was 2.3 s, with outlying values of 3 to 4 s. The median daytime PRT was approximately 1.3 s. Interestingly, it was found that typical driver actions did not follow the stop/search/decide maneuver sequence implied by the model; in fact, drivers continued to search and appeared ready to terminate or modify their maneuver even after they had begun to move into the intersection. This finding resulted in the study authors' conclusion that the behavioral model on which ISD is based is conservative.

Harwood, et al. (1996) evaluated current AASHTO policy on ISD for Cases I, II, III, IV, and V during performance of NCHRP project 15-14(1), based on a survey of current highway agencies' practices and a consideration of alternative ISD models and computational methodologies, as well as findings from observational studies for selected cases. Although this work culminated in recommendations for minimum distances for the major and minor legs of the sight triangle for all cases, driver age was not included as a study variable; therefore, specific values for these design elements were not included within the treatments presented in this *Handbook*, nor is an exhaustive discussion of these materials included in this section. The results of the Harwood et al. (1996) analyses pertaining to ISD for Case IIIB and IIIC—and by extension for Case V—are of particular interest, however, in the interpretation of related findings from an aging driver field study in this area. These analysis outcomes are reviewed below.

Prior to the 1990 AASHTO *Green Book*, the issue of ISD for a driver turning left off of a major roadway onto a minor roadway or into an entrance (Case V) was not specifically addressed. In the 1990 *Green Book*, the issue was addressed at the end of the Case III discussions in two paragraphs. In the 1994 *Green Book*, these same paragraphs have been placed under a new condition referred to as Case V. The equation used for determining ISD for Case V was simply taken from the Case IIIA (crossing maneuver at a stop-controlled intersection) and Case IIIB (left-turn maneuver from a stop-controlled minor road onto a major road) conditions, with the primary difference between the cases being the distance traveled during the maneuver. A central issue in defining the ISD for Case V involves a determination of whether the tasks that define ISD for Cases IIIA and IIIB are similar enough to the tasks associated with Case V to justify using the same equation, which follows:

$$\mathbf{ISD=0.28\ V\ (J + t_a)}$$

where:

ISD = intersection sight distance (m).

V = design speed on the major roadway (km/h).

J = time required to search for oncoming vehicles, to perceive that there is sufficient time to make the left turn, and to shift gears, if necessary, prior to starting (J is assumed to be 2.0 s).

$t_a$ = time required to accelerate and traverse the distance to clear traffic in the approaching lane(s); obtained from Figure IX-33 in the 1994 AASHTO *Green Book*.

For Case IIIA (crossing maneuver), the sight distance is calculated based on the need to clear traffic on the intersecting roadway on both the left and right sides of the crossing vehicle. For Case IIIB (left turn from a stop), sight distance is based on the requirement to first clear traffic approaching from the left and then enter the traffic stream of vehicles from the right. It has been demonstrated that the perceptual judgments required of drivers in both of these maneuver situations increase in difficulty when opposing through traffic must be considered.

The perceptual task of turning left from a major roadway at an unsignalized intersection or during a permissive signal phase at a signalized intersection requires a driver to make time-distance estimates of a longitudinally moving target as opposed to a laterally moving target. Lateral movement (also referred to as tangential movement) describes a vehicle that is crossing an observer's line of sight, moving against a changing visual background where it passes in front of one fixed reference point after another. Longitudinal movement, or movement in depth, results when the vehicle is either coming toward or going away from the observer. In this case there is no change in visual direction, only subtle changes in the angular size of the visual image, typically viewed against a constant background. Longitudinal movement is a greater problem for drivers because the same displacement of a vehicle has a smaller visual effect than when it moves laterally—that is, lateral movement results in a much higher degree of relative motion (Hills, 1980).

In comparison with younger subjects, a significant decline for older subjects has been reported in angular motion sensitivity. In a study evaluating the simulated change in the separation of taillights indicating the overtaking of a vehicle, Lee (1976) found a threshold elevation greater than 100 percent for drivers' ages 70–75 compared with drivers ages 20–29 for brief exposures at night. Aging persons may in fact require twice the rate of movement to perceive that an object is approaching, versus maintaining a constant separation or receding, given a brief duration (2.0 s) of exposure. In related experiments, Hills (1975) found that aging drivers required significantly longer time to perceive that a vehicle was moving closer at constant speed: at 19 mph, decision times increased 0.5 s between ages 20 and 75. This body of evidence suggests that the 2.0-s PRT (i.e., variable J in the ISD equation above) used for Cases III and V may not be sufficient for the task of judging gaps in opposing through traffic by aging drivers. A revision of Case V to determine a minimum required sight distance value which more accurately reflects the perceptual requirements of the left-turn task may therefore be appropriate.

Harwood et al. (1996) suggested that at locations where left turns from the major road are permitted at intersections and driveways, at unsignalized intersections, and at signalized intersections without a protected turn phase, sight distance along the major road should be provided based on a critical gap approach, as was recommended for left and right turns from the minor road at stop-controlled intersections. The Gap Acceptance model developed and proposed to replace the 1994 AASHTO ISD model is:

$$\mathbf{ISD = 1.47\ VG}$$

where:

ISD = intersection sight distance (feet).

V = operating speed on the major road (mph).

G = the specified critical gap (in seconds); equal to 5.5 s for crossing one opposing lane plus an additional 0.5 s for each additional opposing lane.

Field data were collected in the NCHRP study to better quantify the gap acceptance behavior of passenger car and truck drivers, but only for left- and right-turning maneuvers from minor roadways controlled by a STOP sign (Cases IIIB and C). In the Phase I interim report produced during the conduct of the NCHRP project, Harwood et al. (1993) reported that the critical gap currently used by the California Department of Transportation is 7.5 s. When AASHTO Case IIIB ISD criteria were translated to time gaps in the major road traffic stream, the gaps ranged from 7.5 s (220 ft at a 20-mph operating speed to 15.2 s (1,560 ft) at a 70-mph operating speed. Harwood et al. (1993) stated that the rationale for gap acceptance as an ISD criterion is that drivers safely accept gaps much shorter than 15.2 s routinely, even on higher speed roadways.

In developing the Gap Acceptance model for Case V, Harwood et al. (1996) relied on data from studies conducted by Kyte (1995) and Micsky (1993). Kyte (1995) recommended a critical gap value of 4.2 s for left turns from the major road by passenger cars for inclusion in the unsignalized intersection analysis procedures presented in the *Highway Capacity Manual* (Transportation Research Board, 1994). A constant value was recommended regardless of the number of lanes to be crossed; however, a heavy-vehicle adjustment of 1.0 s for two-lane highways and 2.0 s for multilane highways was recommended. Harwood et al. (1996) reported that Micsky's 1993 evaluation of gap acceptance behavior for left turns from the major roadway at two Pennsylvania intersections resulted in critical gaps with a 50 percent probability of acceptance (determined from logistic regression) of 4.6 s and 5.3 s. Using the rationale that design policies should be more conservative than operational criteria such as the *Highway Capacity Manual*, Harwood et al. (1996) recommended a critical gap for left turns from the major roadway of 5.5 s, and an increase in the critical gap to 6.5 s for left turns by single-unit trucks and to 7.5 s for left turns by combination trucks. In addition, if the number of opposing lanes to be crossed exceeds one, an additional 0.5 s per additional lane for passenger cars and 0.7 s per additional lane for trucks was recommended.

It is important to note that the NCHRP study did not consider driver age as a variable. However, Lerner et al. (1995) collected judgments about the acceptability of gaps in traffic as a function of driver age for left turn, right turn, and through movements at stop-controlled intersections. While noting that these authors found no significant differences between age groups in the total time required to perceive, react, and complete a maneuver in a related Case III PRT study, the Lerner et al. (1995) findings indicate that younger drivers accept shorter gaps than older drivers. The 50th percentile gap acceptance point was about 7 s (i.e., if a gap is 7 s long, only about half of the subjects would accept it). The 85th percentile point was approximately 11 s. The oldest group required about 1.1 s longer than the youngest group.

Staplin, et al. (1997) conducted an observational field study of driver performance as a function of left-turn lane geometry and driver age at four locations where the main road operating speed was 35 mph. The mean left-turn critical gap sizes across all sites, for drivers who had positioned their vehicles within the intersection, were as follows: 5.90 s for the young/middle-aged (ages 25–45) females; 5.91 s for the young/middle-aged males; 6.01 s for the young-old (ages 65–74) females; 5.84 s for the young-old males; 6.71 s for the old-old (age 75 and older) females; and 6.55 s for the old-old males. Prominent trends indicated that aging drivers demonstrated larger critical gap values at all locations. The young/middle-aged and young-old groups were not significantly different from each other; however, both were significantly different from the old-old group. Critical gap data were not collected in this study for drivers who did not position themselves within the intersection, but it is important to note that the older drivers were less likely to position themselves within the intersection than the young and middle-aged drivers.

Critical gap sizes displayed in a laboratory simulation study in the same project, where oncoming vehicles traveling at 35 mph were viewed on a large screen display in correct perspective, ranged from 6.4 s to 8.1 s for young/middle-aged drivers and from 5.8 to 10.0 s for drivers age 75 and older. This increase in size and variability of the critical gap for left turns by aging drivers suggests that the value for G in the Gap Acceptance model must be increased to accommodate this user group, beyond levels recommended in NCHRP 383 (where the performance of aging drivers, per se, was not at issue).

The culmination of this work was a rigorous exercise of competing models and theoretical approaches for calculating sight distance requirements. As reported by Staplin et al. (1997), several different sight distance models were exercised using data collected in the observational field study. This study was conducted at four intersections which differed in the amount that the opposite left-turn lanes were offset. The goal was to determine which model(s), including existing and modified 1994 AASHTO models and a Gap Acceptance model (which is the current 2004 AASHTO model) best predicted the data observed in the field.

Several data elements collected in the field received special attention. One of these data elements was the maneuver time of the left-turning driver. This time is equivalent to $t_a$ in the 1994 AASHTO model, as shown in Figure IX-33 in the AASHTO (1994) *Green Book*. These times were measured at each of four intersections included in the study, for positioned and un-positioned drivers. That is, separate maneuver-time measures were obtained, depending on whether the drivers positioned themselves within the intersection prior to turning. Staplin et al. (1997) found no significant differences in maneuver time as a function of age for the drivers turning left at the four intersections studied (which had distances ranging from 84 to 106 ft). Maneuver times for drivers positioned within the intersection versus unpositioned drivers, however, were significantly different. Since aging drivers less frequently positioned themselves in the field study, the design value for this factor (maneuver time) should be based on that obtained for unpositioned drivers.

A comparison between 1994 AASHTO values and the 95th percentile clearance times demonstrated by positioned drivers and unpositioned drivers in this study is presented in Table 15. In Table 15, the “positioned” vehicles were located within the intersection, approaching the median or centerline of the cross street. The “unpositioned” vehicles were at or behind the stop line or end of the left-turn bay. (See Figure 76, located in the discussion for Design Element 5 — Offset Left Turn Lanes, for an illustration of driver positioning within an intersection).

**Table 15.** Comparison of Clearance Times Obtained in the Staplin et al. (1997) Field Study with 1994 AASHTO *Green Book* Values Used in Sight Distance Calculations.

| Vehicle Location | Measure | Left-Turn Lane Geometry | | | |
|---|---|---|---|---|---|
| | | -14 ft Offset | -3 ft Offset | 0 ft Offset | +6 ft Offset |
| Positioned | Distance Traveled (ft) | 70 ft | 67 ft | 64 ft | 70 ft |
| Positioned | 95th Percentile Clearance Time (s) From Field Study | 3.8 s | 3.9 s | 3.9 s | 3.9 s |
| Positioned | AASHTO Clearance Time (s) From Figure IX-33 | 5.1 s | 5.0 s | 5.0 s | 5.1 s |
| Unpositioned | Distance Traveled (ft) | 106 ft | 98 ft | 84 ft | 88 ft |
| Unpositioned | 95th Percentile Clearance Time (s) From Field Study | 6.7 s | 6.4 s | 6.6 s | 5.7 s |
| Unpositioned | AASHTO Clearance Time (s) From Figure IX-33 | 6.5 s | 6.2 s | 5.9 s | 6.0 s |

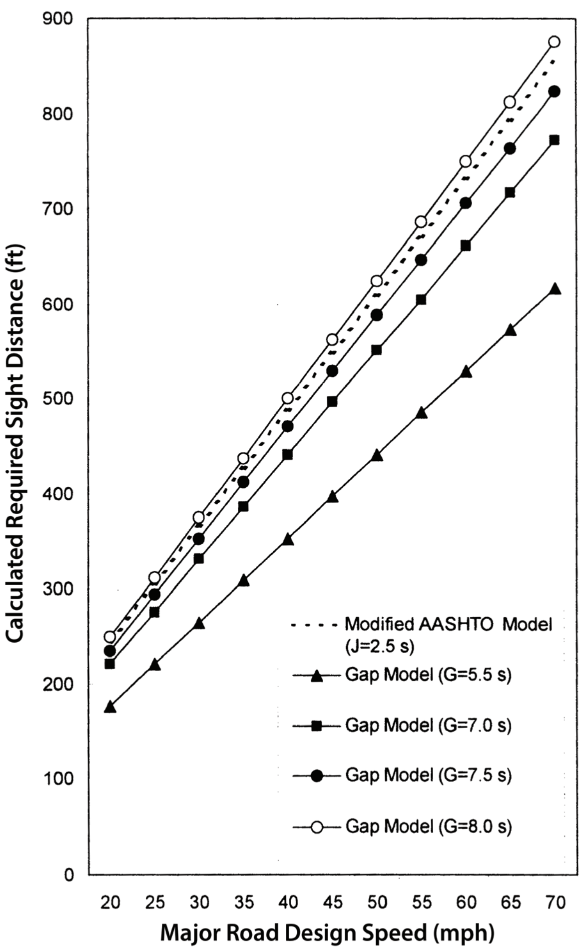



**Figure 73.** Comparison of Required Intersection Sight Distance Values from the Modified AASHTO Model (with J = 2.5 S) and the Gap Acceptance Model (with Gap Values of 5.5 S, 7.0, 7.5 S, and 8.0 S)

A detailed discussion of the outputs from the model exercise is provided in the publication Intersection Geometric Design and Operational Guidelines for Older Drivers and Pedestrians (Staplin, et al. 1997). However, the most significant result for purposes of this discussion is as follows: the required sight distances computed using a modified 1994 AASHTO model (where PRT was increased to 2.5 s) produced values that were most predictive of actual field operations.

Thus, when ISD is calculated using the AASHTO model as it relates to drivers turning left from a major roadway, there is evidence that the PRT value should be increased to 2.5 s to provide adequate sight distance. The Gap Acceptance model, on the other hand, produced sight distance values that were approximately 23 percent shorter than the current AASHTO model that uses a PRT of only 2.0 s. If the Gap Acceptance model is going to be used, particularly where there are significant volumes of aging left-turning drivers, an adjustment factor applied to increase the sight distance to better accommodate this driver age group therefore appears warranted.

To determine what adjustment is most appropriate in this regard, a set of analyses were performed in which the goal was to identify a value of G that would yield required sight distance values meeting or exceeding those derived from the modified AASHTO model formula (i.e., where J = 2.5 s). By extension, this result would also best match the behavior of drivers 75 and older observed in the field study. Very simply, alternate values for G were substituted into the gap formula for calculating minimum required sight distance (1.47VG). These included 5.5 s, as recommended by Harwood et al. (1996), as well as values which increase in 0.5 s increments. The results of these calculations for alternate values of G, beginning at 7.0 s, are plotted against the required sight distance calculated using the modified AASHTO formula [$1.47V(J+ t_a)$; where J=2.5 s and $t_a$ is obtained from Table IX-33 in the 1994 *Green Book*] in Figure 73. As shown in this figure, a gap of 8.0 s affords sight distance for left-turning drivers that equals or exceeds the requirements calculated using the modified AASHTO model for major road design speeds from 20 to 70 mph.

Finally, in a driving simulator study, Yan, Radwan, and Guo (2007) evaluated the effects of age, gender, and major road speed on drivers' left turn gap acceptance judgments at stop-controlled intersections. The study sample included 28 younger subjects (ages 20 to 30), 21 middle-aged subjects (ages 31 to 55), and 14 older subjects (ages 56 to 83). Subjects "drove" along the minor road and stopped at a stop sign at a major road, with approaching vehicle speeds of either 25 mph or 55 mph. Vehicle gap sizes ranged from 1 to 16 s. The driver's task was to wait at the stop sign on the minor road for an appropriate gap to turn into on the major road.

In general, older drivers accepted larger gaps than young and middle-aged drivers (7.94 s vs. 6.29 s and 6.20 s, respectively) and females accepted larger gaps than males (6.93 s vs. 6.38 s, respectively). Oncoming vehicle speed played an important role in the gap size accepted by drivers, with drivers accepting smaller gaps for the higher major road approach speed than for the lower approach speed scenario. This implies that drivers show more sensitivity to oncoming vehicle distance than to oncoming vehicle approach speed. An interaction effect between age and speed showed that for the lower approach speed scenario (25 mph), the older drivers accepted larger gaps (females =10.99 s; males 8.76 s) than the young drivers (females =7.56 s; males = 6.35 s) and middle-aged drivers (females = 6.97 s; males = 6.60 s). However, for the higher-speed approach (55 mph), the minimum gaps accepted by the older drivers (females = 7.11 s; males = 6.23 s) were not significantly larger than the younger drivers (females = 6.0 s; males = 5.26 s). During the process of turning, older drivers turned the steering wheel slower and used smaller acceleration rates to achieve the major road traffic speed than young and middle-aged drivers. The larger gaps that drivers accepted, the slower their accelerations to turn onto the road, reflecting older drivers' conservative driving attitude. Speed reduction rates of following vehicles (to accommodate the turning vehicle) were higher for all driver ages when turning into higher-speed traffic than into lower- speed traffic. However, older drivers contributed to more speed reduction rates on the major road than young and middle-aged drivers, with older females causing the highest speed reduction rates of following vehicles.

The finding that older drivers did not select larger gaps than younger drivers at higher speed roads indicates that they rely exclusively on perceived distance to make gap acceptance judgments. This puts them at a higher crash risk, because at the same time they are causing a shorter separation from the following vehicle, they are steering slower and accelerating slower than the younger drivers, and causing more effects on major road traffic. This suggests that at stop-controlled intersections, older drivers— in particular, older female drivers—are more likely to collide with speeding vehicles approaching on the major road.

# 5 Offset Left-Turn Lanes

Studies examining crashes involving aging drivers and the types of maneuvers being performed just prior to the collision have consistently found this group to be over-involved in left-turning crashes at both rural and urban signalized intersections and have indicated that failure to yield the right-of-way (as the turning driver) was the principal violation type (Staplin and Lyles, 1991; Council and Zegeer, 1992). Underlying problems for the maneuver errors include the misjudgment of oncoming vehicle speed, misjudgment of available gap, assuming the oncoming vehicle was going to stop or turn, and simply not seeing the other vehicle. Joshua and Saka (1992) noted that sight distance problems at intersections which result from queued vehicles in opposite left-turn lanes pose safety and capacity deficiencies, particularly for unprotected (permissive) left-turn movements. These researchers found a strong correlation between the offset for opposite left-turn lanes—i.e., the distance from the inner edge of a left-turn lane to the outer edge of the opposite left-turn lane—and the available sight distance for left-turning traffic.

The alignment of opposite left-turn lanes and the horizontal and vertical curvature on the approaches are the principal geometric design elements that determine how much sight distance is available to a left-turning driver. Operationally, vehicles in the opposite left-turn lane waiting to turn left can also restrict the (left-turning) driver's view of oncoming traffic in the through lanes. The level of blockage depends on how the opposite left-turn lanes are aligned with respect to each other, as well as the type/size of vehicles in the opposing queue. Restricted sight distance can be minimized or eliminated by offsetting opposite left-turn lanes so that left-turning drivers do not block each other's view of oncoming through traffic. When the two left-turn lanes are exactly aligned, the offset distance has a value of zero. Negative offset describes the situation where the

**Table 16.** Cross-References of Related Entries for Offset Left-Turn Lanes.

| Applications in Standard Reference Manuals | | | | |
|---|---|---|---|---|
| *MUTCD* (2009) | AASHTO *Green Book* (2011) | NCHRP 500 – Volume 9 (2004) | NCHRP 279 Intersection Channelization Design Guide (1985) | Traffic Engineering Handbook (2009) |
| Sections 1A.13 (*median, regulatory sign, delineator, stop line, & wrong-way arrow*), 2A.23, 2B.03, 2B.37, 2B.38, 2B.40, 2B.41, 2B.42, 3B.04,3B.11, 3B.16, 3B.20, 3B.23, 3F.03, 3G.01, 3I.04 through 3I.06<br><br>Table 2B-1<br><br>Figures 2A-3, 2B-14 through 2B-16, 2B-18,d 2B-19, 3B-13 a, b & d, 3B-23, 3B-27 | Pg. 2-39, Para. 3<br><br>Pgs. 9-99 through 9-105, Sects. on *Island Size and Designation & Island Delineation and Approach Treatment*<br><br>Pgs. 9-133 through 9-138, Sects. on *Median Left-Turn Lanes, Median End Treatment, & Offset Left-Turn Lanes* | Pgs. V-19-V-21, Sect. on *Strategy 3.1 B6:Provide Offset Left-Turn Lanes at Intersections (T)* | Pg. 1, 1st bullet<br><br>Pg. 3, 2nd col., Para. 5<br><br>Pg. 6, Table 2-1<br><br>Pg. 10, Table 2-4 & 2nd col., Para. 3<br><br>Pg. 14, Sect. on *Decision Sight Distance*<br><br>Pg. 17, Middle fig.<br><br>Pg. 29, Para. 1<br><br>Pg. 34, Para. 1 and top fig.<br><br>Pg. 35, Paras. 2-3<br><br>Pg. 60, Middle fig. | Pgs. 631, Sect. on *Intersection Sight Distance*<br><br>Pg. 246, Para. 5 |

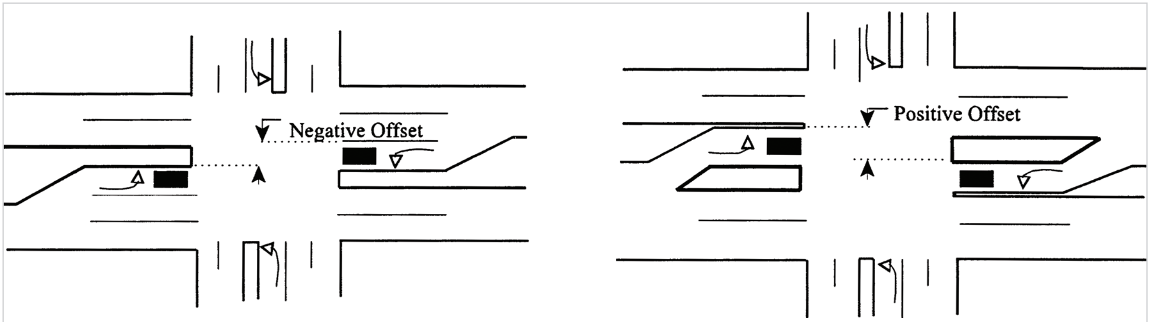



**Figure 74.** Alignment of Left-Turn Lanes for Negative and Positive Offset

opposite left-turn lane is shifted to the left. Positive offset describes the situation where the opposite left-turn lane is shifted to the right. Figure 74 illustrates the relationships between the opposite left-turn lanes for negative and positive offset lane geometry. Positive offset left-turn lanes and aligned left-turn lanes provide greater sight distances than negative offset left-turn lanes, and a positive offset provides greater sight distance than the aligned configuration.

Aging drivers may experience greater difficulties at intersections as the result of diminished visual capabilities such as depth and motion perception, as well as diminished attention-sharing (cognitive) capabilities. Studies have shown that there are age differences in depth and motion perception. Staplin, Lococo, and Sim (1993) found that the angle of stereopsis (seconds of arc) required for a group of drivers age 75 and older to discriminate depth using a commercial vision tester was roughly twice as large as that needed for a group of drivers ages 18 to 55 to achieve the same level of performance. However, while accurate perception of the distance to geometric features delineated at intersections—as well as to potentially hazardous objects such as islands and other raised features—is important for the safe use of these facilities, relatively greater attention by researchers has been placed upon motion perception, where dynamic stimuli (usually other vehicles) are the primary targets of interest. It has been shown that aging persons require up to twice the rate of movement to perceive that an object is approaching, and they require significantly longer to perceive that a vehicle is moving closer at a constant speed (Hills, 1975). A study investigating causes of aging driver over-involvement in turning crashes at intersections, building on the previously reported decline for detection of angular expansion cues, did not find evidence of overestimation of time-to-collision (Staplin et al., 1993). At the same time, a relative insensitivity to approaching (conflict) vehicle speed was shown for older versus younger drivers; this result was interpreted as supporting the notion that older drivers rely primarily or exclusively on perceived distance—not time or velocity—to perform gap acceptance judgments, reflecting a reduced ability to integrate time and distance information with increasing age. Thus, a principal source of risk at intersections is the error of an older, turning driver when judging gaps in front of fast vehicles.

In a retrospective site-based review and crash analysis that included a detailed investigation of over 400 crashes involving drivers age 65 years and older at 62 sites in Australia, limited or restricted sight distance at right turns (equivalent to left turns in the U.S.) contributed to 23 percent of the crashes, and restricted sight distance plus a lack of right-turn offsets (i.e., left-turn offsets in the U.S.) contributed to an additional 10 percent of the crashes (Oxley, et al., 2006).

Several studies examining the minimum required sight distance for a driver turning left from a major roadway to a minor roadway, as a function of major road design speed, have provided data necessary to determine: (1) the left-turn lane offset value needed to achieve the minimum required sight distance; and (2) the offset value that will provide unlimited sight distance. A fundamental premise in these studies, which are described below, is that it is not the amount of left-turn lane offset per se, but rather the sight distance that a given level of offset provides that should be the focus of any recommendations pertaining to the design of opposite left-turn lanes.

In a study conducted by McCoy, Navarro, and Witt (1992), guidelines were developed for offsetting opposite left-turn lanes to eliminate the left-turn sight distance problem. All minimum offsets specified in the guidelines are positive. For 90-degree intersections on level tangent sections of four-lane divided roadways, with 12-ft wide left-turn lanes in 16-ft wide medians with 4-ft wide medial separators, the following conclusions were stated by McCoy et al. (1992): (1) a 2-ft positive offset provides unrestricted sight distance when the opposite left-turn vehicle is a passenger car, and (2) a 3.5-ft positive offset provides unrestricted sight distance when the opposite left-turn vehicle is a truck, for design speeds up to 70 mph.

Harwood, et al. (1995) conducted an observational field study and a crash analysis to develop design policy recommendations for the selection of median width at rural and suburban divided highway intersections based on operational and safety considerations. They found that at rural unsignalized intersections, both crashes and undesirable driving behaviors decrease as median width increases. However, at suburban signalized and unsignalized intersections, crashes and undesirable behaviors increase as the median width increases. At suburban intersections, it is therefore suggested that the median should not generally be wider than necessary to accommodate pedestrians and the appropriate median left-turn treatment needed to serve current and anticipated future traffic volumes. Harwood et al. stated that wider medians generally have positive effects on traffic operations and safety; however, wider medians can result in sight restrictions for left-turning vehicles due to the presence of opposite left-turn vehicles. The most common solution to this problem is to offset the left-turn lanes, using either parallel offset or tapered offset left-turn lanes.

Figure 75 compares conventional left-turn lanes with these two alternative designs. As noted by Harwood et al. (1995), parallel and tapered offset left-turn lanes are still not common, but are used increasingly to reduce the risk of crashes due to sight restrictions from opposite left-turn vehicles. Parallel offset left-turn lanes with 12-ft widths can be constructed in raised medians with widths as narrow as 24 ft, and can be provided in narrower medians if restricted lane widths or curb offsets are used or a flush median is provided (Bonneson, McCoy, and Truby, 1993). Tapered offset left-turn lanes generally require raised medians of 24 ft or more in width.

For separation of the left-turn lane from through traffic in alternative designs such as those discussed above, the practitioner must choose between raised channelization and channelization accomplished through the use of pavement markings. As noted earlier, left-turn channelization separating through and turning lanes may, because of its placement, constitute a hazard when a raised treatment is applied, especially on

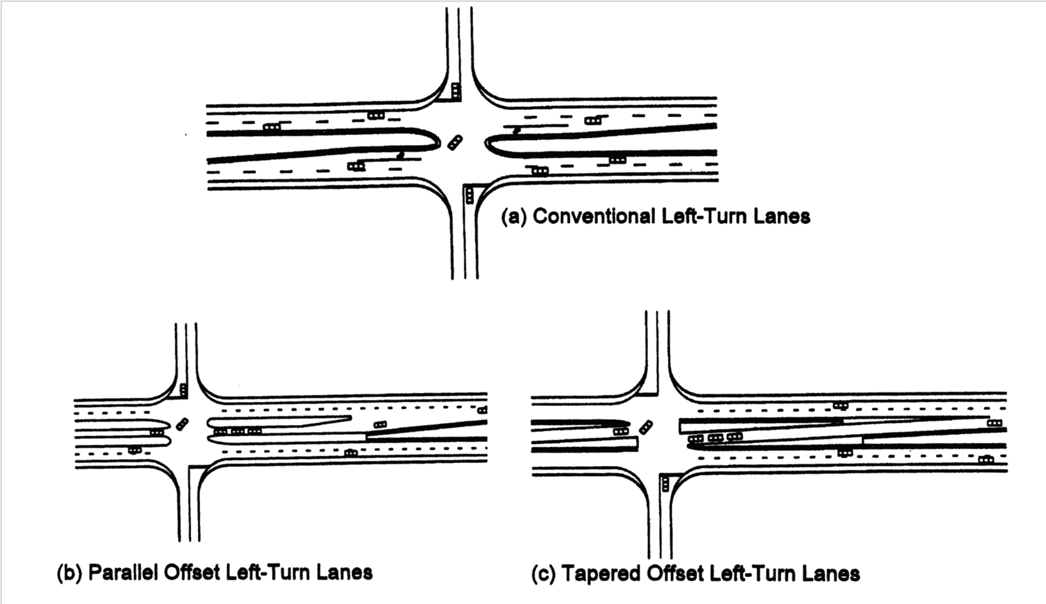



**Figure 75.** Alternative Left-Turn Treatments for Rural and Suburban Divided Highways (Bonneson et al., 1993)

high-speed facilities. Detection and avoidance of such hazards requires visual and response capabilities known to decline significantly with advancing age, supporting recommendations for treatments to improve the contrast for these channelizing features at intersections (see Design Element 3 — Channelization).

As discussed in some detail under Design Element 4 — Intersection Sight Distance, Staplin, et al. (1997) performed a laboratory study, field study, and sight distance analysis to measure driver age differences in performance under varying traffic and operating conditions, as a function of varying degrees of offset of opposite left-turn lanes at suburban arterial intersections. Research findings indicated that an increase in sight distance through positively offsetting left-turn lanes can be beneficial to left-turning drivers, particularly aging drivers. In the field study, where left-turn vehicles needed to cross the paths of two or three lanes of conflicting traffic (excluding parking lanes) at 90-degree, four-legged intersections, four levels of offset of opposite left-turn lane geometry were examined. These levels include: (a) 6-ft "partial positive" offset, (b) aligned (no offset) left-turn lanes, (c) 3-ft "partial negative" offset, and (d) 14-ft "full negative" offset. All intersections were located within a growing urban area where the posted speed limit was 35 mph. Additionally, all intersections were controlled by traffic-responsive semi-actuated signals, and all left-turn maneuvers were completed during the permissive left-turn phase at all study sites.

In the analysis of the field study lateral positioning data, it was found that the partial positive offset and aligned locations had the same effect on the lateral positioning behavior of drivers. Drivers moved approximately 5 ft to the left when there was a large negative offset, clearly indicating that sight distance was limited. There was a significant difference between the partial negative offset geometry and the partial positive offset or aligned geometries, suggesting a need for longer sight distance when opposite left-turn lanes are even partially negatively offset. The fact that aging drivers (and females) were less likely to position themselves (i.e., pull into the intersection) in the field studies highlights the importance of providing adequate sight distance for unpositioned drivers, for all left-turn designs. Vehicle positioning refers to the location within an intersection at which a left-turning vehicle waits for an acceptable gap in the opposing through traffic stream; specifically, at issue is the positioning behavior of drivers attempting to make a left turn through the conflicting through traffic while being opposed or blocked by at least one vehicle trying to make a left-turn maneuver from the opposite direction. The restriction of sight distance for an unpositioned versus a positioned driver at an intersection with aligned left-turn lanes is shown in Figure 76.

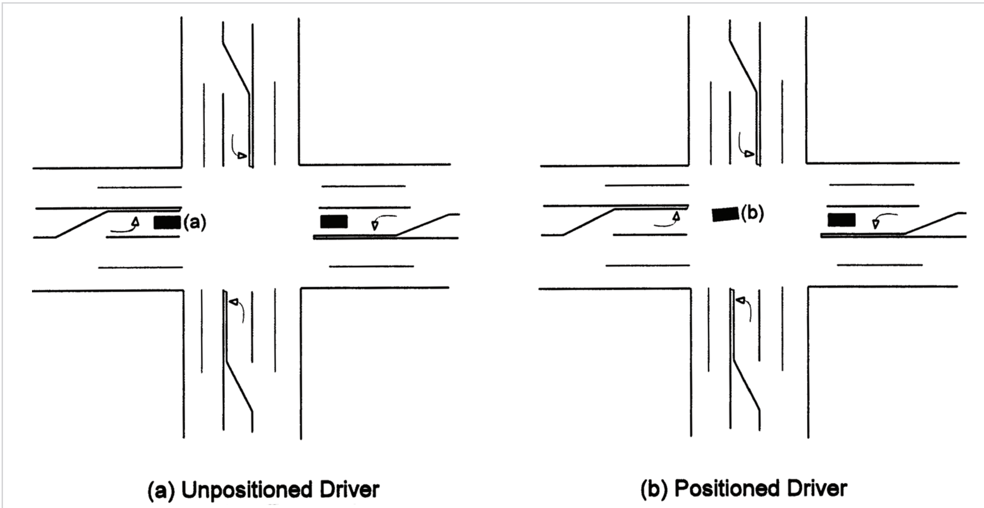



**Figure 76.** Sight Distance Restrictions for a Positioned and Unpositioned Left-Turning Driver at an Aligned Intersection with an Opposing Left-Turning Vehicle

Shechtman et al. (2007) compared older and younger driver performance at improved and unimproved intersections in a high-fidelity, virtual reality driving simulator to test the effectiveness of FHWA's recommendations for intersection designs to accommodate older road users. In this study, 19 drivers ages 25 to 45, and 20 drivers ages 65 to 85 viewed visual representations of actual intersections on urban and residential streets in Gainesville, FL, and made braking, accelerating, and steering responses using controls integrated into an actual vehicle. A driving evaluator sat in the car and recorded behavioral errors as subjects "drove" through 8 intersections. One of the improved intersections included left-turn lanes offset at 4 to 5 feet to improve the sight distance of oncoming vehicles by the left-turning driver. The comparison unimproved intersection included aligned left-turn lanes, which resulted in restricted sight distance. Both kinematic data (vehicle control responses during the turn phase including longitudinal and lateral accelerations, yaw, and speed) and behavioral data (driving errors including vehicle position, lane maintenance, speed, yielding, signaling, visual scanning, adjustment to stimuli/traffic signs, and left-turn gap acceptance) were recorded. Gap acceptance was also evaluated for left turns. Of the kinematic measures, only maximum yaw was reduced for the improved intersection, for both older and younger drivers, indicating better lateral control of the vehicle for the offset left-turn lanes compared to the aligned left-turn lanes. There were no differences in the other kinematic measures when comparing the two age groups. There were no differences in behavioral errors between the two intersections or between the two age groups. These findings suggest that both older and younger drivers may benefit from increased sight distance offered by offsetting left turn lanes, with better lateral control of their vehicles when negotiating these intersections.

Several issues were raised in the research conducted by Staplin et al. (1997) regarding the adequacy of the 1994 AASHTO and new intersection sight distance (ISD) models for a driver turning left from a major roadway. The researchers exercised alternative sight distance models, including the 1994 AASHTO Case V model using 2.0 s for perception-reaction time (PRT), a modified 1994 AASHTO model using a 2.5-s PRT, and a Gap Acceptance model proposed in NCHRP 383 by Harwood, et al. (1996). The new Gap Acceptance model relies on a critical gap value in place of PRT and maneuver time. A detailed description of the model parameters and output can be found in the FHWA report entitled Intersection Geometric Design and Operational Guidelines for Older Drivers and Pedestrians (Staplin et al., 1997). Of particular significance was the finding that the modified 1994 AASHTO model with the longer PRT of 2.5 s was the model most predictive of actual field operations. Also of significance was the dramatic decrease in required sight distance that occurred with the gap acceptance model compared with the traditional AASHTO model. Across all intersections and all design speeds, the required sight distance was approximately 23 percent less using the gap acceptance model. However, this was expected since the rationale behind the use of a gap acceptance model (cf. Harwood et al., 1996), in place of the 1994 AASHTO model, is the fact that drivers are commonly observed accepting shorter gaps than those implied by the 1994 AASHTO model. As discussed under Design Element 4, subsequent analyses established a recommendation for use of an 8.0-s gap size (plus 0.5 s for each additional lane crossed) to adjust the Gap Acceptance to accommodate aging driver needs for increased sight distance.

Regardless of which model is used to compute ISD for drivers turning left off a major roadway, a practical countermeasure to increase the sight distance is through positive offset of left-turn lanes. As shown in the study by Staplin et al. (1997), such designs result in significantly better performance on the part of all drivers, but especially for aging drivers. Prior work by McCoy et al. (1992) examined the issue of offset left-turn lanes, and developed an approach that could be used to compute the amount of offset that is required to minimize or eliminate the sight restriction caused by opposing left-turn vehicles.

This approach, incorporating the parameters represented in the intersection diagram shown earlier in Figure 72 (see Design Element 4 — Intersection Sight Distance), was applied to the intersections in the study by Staplin et al. (1997) to determine the amount of offset that would be required when using the modified 1994 AASHTO model (i.e., J = 2.5 s). The left-turn lane offsets required to achieve the minimum required sight distances calculated using this model are shown in Figure 77, in addition to the offsets required to provide unrestricted sight distance. Based on intersections examined in the study, the offset necessary to achieve unrestricted sight distance for opposing left-turning cars is 4.1 ft and for opposing left-turning trucks is 5.6 ft.

Finally, the potential for wrong-way maneuvers, particularly by aging drivers, at intersections with positive offset channelized left-turn lanes was raised during a panel meeting comprised of aging driver experts and highway design engineers, during the conduct of the research performed by Staplin et al. (1997). The concern expressed was that drivers turning left from the minor road may turn too soon and enter the channelized left-turn lane, instead of turning around both medians. Similar concern

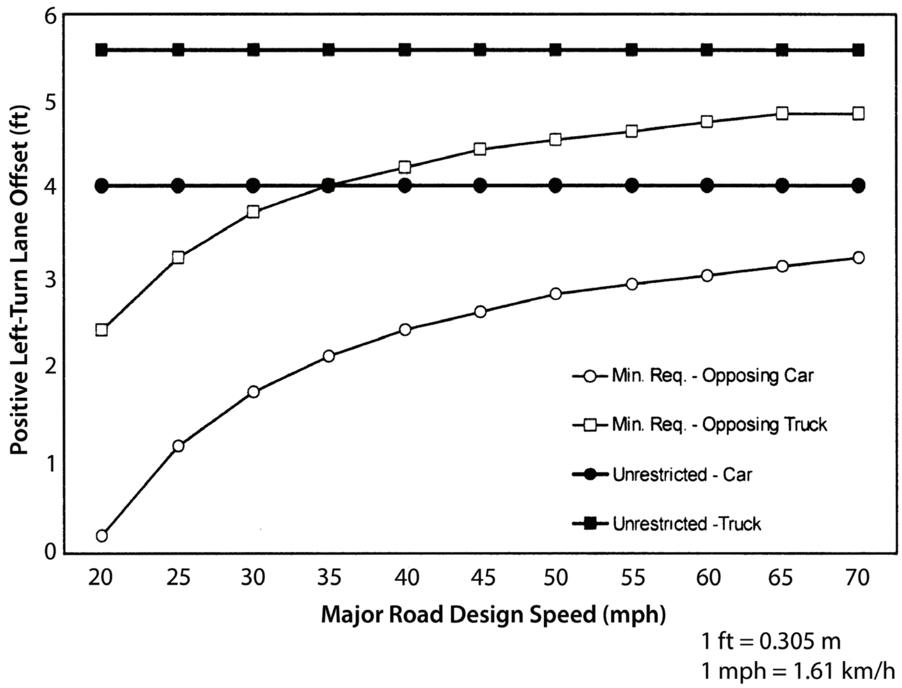



**Figure 77.** Left-Turn Lane Offset Design Values Necessary to Achieve Unrestricted Sight Distances Calculated with Either the Modified AASHTO Model (J = 2.5 s) or the Gap Acceptance Model (G = 8.0 s)

was raised by highway engineers surveyed by Harwood et al. (1995) during the conduct of NCHRP project 15-14(2). These authors reported that the potential for wrong-way movements by opposing-direction vehicles entering the left-turn roadway is minimal if proper signing and pavement markings are used.

Researchers studying wrong-way movements at intersections—particularly the intersection of freeway exits with secondary roads—have found that such movements resulted from left-turning vehicles making an early left turn rather than turning around the nose of the median, and have proposed and tested several countermeasures. Scifres and Loutzenheiser (1975) reported that indistinct medians are design elements that reduce a driver's ability to see and understand the overall physical and operational features of an intersection, increasing the frequency of wrong-way movements. They suggested delineation of the median noses to increase their visibility and improve driver understanding of the intersection design and function. Also, increasing the conspicuity of ONE WAY, WRONG WAY, and DO NOT ENTER signs by using larger-than-standard (*MUTCD*) size signs, and using retroreflective sheeting on these signs that provides for high brightness at the wide observation angles typical of the sign placements and distances at which these signs are viewed (e.g., 1.0+ degrees) will be of benefit to drivers, particularly those with age-related diminished visual and attentional capabilities. Parsonson and Marks (1979) found that the use of the two-piece, 23.5-ft arrow pavement marking (wrong-way arrow) was effective in preventing wrong-way entries onto freeway exit ramps in Georgia. Later work in this State found a benefit of pulling the nose back from the intersection, and extending the median line from the nose to the intersection using painted markings and raised retroreflectors; this treatment reduced the frequency of impacts with the median by turning vehicles, particularly trucks (per feedback provided by State engineers during a training workshop conducted by *Handbook* authors on August 6–7, 1998).

# 6 Delineation of Edge Lines and Curbs

The discrimination at a distance of gross highway features, as opposed to the fine detail contained in a sign message, governs drivers' perceptions of intersection geometric elements. Thus, the conspicuity of such elements as curbs, medians, and obstacles, as well as all raised channelization, is of paramount importance in the task of safely approaching and choosing the correct lane for negotiating an intersection, as well as avoiding collisions with the raised surfaces. During the conduct of their driving task analysis, McKnight and Adams (1970a, 1970b) identified five driving tasks related specifically to the conspicuity of intersection geometric elements: (1) maintain correct lateral lane position; (2) survey pavement markings; (3) survey physical boundaries; (4) determine proper lane position for the intended downstream maneuver; and (5) search for path guidance cues. The visual/perceptual requirement common to the performance of these tasks is contrast sensitivity: for detecting lane lines, pavement word and symbol markings, curbs and roadway edge features, and median barriers.

Aging drivers' decreased contrast sensitivity, reduced useful field of view, increased decision time—particularly in response to unexpected events—and slower vehicle control movement execution combine to put these highway users at greater crash risk when approaching and negotiating intersections. The smaller the attentional demand required of a driver to maintain the correct lane position for an intended maneuver, the greater

**Table 17.** Cross-References of Related Entries for Delineation of Edge Lines and Curbs.

| Applications in Standard Reference Manuals | | | | |
|---|---|---|---|---|
| *MUTCD* (2009) | AASHTO *Green Book* (2011) | Roadway Lighting Handbook (1978) | NCHRP 279 Intersection Channelization Design Guide (1985) | Traffic Engineering Handbook (2009) |
| Sect. 1A.13, *Edge Line Markings, Island, & Object Marker*<br>Sects. 2C.63 through 2C.65<br>Sect. 3A.06<br>Sects. 3B.09, 3B.10, 3B.11, 3B.13, & 3B.23<br>Sect. 3G.01<br>Sect. 3H.01<br>Sects. 3I.01 through 3I.06 | Pg. 2-39, Para. 3<br>Pg. 3-176, Paras. 3-4<br>Pgs. 4-17 through 4-19, Sect. on *Curb Configurations*<br>Pg. 6-15, Para. 3<br>Pg. 7-32, Para. 3<br>Pg. 9-19, Para. 2<br>Pg. 9-18, Fig. 9-9B<br>Pgs. 9-99 through 9-105, Sects. on *Island Size and Designation & Island Delineation and Approach Treatment*<br>Pgs. 9-106 through 9-112, Sect. on *Right-Angle Turns with Corner Islands*<br>Pg. 9-148, Sect. on *Shape of Median End*<br>Pgs. 694-696, Figs. 9-55 through 9-58<br>Pg. 9-133, Paras. 5-6<br>Pgs. 9-134 through 9-136, Figs. 9-50 & 9-51<br>Pgs. 9-137, Sect. on *Median End Treatment* | Pg. 2, 2nd col, Para. 1<br>Pg. 3, Para. 4<br>Pg. 4, 1st bullet<br>Pg. 9, Sect. on *Contrast*<br>Pg. 17, Form 1<br>Pg. 21, Table 1<br>Pg. 24, Example Form 1<br>Pgs. 29-30, Sect. on *Adverse Geometry and Environment Warrant*<br>Pg. 31, Item, A | Pg. 24, Para. 1<br>Pg. 35, Para. 2 & bottom left fig.<br>Pg. 39, All figs.<br>Pg. 66, 2nd col., Para. 1<br>Pgs. 69 & 75, Sects. on *Traffic Islands & Guide-lines for Selection of Island Type*<br>Pg. 74, Fig. 4-31<br>Pg. 76, Item 1<br>Pgs. 102-103, Intersct. No. 8 | Pg. 382, Sect. on *Centerline and Edge Line Markings*<br>Pg. 573, Sect. on *Marking of Curb Extensions and Edge Islands*<br>Pg. 391-392, Sect. on *Older Drivers and Pedestrians* |

the attentional resources available for activities such as the recognition and processing of traffic control device messages and detection of conflict vehicles and pedestrians.

A variety of conspicuity-enhancing treatments are mandated in current practice. The *MUTCD* (section 3B.10, Approach Markings for Obstructions) specifies that pavement markings shall be used to guide traffic away from fixed objects (such as median islands and raised channelization islands) within a paved roadway. Section 3B.23 (Curb Markings) states that retroreflective solid yellow markings should be placed on the curbs of islands that are located in the line of traffic flow where the curb serves to channel traffic to the right of the obstruction, and that retroreflective solid white markings should be used (on curbs) when traffic may pass on either side of the island. Section 3G.01 (Colored Pavements) describes the use of colored pavements as traffic control devices, where yellow shall be used for median islands and white for channelizing islands, and section 3I.03 (Island Marking Application) describes the use of pavement and curb markings; object markers; and delineators for island marking application. Supplementary treatments, and requirements for in-service brightness levels for certain elements contained in existing guidelines, are presently at issue.

The conspicuity of curbs and medians, besides aiding in the visual determination of how an intersection is laid out, is especially important when medians are used as pedestrian refuges. Care must be taken to ensure that pedestrian refuges are clearly signed and made as visible as possible to passing motorists.

Research findings describing driver performance differences directly affecting the use of pavement markings and delineation focus upon (age-related) deficits in spatial vision. In a pertinent laboratory study conducted by Staplin, Lococo, and Sim (1990), two groups of subjects (ages 19–49 and 65–80) viewing a series of ascending and descending brightness delineation targets were asked to report when they could just detect the direction of roadway curvature at the horizon (roadway heading)—left versus right—from simulated distances of 100 ft and 200 ft. Results showed that the older driver group required a contrast of 20 percent higher than the younger driver group to achieve the discrimination task in this study.

To describe the magnitude of the effects of age and visual ability on delineation detection/recognition distance and retroreflective requirements for threshold detection of pavement markings, a series of analyses using the Ford Motor Company PC DETECT computer model (Matle and Bhise, 1984) yielded the stripe contrast requirements shown in Table 18 (ADI Limited, 1991). PC DETECT is a headlamp seeing-distance model that uses the Blackwell and Blackwell (1971, 1980) human contrast sensitivity formulations to calculate the distance at which various types of targets illuminated by headlamps first become visible to approaching drivers, with and without glare from opposing headlights. The top 5 percent of 25-year-olds (the best-performing younger drivers) and bottom 5 percent of 75-year-olds (the worst-performing older drivers) were compared in this analysis.

**Table 18.** Contrast Requirements for Edge Line Visibility at 400 ft With 5-S Preview at a Speed of 55 mph, as Determined by PC Detect Computer Model (ADI, 1991).

| Driver age group/ % accommodated | Worst-case glare | No glare |
|---|---|---|
| Age 25 / top 5% | 0.11 | 0.05 |
| Age 75 / bottom 5% | 7.21 | 3.74 |

Blackwell and Taylor (1969) conducted a study of surface pavement markings employing an interactive driving simulator, plus field evaluations. They concluded that driver performance —measured by the probability of exceeding lane limits—was optimized when the perceived brightness contrast between pavement markings and the roadway was 2.0. A study by Allen, O'Hanlon, and McRuer (1977) also concluded that delineation contrast should be maintained above a value of 2.0 for adequate steering performance under clear night driving conditions. In other words, because contrast is defined as the difference between target and background luminance, divided by the background luminance alone, these studies have asserted that markings must appear to be at least three times as bright as the road surface. Also, because these studies were not specifically focused on the accommodation of aging drivers—particularly the least capable members of this group—the contrast requirements defined in the 1991 modeling studies and analyses, as presented in Table 18, are accorded greater emphasis. Taking the indicated value for the least capable 5 percent of 75-year-olds into account, as well as the prior field evaluations, a contrast requirement of 3.0 for pavement markings appears most reasonable.

It is important to note that, whether luminance is measured in metric or English units [candelas per square meter ($cd/m^2$) or footlamberts (fL)], contrast is a dimensionless number; thus the present recommendations as well as the calculation of contrast level are independent of the unit of measure.

Finally, inadequate conspicuity of raised geometric features at intersections has been brought to the attention of researchers during the conduct of several focus group studies involving aging drivers. Subjects reported difficulty knowing where to drive, due to missing or faded roadway lines on roadway edges and delineation of islands and turning lanes. They also reported hesitating during turns, because they did not know where to aim the vehicle (Staplin, Lococo, and Sim, 1990). In another focus group, subjects suggested that the placement of advance warning pavement markings be located as far in advance of an intersection as practicable (Council and Zegeer, 1992). Drivers ages 66–77 and older participating in focus group discussions conducted by Benekohal, et al. (1992), reported that intersections with too many islands are confusing because it is hard to find which island the driver is supposed to go around. Raised curbs that are unmarked are difficult to see, especially in terms of height and direction, and result in people running over them. These aging drivers stated that they would prefer to have rumble strips in the pavement to warn them of upcoming concrete medians and to warn them about getting too close to the shoulder. In other focus group discussions conducted to identify intersection geometric design features that pose difficulty for aging drivers and pedestrians (Staplin, et al., 1997), drivers mentioned that they have problems seeing concrete barriers in the rain and at night, and characterized barriers as "an obstruction waiting to be hit."

An inventory of the materials and devices commonly employed to delineate roadway edges, curbs, medians, and obstacles includes: retroreflective paint or tape, raised pavement markers (RPM's), post-mounted delineators (PMD's), object markers, and chevron signs.

# 7 Curb Radius

Recommendations for this design element address the radius of the curb that joins the curbs of adjacent approaches to an intersection. The size of the curb radius affects the size of vehicle that can turn at the intersection, the speed at which vehicles can turn, and the width of intersection that must be crossed by pedestrians. If curb radii are too small, lane encroachments resulting in traffic conflicts and increased crash potential can occur. If the radii are too large, pedestrian exposure may be increased (although, if large enough, refuge islands may be provided). The procedures used in the design of curb radii are well detailed in the *Green Book* (AASHTO, 2011).

McKnight and Stewart (1990) identified the task of positioning a vehicle in preparation for turning as a critical competency. A significant problem identified in a task analysis to prioritize aging drivers' problems with intersections is carrying out the tight, right-turn maneuver at normal travel speed on a green light (Staplin, et al., 1994). The problems are somewhat moderated when right turns are initiated from a stop, because the turn can be made more slowly, which reduces difficulties with short radii. Aging drivers may seek to increase the turning radius by moving to the left before initiating the turn, often miscommunicating an intention to turn left and encouraging following drivers to pass on the right. Or, they may initiate the turn from the correct position, but swing wide into a far lane in completing the turn in order to lengthen the turning radius and thus minimize rotation of the steering wheel. Encroaching upon a far lane can lead to conflict with vehicles approaching from the right or, on multilane roads, oncoming drivers turning to their left at the same time. The third possibility is to cut across the apex of the turn, possibly dragging the rear wheels over the curb. Each of these shortcomings in lanekeeping can be overcome by a channelized right-turn lane or wider curb radii.

**Table 19.** Cross-References of Related Entries for Curb Radius.

| Applications in Standard Reference Manuals | | | |
|---|---|---|---|
| **AASHTO**<br>*Green Book*<br>**(2011)** | **NCHRP 279 Intersection Channelization Design Guide (1985)** | | **Traffic Engineering Handbook (2009)** |
| Pgs. 9-83 through 9-92, Sects. on *Effect of Curb Radii on Turning Paths & Effect of Curb Radii on Pedestrians*<br>Pg. 9-96, Paras. 1-2<br>Pgs. 9-141 through 9-149, Sect. 9.8.2 *Control Radii for Minimum Turning Paths*<br>Pgs. 9-149 through 9-151, Sect. on *Median Openings Based on Control Radii for Design Vehicles* | Pg. 1, 2nd bullet<br>Pg. 6, Paras. 4-5<br>Pg. 10, Table 2-4<br>Pg. 20, Bottom fig.<br>Pg. 21, 2nd col, Item 4 & Fig. 3-1<br>Pg. 22, 2nd fig from bottom of pg.<br>Pg. 23, Bottom right fig.<br>Pg. 26, Bottom fig.<br>Pg. 35, Para. 2<br>Pg. 36, Middle fig. & associated notes<br>Pg. 38, Middle fig. & associated notes<br>Pgs. 66-69, Sects. on *Corner Radius Design & Radius of Turn* | Pgs. 70-73, Figs. 4-27 through 4-29<br>Pg. 77, Fig. 4-32<br>Pg. 83, Sects. on *Driveways Along Major Arterials and Collectors & Consideration of Pedestrians*<br>Pgs. 84-87, Figs. 4-37 through 4-39<br>Pgs. 93-94, Intersct. No. 2<br>Pgs. 96-97, Intersct. No. 4<br>Pgs. 122-125, Intersct. Nos. 18-19<br>Pgs. 128-129, Intersct. No. 20B<br>Pgs. 132-135, Intersct. Nos. 22-23 | Pg. 247, Sect. on Curb RadiusParas. 5-6<br>Pg. 254, first bullet |

Chu (1994) found that relative to middle-aged drivers (ages 25–64), older drivers (age 65 and older) tend to drive larger automobiles and drive at slower speeds. Although large heavy cars are associated with a crash fatality rate that is less than one-quarter of that associated with the smallest passenger cars (Insurance Institute for Highway Safety, 1991) and are, therefore, a wise choice for older drivers who are more frail than their middle-aged counterparts, large vehicles have larger turning radii, which may exacerbate the problems older drivers exhibit in lanekeeping during a turn. Roberts and Roberts (1993) reported that common arthritic illnesses such as osteoarthritis, which affects more than 50 percent of the elderly population, and rheumatoid arthritis, affecting 1 to 2 percent, are relevant to the tasks of turning and gripping the steering wheel. A hand deformity caused by either osteoarthritis or rheumatoid arthritis may be very sensitive to pressure, making the driver unwilling to apply full strength to the steering wheel or other controls. In an assessment of 83 drivers with arthritis, Cornwell (1987) found that 83 percent of the arthritic group used both hands to steer, 7 percent used the right hand only, and 10 percent the left hand only; in this study, more than one-half of the arthritic group required steering modifications, either in the form of power steering or other assistive device such as a smaller steering wheel.

The *Intersection Channelization Design Guide* (Neuman, 1985) states that intersections on high-speed roadways with smooth alignment should be designed with sufficient radii to accommodate moderate- to high-speed turns. At other intersections, such as in residential neighborhoods, low-speed turns are desirable, and smaller corner radii are appropriate in these cases. Additionally, selection of a design vehicle is generally based on the largest standard or typical vehicle type that would regularly use the intersection. For example, a corner radius of 50 ft will accommodate moderate-speed turns for all vehicles up to WB-50 (combination truck/large semitrailer with an overall length of 55 ft). However, many agencies are designing intersections along their primary systems to accommodate a 70 ft, single trailer design vehicle (C-70). Table 4-8 (p. 66) of the *Intersection Channelization Design Guide* provides guidelines for the selection of a design vehicle. It further specifies in Table 4-9 the operational characteristics for various corner radii. For example, a corner radius of less than 5 ft is not appropriate even for P design vehicles (passenger cars), whereas a corner radius of 20–30 ft will accommodate a low-speed turn for P vehicles, and a crawl-speed turn for SU vehicles (single unit truck, 30 ft in length) with minor lane encroachment.

Of equal importance to the right-turning design vehicle in determining curb radii is a consideration of pedestrian crossing time, particularly in urban areas. Smaller corner radii (less than 30 ft) can decrease right-turn speeds and reduce open pavement area for pedestrians crossing the street. A consideration of vehicle turning speed and pedestrian crossing distance can contribute to the safe handling of vehicle/pedestrian crossing conflicts (Neuman, 1985). Hauer (1988) noted that "the larger the curb-curve radius, the larger the distance the pedestrian has to cover when crossing the road. Thus, for a sidewalk whose centerline is 6 ft from the roadway edge, a 15-ft corner radius increases the crossing distance by only 3 ft. However, a 50-ft radius increases this distance by 26 ft, or 7 s of additional walking time." Hauer further stated that the following are widely held concerns with the widening of curb radii: (1) the longer the crossing distance, the greater the hazard to pedestrians, even though there may be space for refuge islands when the corner radius is large enough; (2) larger curb radii may induce drivers to negotiate the right turn at a higher speed; and (3) the larger the radius, the wider the turn, which makes it more difficult for the driver and the pedestrian to see each other. For these reasons, the safety of aging persons at intersections, particularly pedestrians, may be adversely affected when large curb radii are provided.

In focus group discussions with 46 drivers ages 65–74 (young-old group) and 35 drivers age 75 and older (old-old group), 74 percent of drivers in each age group reported that tight intersection corner radii posed difficulty in maneuvering through the intersection for the following reasons: (1) there are visibility problem with sharp corners; (2) drivers sometimes hit curbs and median barriers; and (3) with sharp turns, trucks turning left into the adjacent opposing traffic lane end up face-to-face with drivers, requiring them to back up (Staplin, et al. 1997). Approximately 24 percent of the young-old drivers and 34 percent of the old-old drivers suggested that medium rounding is sufficient to facilitate turning maneuvers and is safer than very broadly rounded corners because the latter encourages high-speed turns.

In a design preference study using slides to depict varying radii of corner curb cuts, four alternative curb geometries were presented to 30 drivers ages 65–74 (young-old group) and 30 drivers age 75 and older (old-old group) (Staplin et al., 1997). The four alternative geometries (depicted in Figure 78) were: (1) a simple circular radius of 18 ft; (2) a simple circular radius of 12 m; (3) a simple circular radius of 48 ft; and (4) a three-sided/truncated curve with the center side measuring 54 ft. The alternatives were identically ranked by both groups of drivers: Alternative 3 was consistently preferred, Alternative 4 placed second, Alternative 2 placed third, and Alternative 1 was least preferred. Both young-old and old-old drivers in this study were most concerned about ease of turning, citing the better maneuverability and less chance of hitting the curb as their primary basis of response. The second most common—but also strongly weighted—reason for the preference responses of both groups related to the degree of visibility of traffic on intersecting roadways, possibly explaining the slight preference for Alternative 2 over Alternative 1. Alternatives 3 and 4 both are described by corner curb line geometries offering ease of turning and good visibility; however, isolated responses to the truncated corner geometry (Alternative 4) indicated concerns that providing too much room in the right-turn path might result in a lack of needed guidance information and could lead to a maneuver error, and that it could be harder to detect pedestrians with this design.

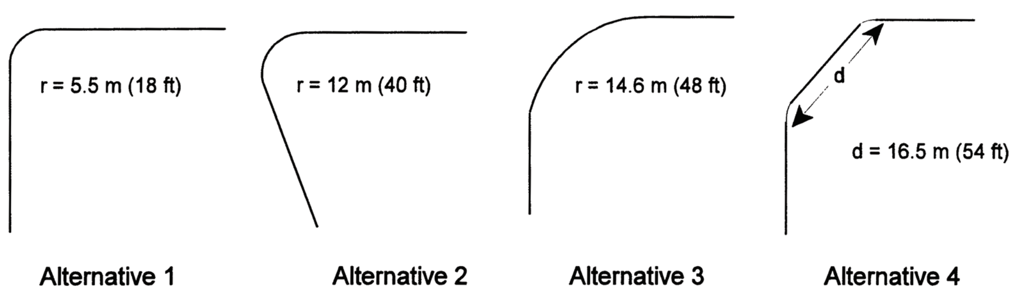



**Figure 78.** Alternative Curb Radii Evaluated in Laboratory Preference Study of Intersection Geometries (Staplin et al., 1997)

In a field study conducted as part of the same project, three intersections providing right-turn curb radii of 40 ft, 25 ft, and 15 ft were evaluated to examine the effects of curb radii on the turning paths of vehicles driven by drivers in three age groups. One hundred subjects divided across three age groups drove their own vehicles around test routes using the local street network in Arlington, VA. The three age groups were "young/middle-aged" (ages 25–45), which contained 32 drivers; "young-old" (ages 65–74), containing 36 drivers; and "old-old" (age 75 and older), containing 32 drivers. The speed limit was 35 mph and all intersections were located on major or minor arterials within a growing urban area. Data were only collected for turns executed on a green-signal phase.

Analysis of the free-flow speeds showed that all factors (age, gender, and geometry), and their interactions, were significant. Mean free-flow speeds were highest at the largest (40 ft) curb radius location, for all age groups. A consistent finding showed that the slowest mean free-flow speeds were measured at the 15 ft curb radius location for all age groups. Thus, larger curb radii increased the turning speeds of all drivers, with young/middle-aged and young-old drivers traveling faster than old-old drivers when making right turns.

# 8 Left-Turn Traffic Control for Signalized Intersections

Crash analyses have shown that aging drivers, ages 56–75 and age 76 and older, are overinvolved in left-turn maneuvers at signalized intersections, with failure to yield right-of-way or disregarding the signal the principal violation types (Staplin and Lyles, 1991; Council and Zegeer, 1992). Old-elderly drivers (age 75 and older) were more likely than younger drivers (ages 30–50) to be involved in left-turn crashes at urban signalized intersections, and both young-elderly (ages 65–74) and old-elderly were more likely to be involved in left-turn crashes at rural signalized intersections. In both cases, the crash-involved older drivers were more likely to be performing a left-turn maneuver than the younger drivers. In addition, Stamatiadis, Taylor, and McKelvey (1991) found that the relative crash involvement ratios for aging drivers were higher at two-phase (no turning phase) signalized intersections than for multiphase (includes turn arrow) signalized intersections. This highlights problems aging drivers may have determining acceptable gaps and maneuvering through traffic streams when there is no protective phase. Further, crash percentages increased significantly for aging drivers when an intersection contained flashing controls, as opposed to conventional (red, yellow, green) operations. In this analysis, the greatest crash frequency at signalized intersections occurred on major streets with five lanes, followed closely by roadways containing four lanes. These configurations were most often associated with low-speed, high-volume urban locations, where intersection negotiation requires more complex decisions involving more conflict vehicles and more visually distracting conditions. Not surprisingly, Garber and Srinivasan's (1991) analysis of 7,000 intersection crashes involving drivers ages 50–64 and age 65 and older, found that the provision of a protected left-turn phase will aid in reducing the crash rates of the elderly at signalized intersections.

The change in the angular size of a moving object, such as an approaching vehicle observed by a driver about to turn left at an intersection, provides information crucial to gap judgments (i.e., speed and distance). Age-related declines (possibly exponential) in the ability to detect angular movement have been reported. Aging persons may in fact require twice the rate of movement than younger persons to perceive that an object is approaching, given a brief (2.0 s) duration of exposure. Also, older persons participating in laboratory studies have been observed to require significantly longer intervals than younger persons to perceive that a vehicle was moving closer at constant speed: at 19 mph, decision times increased 0.5 s between ages 20 and 75 (Hills, 1975).

Compounding this age-related decline in motion perception, some research has indicated that, relative to younger subjects, older subjects underestimate approaching vehicle speeds (Hills and Johnson, 1980). Specifically, Scialfa, et al. (1991) showed that older adults tend to overestimate approaching vehicle velocities at lower speeds and underestimate at higher speeds, relative to younger adults. Staplin, Lococo, and Sim (1993), while investigating causes of aging driver over-involvement in turning crashes

**Table 20.** Cross-References Of Related Entries For Left-Turn Traffic Control For Signalized Intersections.

| **Applications in Standard Reference Manuals** | | | | |
|---|---|---|---|---|
| ***MUTCD*** **(2009)** | **AASHTO** *Green Book* **(2011)** | **NCHRP 500–Volume 9 (2004)** | **NCHRP 279 Intersection Channelization Design Guide (1985)** | **Traffic Engineering Handbook (2009)** |
| Figs. 3B-13b, c, d, 3B-24, & 3B-27<br><br>Sect. 1A.13, *Approach, Intersection, Lane-Use Control Signal, Regulatory Sign, Sign Legend, & Traffic Control Signal*, Table 2B-1<br><br>Sects. 2B.18 through 2B.22, 2B.52, 2B.53, 3B.08 & 3B.20<br><br>Sect. 4D.04 through 4D. 20, 4D.25 through 4D.31<br><br>Sects. 4M.02 through 4M.04 | Pg. 3-176, Para. 4<br><br>Pgs. 9-15 through 9-19, sect. on *Channelized Four-Leg Intersections*<br><br>Pg. 10-38, Para. 1<br><br>Pg. 10-39, Fig. 10-17<br><br>Pgs. 10-42 through 10-47, Sect. on *Single-Point Diamond Interchanges* | Pgs. V-12-V-14, Sect. on *Strategy 3.1 B2: Provide Advance Guide Signs and Street Name Signs (T)*<br><br>Pgs. V-18-V-19, Sect. on *Strategy 3.1 B5: Provide More Protected Left-Turn Signal Phases at High-Volume Intersections (P)* | Pg. 1, Item 3, 4th bullet<br><br>Pg. 3, 2nd col., Para. 3<br><br>Pg. 21, Fig. 3-1<br><br>Pg. 28, Top fig.<br><br>Pg. 29, Top left fig.<br><br>Pg. 34, Top fig. & associated notes<br><br>Pg. 37, Top left fig.<br><br>Pg. 48, Para. 5 & Table 4-3<br><br>Pg. 49, Paras. 1, 2, & 4 and 2nd col, item 2<br><br>Pg. 54, Fig. 4-16, bottom left photo<br><br>Pg. 57, Sects. on *Double Left-Turn Lanes—Guidelines for Use & Design of Double Left-Turn Lanes*<br><br>Pgs. 58-60, Figs. 4-20 & 4-21<br><br>Pgs. 100-101, Intersct. No. 7<br><br>Pgs. 104-119, Intersct. Nos. 9-16<br><br>Pgs. 132-135, Intersct. Nos. 22-23<br><br>Pg. 144, Intersct. No. 33<br><br>Pgs. 148-151, Intersct. Nos. 35-36 | Pgs. 245-246<br><br>Pgs. 462-465, Sect. on *Turn Lanes*<br><br>Pg. 413-415, Sect. on *Left Turns*<br><br>Pgs. 632-634, Sect. on *Turn Restrictions* |

at intersections, did not find evidence of overestimation of time-to-collision by aging drivers in their perception of the closing distance between themselves and another vehicle approaching either head-on or on an intersecting path. However, a relative insensitivity to approach (conflict) vehicle speed was shown for older versus younger drivers, in that younger drivers adjusted their gap judgment of the "last safe moment" to proceed with a turn appropriately to take higher approach speeds into account, while older drivers as a group failed to allow a larger gap for a vehicle approaching at 60 mph than for one approaching at 30 mph. The interpretation of this and other data in this study was that aging drivers rely primarily or exclusively on perceived vehicle separation distance to reach maneuver "go/no go" decisions, reflecting a reduced ability to integrate time and distance information with increasing age. Thus, a principal source of risk at intersections is the error of an aging, turning driver in judging gaps in front of fast vehicles.

Aside from (conflict vehicle) motion detection, an additional concern is whether there are age differences in how well drivers understand the rules under which the turns will be made—that is, whether aging drivers have disproportionately greater difficulty in understanding the message that is being conveyed by the signal and any ancillary (regulatory) signs. If the signals and markings are not understood, at a minimum there may be delay in making a turn or, in the worst case, a crash could result if a protected operation is assumed where it does not exist.

A driver comprehension analysis conducted in a laboratory setting with drivers 30–60 years of age and older showed that green displays (those with the circular green indication alone, green arrow alone, or combinations of circular green and green arrow on the left-turn signal) were correctly interpreted with widely varying frequency, depending on the signals shown for the turning and through movements (Curtis, Opiela, and Guell, 1988). In most cases, performance declined as age increased; aging drivers were correct approximately half as often as the youngest drivers. Most driver errors, and especially aging driver errors, indicated signal display interpretations that would result in conservative behavior, such as stopping and/or waiting. Overall, green arrows were better understood than circular green indications. Conversely, red and yellow arrows were less comprehensible than circular red and circular yellow indications. Potentially unsafe interpretations were found for red arrow displays in protected-only operations. The yellow arrow display was more often treated as a last chance to complete a turn when compared with a circular yellow indication. Driver errors were most frequent in displays that involved flashing operations, and multiple faces with different colors illuminated on the left-turn signal head, and in particular, different colors on the turn and through signals.

More specifically, Curtis et al. (1988) found that the circular green indication under permissive control was correctly interpreted by approximately 60 percent of the subjects. For protected-only operations, the green arrow (with circular red for through movement) was correctly answered by approximately 75 percent of drivers. For protected/permissive operation, the circular green alone was correctly answered by only 50 percent of the respondents, while the green arrow in combination with the circular green had approximately 70 percent correct responses. When the circular green with the green arrow was supplemented by the R10-12 sign LEFT TURN YIELD ON GREEN ●, only 34 percent of drivers answered correctly. This test result suggests that the *MUTCD* recommended practice may result in some driver confusion, as test subjects answered correctly more often when the sign was not present, even when the effects of regional differences in familiarity with the sign were considered. Apparently reinforcing this notion, the Maryland State Highway Administration (MSHA, 1993) reported a higher rate of left-turn collisions at three intersections where the R10-12 sign was installed than at three intersections where the sign was not installed. Unfortunately, driver age was not a study variable; also, medians were present (only) at sites with the R10-12 signs, and differences between sites in terms of signal phasing, traffic volumes and delays, and alignment and other aspects of intersection geometry, though noted, were not described. Other researchers have found improved driver comprehension with the use of the R10-12 sign, compared to other messages informing drivers of the decision rule for protected/permissive operations, as described later in this section.

When Hummer, Montgomery, and Sinha (1990) evaluated motorists' understanding of left-turn signal alternatives, they found that the protected-only signal was by far the best understood, permissive signals were less understood, and the protected/permissive the least understood. When a circular green for through traffic and a green arrow for left turns were displayed, the protected signal was clearly preferred over the permissive and protected/permissive signals, and the leading signal sequence was preferred more often than the lagging sequence. Respondents stated that the protected-only signal caused less confusion, was safer, and caused less delay than the permissive and protected/permissive signals. It should be noted, however, that while aging persons were in the sample of drivers studied, they made up a very small percentage (8 of 402) and differences were hard to substantiate.

Knoblauch, et al. (1995) examined the lack of understanding associated with a variety of protected and permissive left-turn signal displays. They found that many drivers, both younger and older, do not understand the protected/permissive signal phasing, and they suggested that efforts to improve motorist comprehension of left-turn signal phasing should be targeted at the entire driving population. In focus group discussions, many aging drivers reported that they avoid intersections that do not have a protected-only phase or those where the time allowance for left turns was too short. In addition, the situation where the green arrow eventually turns to a circular green was generally confusing and not appreciated by the aging participants. Among the recommendations made by the aging drivers were:

- Provide as many protected left-turn opportunities as possible.
- Standardize the sequence for the left-turn green arrow so that it precedes solid green or red.
- Lengthen the protected left-turn signal.
- Lengthen the left-turn storage lanes so that turning traffic does not block through traffic.
- Make traffic signal displays more uniform across the United States, including the warning or amber phase.
- Standardize the position and size of signals.
- Provide traffic lights overhead and to the side at major intersections.

- Paint a yellow line in the pavement upstream of the signal in a manner that, if the driver has not reached the line before the light has turned yellow, he/she cannot make it through before the red light.
- Provide borders (backplates) around lights to minimize the effects of glare.
- Eliminate holiday decorations located overhead at intersections, because they are often green and red and may be confusing near signal faces.

Bonneson and McCoy (1994) also found a decreased understanding of protected and permissive left-turn designs with increased age, in a survey conducted in Nebraska with 1,610 drivers. In this study, the overlap phase (left-turn green arrow and through circular green illuminated) was the least understood by drivers wishing to turn left, with only one-half of the respondents answering correctly; most of the respondents who erred chose the safer course of action, which was to wait for a gap in oncoming traffic. In terms of signal head location, 4 to 5 percent more drivers were able to understand the protected/permissive display when it was centered in the left-turn lane (exclusive) as opposed to having the head located over the lane line (shared). Although the difference was statistically significant, Bonneson and McCoy point out that the difference may be too small to be of practical significance. In terms of lens arrangement, significantly more drivers understood both the permissive indication and the protected/*MUTCD* indication (left-turn green arrow and through circular red) in vertical and horizontal arrangements than in the cluster arrangement. Comparisons between the protected/*MUTCD* indication and a modified protected indication (green arrow with no circular red), showed that for the horizontal protected/permissive designs, 25 percent more drivers were able to understand the protected indication when the circular red was not shown with the green arrow, and for the vertical and cluster protected/permissive designs, 12 percent more drivers understood the modified protected indication. The point is that from an operational perspective, hesitancy as a result of misunderstanding will decrease the level of service and possibly result in crash situations.

Noyce and Kacir (2002) conducted a survey of 2,465 drivers in 8 locations across the U.S. to determine driver understanding of simultaneous traffic signal indications in protected left turn displays. Drivers ranged in age from less than 25 to 65 and older, with 7 percent of the sample over age 65. The survey included 200 different scenarios, of which 68 contained protected left-turn indications. Drivers were shown photographs of left turn displays from various signalized intersections around the country. Each photograph was taken from approximately the driver's eye location as if the driver were positioned as the first left-turn vehicle in queue in an exclusive left-turn lane. Animated signal displays were created and replaced the existing signal displays in each photograph. Five-section protected and permissive left-turn (PPLT) displays in the protected phase illuminated both the green-arrow and through movement (green-ball or red-ball) indications as required by *MUTCD*. The four and three section displays presented only the green arrow. The drivers were asked to respond to the following question by selecting either GO, YIELD-wait for gap, STOP-then wait for gap, or STOP: "If you want to turn left, and you see the traffic signals shown, you would….". The time duration for each response was also recorded.

In the Noyce and Kacir (2002) study, age played a significant role in the percentage of correct responses when green arrow and red ball indications were shown simultaneously: for drivers less than 24 years of age, 75 percent of responses were correct, and for drivers over the age of 65, 62 percent of responses were correct. The majority of incorrect responses to the 5-section displays with the green arrow and red ball indications were "stop, then wait for gap," demonstrating some confusion with the simultaneously illuminated indications. Compared to this, for the 65+ age group, when green arrow was shown with green ball, 86 percent of responses were correct, and when green arrow was shown without a green or red ball, 89 percent of responses were correct. When the green-arrow and red-ball indications were shown simultaneously in the 5-section signal display, driver understanding was lowest with the horizontal arrangement. The authors indicate that locating the green arrow to the right of the red-ball indication in a 5-section horizontal display arrangement appears to provide confusion. For the 5-section horizontal display with green arrow and red ball, only 49 percent of drivers age 65 and older gave the correct answer.

Regarding the response times to the signals in the Noyce and Kacir (2002) study, the average response increased with driver age. The 3- and 4-section displays showing only the green arrow, had average driver response times ranging from 3 s for the under-24 age group to 6 s for the over-65 group. However, the difference was more pronounced with the 5-section horizontal display showing a green arrow and red ball simultaneously; in this display, the under-24 age group had an average response time of 5 s, and the over-65 age group had an average response time of 10 s. The average response time for drivers over age 65 was 8 s for the 5-section cluster and vertical displays showing green-arrow and red-ball indications simultaneously. The average response time for the 5-section signal displays showing green-arrow and green-ball indications simultaneously was not different from that for the 3- and 4-section displays showing the green-arrow only indication.

The authors recommended that in a 5-section horizontal display, the green arrow and red ball should not be illuminated simultaneously.

An analysis of sign use by Bonneson an McCoy (1994) compared the exclusive cluster lens arrangement over the left-turn lane and exclusive vertical lens arrangement over the through lanes with and without the use of an auxiliary sign (LEFT TURN YIELD ON GREEN ●). Overall, the results indicated that driver understanding of the display increased by about 6 percent when there was no sign, though a closer examination of these data revealed that the specific operation signaled by the display was critical. For the permissive indication, the sign appeared to help driver understanding, whereas during the overlap and protected indications it appeared to confuse drivers.

Numerous studies have found that: (1) protected left-turn control is the safest, with protected/permissive being less safe than protected, but safer than permissive (Fambro and Woods, 1981; Matthais and Upchurch, 1985; Curtis et al., 1988); and (2) transitions from protected-only operations to protected/permissive operations experience crash increases (Cottrell and Allen, 1982; Florida Section of Institute of Transportation Engineers, 1982; Cottrell, 1985; Warren, 1985; Agent, 1987). According to Fambro and Woods (1981), for every left-turn crash during a protected phase, 10 would have occurred without protection. Before-and-after studies where intersections were changed from protected to permissive control have shown four- to seven-fold increases in left-turn crashes (Florida Section of Institute of Transportation Engineers, 1982; Agent, 1987).

Hallmark and Mueller (2004) conducted a crash analysis to evaluate the impact of different types of left-turn phasing on older and younger drivers at high-speed intersections in Iowa. The sample included 101 intersections with at least one intersecting roadway with a speed limit of 45 mph or higher. Data from 2001 to 2003 were included. The induced exposure method was used to determine crash rate for drivers in three different age groups: 14-24 years old, 25-64 years old, and 65 years and older. Crash rate was calculated by dividing the number of drivers that were credited with a crash in a certain age group by the estimated million entering vehicles (MEV) by approach for that age group. Poisson regression was used to model the relationship between left-turn crash rates with age group, type of phasing (protected, permissive, and protected/permissive), and other site characteristics including opposing volume. Older drivers had the highest left-turn crash rates of all age groups for all types of phasing. For older drivers as well as middle-aged drivers, crash rates were highest at the intersections with protected/permissive phasing, followed by permissive phasing. For the younger drivers, crash rates were highest with permissive phasing, followed by protected/permissive phasing. Protected left-turn phasing produced the lowest crash rates for all three age groups. Drivers may have difficulties with both protected/permissive and permissive phasing since left turns can be made during the permissive phase of both types of phasing. This may be the result of difficulties judging gaps. The high crash rate for protected/permissive phasing may also be a reflection of driver misunderstanding of protected/permissive signal displays. Protected/permissive phasing resulted in the most severe crashes for all age groups (as determined by a severity index) of the three phasing options. Further investigation into these results did not provide any insight into the reasons for the increased severity. Hallmark and Mueller (2004) indicated that left-turn volumes were not included in this study (hence the decision to use induced exposure); that may be one of the reasons why protected/permissive phasing performed worse compared to permissive phasing. Based on their study findings, the authors recommend protective phasing for use at high-speed intersections (e.g., those 45 mph or higher).

In a retrospective site-based review and crash analysis that included a detailed investigation of over 400 crashes involving drivers age 65 years and older at 62 sites in Australasia, the lack of separate traffic control for left-turn movements against oncoming traffic (i.e., no protected turn phase) contributed to 23 percent of the crashes (Oxley, et al., 2006).

Shechtman et al. (2007) found that both older and younger drivers may benefit from the implementation of protected left turn phasing at intersections, resulting in less need for hard accelerations to successfully maneuver across oncoming traffic at an intersection (particularly for older drivers), and better lateral control of their vehicles when negotiating intersections. They compared older and younger driver performance at improved and unimproved intersections in a high-fidelity, virtual reality driving simulator to test the effectiveness of FHWA's recommendations for intersection design to accommodate aging road users. In this study, 19 drivers ages 25 to 45, and 20 drivers ages 65 to 85 viewed visual representations of actual intersections on urban and residential streets in Gainesville, FL, and made braking, accelerating, and steering responses using controls integrated into an actual vehicle. A driving evaluator sat in the car and recorded behavioral errors as subjects "drove" through 8 intersections. One of the improved intersections was a signalized intersection with separate signals for each lane, with a leading protected left-turn phase indicated by a green arrow, and redundant upstream signing. The comparison unimproved intersection was signalized, but did not have separate signals for each lane, nor a protected left-turn phase or redundant signing. The simulator scenario was programmed so that gap acceptance at the unimproved intersection was tested as follows: drivers experienced oncoming traffic with one relatively short gap followed by more traffic and eventually a long gap without any oncoming traffic. Acceptance of the first gap required a rapid increase in speed for successful negotiation. There was no gap acceptance task at the improved intersection controlled by the protected left-turn phase. Both kinematic data (vehicle control responses during the turn phase including longitudinal and lateral accelerations, yaw, and speed) and behavioral data (driving errors including vehicle position, lane maintenance, speed, yielding, signaling, visual scanning, adjustment to stimuli/traffic signs, and left-turn gap acceptance) were recorded.

Of the kinematic measures recorded by Shechtman et al. (2007), maximum yaw and maximum forward acceleration were significantly reduced for the improved intersection, for both older and younger drivers, indicating better lateral control of the vehicle, and more stable forward acceleration. Maximum lateral acceleration approached significance with greater values for the unimproved intersection (indicating poorer lateral control during the turn). There were no differences in maximum speed between the improved and unimproved intersection. Older drivers had significantly higher forward acceleration than the younger drivers, indicating a "panicked" attempt to successfully drive through the gap in oncoming traffic at the unimproved intersection. There were no differences in behavioral errors between the two intersections or between the two age groups.

Williams, Ardekani, and Asante (1992) conducted a mail survey of 894 drivers in Texas to assess motorists' understanding of left-turn signal indications and accompanying auxiliary signs. Drivers older than age 65 had the highest percentage of incorrect responses (35 percent). Results of the various analyses are as follows: (1) the use of a green arrow for protected-only left turns produced better comprehension than the use of a circular green indication, even when the circular green indication was accompanied by an auxiliary sign; (2) for a five-section signal head configuration, the display of a green left-turn arrow in isolation produced better driver understanding than the simultaneous display of a circular red indication and a green left-turn arrow; (3) the LEFT TURN YIELD ON GREEN ● auxiliary sign was associated with the smallest percentage of incorrect responses, compared with the LEFT TURN ON GREEN AFTER YIELD sign, the PROTECTED LEFT ON GREEN sign, and the LEFT TURN SIGNAL sign; and (4) the percentage of incorrect responses was 50 percent lower in the presence of a circular red indication compared with a red arrow; the red arrow was often perceived to indicate that a driver may proceed with caution to make a permissive left turn.

In another study conducted by Curtis et al. (1988), it was found that the Delaware flashing red arrow was not correctly answered by any subject. The incorrect responses indicated conservative interpretations of the signal displays which would probably be associated with delay and may also be related to rear-end collisions. Drivers interpreted the Delaware signal as requiring a full stop before turning, because a red indication usually means "stop," even though the signal is meant to remind motorists to exercise caution but not necessarily to stop unless opposing through traffic is present. Hulbert, Beers, and Fowler (1979) found a significant difference in the percentage of drivers younger than age 49 versus those older than age 49 who chose the correct meaning of the red arrow display. Sixty-one percent of the drivers older than age 49 chose "no turning left" compared with 76 percent of those younger than age 49. Although other research has concluded that the left-turn arrow is more effective than the circular red in some left-turn situations in particular jurisdictions where special turn signals and exclusive turn lanes are provided (Noel, Gerbig, and Lakew, 1982), drivers of all ages will be better served if signal indications are consistent.

Hawkins, Womack, and Mounce (1993) surveyed 1,745 drivers in Texas to evaluate driver comprehension of selected traffic control devices. The sample contained 88 drivers age 65 and older. Three alternative signs describing the left-turn decision rule were evaluated: (1) R10-9, PROTECTED LEFT ON GREEN ARROW (in the Texas *MUTCD* but not the national *MUTCD*); (2) R10-9a, PROTECTED LEFT ON GREEN (in the Texas *MUTCD* but not the national *MUTCD*); and (3) R10-12, LEFT TURN YIELD ON GREEN ●. The R10-12 sign did the best job of the signs in the survey informing the driver of a permissive left-turn condition, with 74.5 percent choosing the desirable response. Of those who responded incorrectly, 13.6 percent responded that they would wait for the green arrow, and 4.3 percent made the dangerous interpretation that the left turn was protected when the circular green was illuminated. Incorrect responses were more often made by drivers age 65 and older.

The decisional processes drawing upon working memory crucial to safe performance at intersections may be illustrated through a study of alternative strategies for presentation of left-turn traffic control messages (Staplin and Fisk, 1991). This study evaluated the effect of providing advance left-turn information to drivers who must decide whether or not they have the right-of-way to proceed with a protected turn at an intersection. Younger (mean age of 37) and older (mean age of 71) drivers were tested using slide animation to simulate dynamic approaches to intersection traffic control displays, with and without advance cueing of the "decision rule" (e.g., LEFT TURN MUST YIELD ON GREEN ●) during the intersection approach. Without advance cueing, the decision rule was presented only on a sign mounted on the signal arm across the intersection as per standard practice, and thus was not legible until the driver actually reached the decision point for the turning maneuver. Cueing drivers with advance notice of the decision rule through a redundant upstream posting of sign elements significantly improved both the accuracy and latency of all drivers' decisions for a "go/no go" response upon reaching the intersection, and it was of particular benefit to the older test subjects. Presumably, the benefit of upstream "priming" is derived from a reduction in the requirements for serial processing of concurrent information sources (sign message and signal condition) at the instant a maneuver decision must be completed and an action performed.

Stelmach, Goggin, and Garcia-Colera (1987) found that aging adults were particularly impaired when preparation was not possible, showing disproportionate response slowing when compared with younger subjects. When subjects obtained full information about an upcoming response, reaction time (RT) was faster in all age groups. Stelmach et al. (1987) concluded that aging drivers may be particularly disadvantaged when they are required to initiate a movement in which there is no opportunity to prepare a response. Preparatory intervals and length of precue viewing times are determining factors in age-related differences in movement preparation and planning (Goggin, Stelmach, and Amrhein, 1989). When preparatory intervals are manipulated in a way that aging adults have longer stimulus exposure and longer intervals between stimuli, they profit from the longer inspection times by performing better and exhibiting less slowness of movement (Eisdorfer, 1975; Goggin et al., 1989). Since aging drivers benefit from longer exposure to stimuli, Winter (1985) proposed that signs should be spaced farther apart to allow drivers enough time to view information and decide what action to take. Increased viewing time will reduce response uncertainty and decrease aging drivers' RT.

Differences in maneuver decisions reported by Staplin and Fisk (1991) illustrate both the potential problems aging drivers may experience at intersections due to working memory deficits, and the possibility that such consequences of normal aging can to some extent be ameliorated through improved engineering design practices. Staplin and Fisk (1991) also showed that aging drivers had higher error rates and increased decision latencies for situations where the left turn was not protected. In particular, the most problematic displays were those with only one steady illuminated signal face (circular green) accompanied by a sign that indicated that it was not safe to proceed into the intersection with the assumption of right-of-way (LEFT TURN YIELD ON GREEN ●). A correct response to this combination depends on the inhibition of previously learned "automatic" responses; a signal element with one behavior (go) was incorporated into a traffic control display requiring another, conflicting behavior.

Several evaluations of a novel left-turn display for the permissive phase—the flashing yellow arrow (FYA)— have been conducted. Brehmer, et al. (2003) conducted a laboratory study using 2,465 drivers in 4 age groups: < age 24 (27%); 25-44 (44%); 45-65 (21%); and 66+ (7%). Photographs of existing signalized intersections were presented to drivers at driver license centers using laptop computers. Combinations of protected left-turn indications, permissive left-turn indications, through-movement indications, and protected/permissive left-turn signal display arrangements were shown against these background intersection scenes. Each driver was randomly presented with 30 of the 200 unique scenarios developed for the study. Subjects were instructed to use the computer keyboard to select which of four options was appropriate if the person wanted to turn left and saw the traffic signals presented. The four options were: (1) GO, (2) YIELD and wait for gap, (3) STOP then wait for gap, and (4) STOP. Measures of effectiveness included percent of correct responses to the study scenarios and response time. Response time data were collected as a surrogate measure of driver understanding (longer response times would connote lower levels of driver understanding). Aging drivers provided the fewest correct responses across all display combinations of all age groups: Age 66+ = 67.3% correct, age 45-65 = 71.1% correct; age 24-44 = 73.1% correct, age 24=72.2% correct. Drivers age 66+ had longer response times (2 to 4 seconds of additional time) compared to drivers less than age 24. For the permissive indications across all age groups, the circular green ball had the fewest correct responses at 50.4%, followed by the flashing red arrow (55.6% correct) and the flashing yellow arrow

(56.6% correct). The flashing red ball had the highest correct response rate (63.8%), followed by the flashing yellow ball (61.7%). Response times were faster for the flashing permissive indications than for the solid indications, and circular indications were better understood than arrow indications. Drivers age 66+ had low correct response rates (29%) for the permissive circular green ball when shown with the red through indication. Seventy percent of drivers age 66+ responded correctly to the flashing circular red permissive left-turn indication. Although the correct response rate (across age groups) was higher for the flashing yellow arrow than for the steady green ball, there were 2 other indications that had even higher percent-correct response rates than the flashing yellow arrow: the flashing red ball and the flashing yellow ball.

More recently, Noyce, Bergh, and Chapman (2007) conducted a field study of crashes using 50 signalized intersections with at least 1 year of data after the implementation of flashing yellow arrow. Out of the 50 signalized intersections where the flashing yellow arrow was introduced, in 5 of the locations the phasing was permissive and the round green was replaced by flashing yellow arrow. Twenty-one of the signalized intersections had protected/permissive left-turn (PPLT) phasing, where the round green was replaced by flashing yellow arrow. In the remaining intersections, fully protected phasing was replaced by PPLT with a flashing yellow arrow. Crashes before the implementation of flashing yellow arrow was compared with crashes after the implementation of flashing yellow arrow. Safety was not improved at the intersections where fully protected phasing was replaced by PPLT phasing with flashing yellow arrow. These intersections experienced a change in phasing and hence, it is not possible to determine if flashing yellow arrow was effective. No conclusions could be made regarding the safety effect of replacing the green ball with flashing yellow arrow at the five intersections with permissive phasing. Safety was improved at the 21 intersections that operated on PPLT phasing where the green ball was replaced with the flashing yellow arrow. Although this study indicates that the flashing yellow arrow was effective in reducing crashes at PPLT locations, this result is based on a limited sample of intersections. It is also not clear if the empirical Bayes method used a reference group to account for bias due to regression to the mean and to account for changes in traffic volume. In addition, it is not clear if driver age was considered in this evaluation.

The FYA research noted above targets apparent deficits in the comprehension of the conventional green ball for permissive turning operations at intersections, which has been discussed elsewhere in this section. At the same time, concerns have been raised about confusion by aging motorists regarding the meaning of arrow signal indications elsewhere in this *Handbook*. Given the positive experience of some practitioners who are early adopters of this treatment, further FYA research is a high priority. Such investigations could well lead to a *Handbook* recommendation to adopt this practice, pending reliable evidence that shows a) comprehension rates that equal or exceed those of other viable substitutes for the steady green ball; and b) an absence of performance penalties or safety problems for “young-old” as well as “old-old” drivers upon their initial encounters with such displays, under naturalistic conditions. In particular, it is important to rule out the possibility that the FYA will be (mis)perceived as the timing out of a protected left turn phase, which could actually increase the potential for injurious angle crashes.

Next, Hummer, Montgomery, and Sinha (1991) evaluated leading and lagging signal sequences using a survey of licensed drivers in Indiana, an examination of traffic conflicts, an analysis of crash records, and a simulation model of traffic flow, to evaluate motorists' understanding and preference for leading and lagging schemes as well as determining the safety and delay associated with each scheme. Combinations of permissive and protected schemes included: (1) protected-only/leading, in which the protected signal is given to vehicles turning left from a particular street before the circular green is given to the through movement on the same street; (2) protected-only/lagging, in which the green arrow is given to left-turning vehicles after the through movements have been serviced; (3) protected/permissive, in which protected left turns are made in the first part of the phase and a circular green indication allows permissive turns later in the phase; and (4) protected/permissive, in which unprotected turns are allowed in the first part of the phase and protected left turns are accommodated later in the phase. The protected-only/leading and protected/permissive schemes are known as "leading," and the protected-only/lagging and permissive/protected are known as "lagging" schemes. Of the 402 valid responses received, 248 respondents preferred the leading, 59 preferred the lagging sequence, and 95 expressed no preference. The most frequent reasons given for preference of the leading sequence were: it is more like normal; it results in less delay; and it is safer. There are apparent tradeoffs here, however; the leading sequence was associated with a higher conflict rate with pedestrians and a higher rate of run-the-red conflicts (drivers turning left during the clearance interval for opposing traffic), while the intersections with a lagging sequence were associated with a significantly higher rate of indecision conflicts than the leading intersections due to violations in driver expectancy. Overall, it is judged that consistency in signal phasing across intersections within a jurisdiction, as well as across jurisdictions, should be a priority, and that use of a leading protected left-turn phase offers the most benefits. A discussion of countermeasures for the protection of pedestrians may be found in the material that presents the Rationale and Supporting Evidence for Design Element 15 – Pedestrian Crossings.

Upchurch (1991) compared the relative safety of 5 types of left-turn phasing using Arizona Department of Transportation crash statistics for 523 intersection approaches, where all approaches had a separate left-turn lane, 329 approaches had two opposing lanes of traffic, and 194 approaches had three opposing lanes. The five types of left-turn phasing included (1) permissive, (2) leading protected/permissive, (3) lagging protected/permissive, (4) leading protected-only, and (5) lagging protected-only. For the 495 signalized intersections in the State highway system, most samples represented a 4-year crash history (1983–1986). For the 132 signalized intersections in 6 local jurisdictions in Arizona, samples ranged from 4 months to 4 years, all between 1981 and 1989. When the crash statistics were stratified by various ranges of left-turn volume and various ranges of opposing volume (vehicles per day), the following observations and conclusions were made for sample sizes greater than five, eliminating any conclusions about lagging protected-only phasing:

- Leading protected-only phasing had the lowest left-turn crash rate in almost every case. This was true in every left-turn volume range and every opposing volume range except one (19 out of 20 cases). Lagging protected/permissive was the exception for three opposing lanes and left-turn volumes of 0–1,000.

- When there were two lanes of opposing traffic, lagging protected/permissive tended to have the worst crash rate.
- When there were three lanes of opposing traffic, leading protected/permissive tended to have the worst crash rate.
- When there were two lanes of opposing traffic, the order of safety (crash rate from best to worst) was leading protected-only, permissive, leading protected/permissive, and lagging protected/permissive. However, there was a small difference in the crash rate among the last three types of phasing.
- When there were three lanes of opposing traffic, the order of safety (crash rate from best to worst) was leading protected-only, lagging protected/permissive, permissive, and leading protected/permissive.

Upchurch (1991) compared the crash experience of 194 intersections that had been converted from one type of phasing to another in a simple before-and-after design. For each conversion, four years of before-crash data and four years of after-crash data were used, where available. At approaches having two opposing lanes of traffic, the statistics for conversions from permissive to leading protected/permissive and vice versa reinforced each other, suggesting that leading protected/permissive is safer than permissive. At approaches having three opposing lanes of traffic, the statistics for conversions from leading protected-only to leading protected/permissive and vice versa reinforced each other, suggesting that leading protected-only is safer than leading protected/permissive.

Parsonson (1992) stated that a lagging left-turn phase should be used only if the bay provides sufficient storage, as any overflow of the bay during the preceding through-movement will spill into the adjacent through lane, blocking it. A lag should also be reserved for those situations in which opposing left-turn movements (or U-turns) are safe from the left-turn trap (or are prohibited). The "left-turn trap" occurs when the left-turning driver's right-of-way is terminated, while the opposing (oncoming) approach continues with a green arrow and an adjacent through movement. Thus, left-turning drivers facing a yellow indication are trapped; they believe that the opposing traffic will also have a yellow signal, allowing them to turn on the yellow or immediately after. Since the opposing traffic is not stopping, the turning driver is faced with a potentially hazardous situation. Locations where the left-turn trap is not a hazard include T-intersections, and those where the left turn (or U-turn) opposing the green arrow is prohibited or is allowed only on a green arrow (protected-only phasing). In addition, driver expectancy weighs heavily in favor of leading left turns, and driver confusion over lagging left turns results in losses in start-up time.

# 9 Right-Turn Traffic Control for Signalized Intersections

The right-turn-on-red (RTOR) maneuver provides increased capacity and operational efficiency at a low cost (Institute of Transportation Engineers [TEH], 1999). However, traffic control device violations and limited sight distances need to be addressed in order to reduce the potential for safety problems. TEH concluded that a significant proportion of drivers do not make a complete stop before executing an RTOR, and a significant portion of drivers do not yield to pedestrians. In a review of the literature on RTOR laws and motor vehicle crashes, Zador (1984) reported findings that linked RTOR to a 23 percent increase in all right-turning crashes, a 60 percent increase in pedestrian crashes, and a 100 percent increase in bicyclist crashes. Analysis of police crash reports in four States indicated that drivers who are stopped at a red light are looking left for a gap in traffic and do not see pedestrians and bicyclists coming from their right (Preusser, Leaf, DeBartolo, and Levy, 1982). Eldritch (1989) noted that, adding to the adverse effects RTOR has on pedestrian crashes, many motorists persist in making right turns on red even when there is a sign that prohibits the maneuver.

Data describing the safety impact of RTOR were provided by Compton and Milton (1994) in a report to Congress by the National Highway Traffic Safety Administration. Using the Fatality Analysis Reporting System (FARS) data and data from four State files for 1989–1992, it was concluded that RTOR crashes represented a small proportion of the total number of traffic crashes in the four States (0.05 percent) and of all fatal (0.03 percent), injury (0.06 percent), and signalized-intersection crashes (0.40 percent). FARS data showed that approximately 84 fatal crashes per year occurred involving a right-turning vehicle at an intersection where RTOR is permitted; however, because the status of the traffic signal indication is not available in this database, the actual number of fatal crashes that occurred when the signal was red is not known. Slightly less than one-

**Table 21.** Cross-References of Related Entries for Right-Turn Traffic Control for Signalized Intersections.

| Applications in Standard Reference Manuals | | | |
|---|---|---|---|
| *MUTCD* (2009) | AASHTO *Green Book* (2011) | NCHRP 279 Intersection Channelization Design Guide (1985) | Traffic Engineering Handbook (2009) |
| Sect. 1A.13, *Intersection, Right-of-Way [Assignment], Sign Legend, & Traffic Control Signal (Traffic Signal)*<br>Table 2B-1<br>Sects. 2B.18 through 2B.22, 2B.46, 2B. 52 through 2B. 54<br>Sects. 3B.08 & 3B.21<br>Figs. 3B-13b and d, 3B-24, 3B-27<br>Sects. 4D.04 through 4D.17, 4D.22 through 4D.31 | Pg. 3-176, Para. 4<br>Pg. 7-43, Paras. 3-5<br>Pgs. 9-15 through 9-19, sect. on *Channelized Four-Leg Intersections*<br>Pg. 9-51, Para. 2 | Pg. 3, 2nd col, Para. 2<br>Pg. 37, Para. 2 & top right fig.<br>Pgs. 61-65, Sect. on *Exclusive Right-Turn Lanes*<br>Pg. 100-101, Intersct. No. 7<br>Pgs. 106-113, Intersct. Nos. 10-13<br>Pgs. 124-125, Intersct. No. 19<br>Pgs. 132-135, Intersct. Nos. 22-23<br>Pgs. 148-149, Intersct. No. 35 | Pgs. 245-246<br>Pgs. 462-465, Sect. on *Turn Lanes*<br>Pg. 413-415, Sect. on *Left Turns*<br>Pgs. 632-634, Sect. on *Turn Restrictions* |

half of these crashes involved a pedestrian (44 percent), 10 percent involved a bicyclist, and 33 percent involved one vehicle striking another. Although no data on the age of the drivers involved in RTOR crashes were provided, there are reasons for concern that increasing problems with this maneuver may be observed with the dramatic growth in the number of aging drivers in the United States.

The difficulties that aging drivers are likely to experience making right turns at intersections are a function of their diminishing gap-judgment abilities, reduced neck/trunk flexibility, attention-sharing deficits, slower acceleration profile, and their general reduction in understanding traffic control devices compared with younger drivers. Right-turning drivers face possible conflicts with pedestrians, and restrictions in the visual attention of aging drivers may allow pedestrian and vehicular traffic to go unnoticed. The fact that pedestrians may be crossing the side street, where they enter the path of the right-turning vehicle, places a burden upon the driver to search the right-turning path ahead. The result is the need to share attention between oncoming vehicles approaching from the left and pedestrians in the path to the right. Limitations in the range of visual attention, frequently referred to as "useful field of vision," further contribute to the difficulty of aging drivers in detecting the presence of pedestrians or other vehicles near the driver's path. Aging drivers, who may have greater difficulty maintaining rapid eye movements and associated head movements, are less likely to make correct judgments on the presence of pedestrians in a crosswalk or on their walking speed (Habib, 1980).

Researchers have identified that the right-turn maneuver is more problematic for aging drivers compared with young or middle-aged drivers, presumably as a result of age-related diminished visual, cognitive, and physical capabilities. Knoblauch, et al. (1995) conducted an analysis of right-angle, left-turning, right-turning, side-swipe, and rear-end crashes at intersections in Minnesota and Illinois for the time period of 1985–1987, comparing crash proportions and characteristics of "middle-aged" drivers ages 30–50, "young-elderly" drivers ages 65–74, and "old-elderly" drivers age 75 and older. Turning right accounted for 35.8, 39.3, and 42.9 percent, respectively, of the middle-aged, young-elderly, and old-elderly drivers' crashes at urban locations. It appears that, for right-turning crashes, the middle-aged driver is most likely crossing the intersection on a green signal and the older drivers are turning right on a red signal in front of the oncoming middle-aged driver. Similar patterns emerged from examination of the rural signalized-intersection pre-crash maneuvers, with middle-aged drivers most often traveling straight, and older drivers most often turning left or right. Looking at the contributing factors in angle and turning collisions for both rural and urban signalized locations, the middle-aged group was much more likely to be characterized by the police officer as having exhibited "no improper driving." This occurred in 65 percent of the crashes involving this age group, compared with 30.7 percent of the young-elderly, and 13.4 percent of the old-elderly. The two elderly groups were more likely to be cited for failing to yield (42.0 percent of the old-elderly, 31.9 percent of the young-elderly, and 10.9 percent of the middle-aged); disregarding the traffic control device (30.7 percent of the old-elderly, 22.0 percent of the young-elderly, and 10.3 percent of the middle-aged); and driver inattention (8.2 percent of the old-elderly, 8.9 percent of the young-elderly, and 6.4 percent of the middle-aged).

Knowledge testing has indicated that, compared with younger drivers, older drivers are less familiar with the meaning of traffic control devices and relatively new traffic laws (McKnight, Simone, and Weidman, 1982). “Newness” of traffic laws, in this regard, relates not to the period of time that has elapsed since the device or law was implemented, but the low frequency with which drivers come in contact with the situation. Aging drivers may not encounter right turn on red after stop (RTOR), no turn on red (NTOR), or red right-turn arrow situations on a daily basis, due to the significantly lower amount and frequency of driving in which they are engaged. The demonstrated lack of understanding for the red right-turn arrow (Hulbert, Beers, and Fowler, 1979) and increased violations associated with this display (Owolabi and Noel, 1985) would be of particular concern for aging road users, drivers and pedestrians alike.

Knoblauch et al. (1995) found that both drivers younger than the age of 65 and drivers age 65 and older failed to understand that they could turn right on a circular red after stopping in the right lane. Although the survey indicated that older drivers were more likely to stop and remain stopped (45 percent) than younger drivers (36 percent), the differences were not significant.

Staplin, et al. (1997) conducted a controlled field study to measure differences in drivers’ RTOR behavior as a function of driver age and right-turn lane channelization. In this study, 100 subjects divided across three age groups were observed as they drove their own vehicles around test routes using the local street network in Arlington, Virginia. The three age groups were young/middle-aged (ages 25–45), young-old (ages 65–74), and old-old (age 75+). The percentage of drivers who made RTOR maneuvers at the four intersections was included as a measure of mobility.

Staplin et al. (1997) found that significantly fewer drivers in the old-old driver group attempted to make an RTOR (16 percent), compared with young/middle-aged drivers (83 percent) and young-old drivers (45 percent). Similarly, young/middle-aged drivers made an RTOR nearly 80 percent of the time when they had the chance to do so, compared with nearly 36 percent for the young-old drivers and 15 percent for the old-old drivers. Drivers made significantly fewer RTORs at the skewed channelized intersection than at the other three locations. Analysis of the percentage of drivers who made an RTOR without a complete stop showed that age, right-turn lane geometry, gender, and the age-by-geometry interaction were significant. Young/middle-aged drivers made an RTOR without a complete stop nearly 35 percent of the time, compared with nearly 25 percent for the young-old and 3 percent for the old-old drivers. Channelized intersections, with or without exclusive acceleration lanes, encouraged making an RTOR without a complete stop. The unchannelized and the skewed locations showed the lowest percentage of RTORs without a complete stop, and were not significantly different from each other. The three age groups showed significantly different performance. Old-old drivers almost always stopped before making an RTOR regardless of the right-turn lane geometry. In only 1 of 26 turns did an aging driver not stop before making an RTOR; this occurred at the channelized right-turn lane with an acceleration lane. At the unchannelized intersection (which was controlled by a STOP sign), 22 percent of the young/middle-aged drivers, 5 percent of the young-old drivers, and none of the old-old drivers performed an RTOR without a stop. Where an acceleration lane was available, 65 percent of the young/middle-aged drivers continued through without a complete stop, compared with 55 percent of the young-old drivers and 11 percent of the old-old drivers. The increased mobility exhibited by the younger drivers at the channelized right-turn lane locations (controlled by YIELD signs) was not exhibited by old-old drivers, who stopped in 19 of the 20 turns executed at the channelized locations. In summary, with increases in driver age, the likelihood of RTOR decreases to a very low level for the present cohort of old-old drivers, but when these individuals do engage in this behavior, they are virtually certain to come to a complete stop before initiating the maneuver. Therefore, the emphasis is to ensure adequate sight distance for the aging turning driver, to provide sign and signal indications that are most easily understood by this group, and to prompt these motorists to devote adequate attention to pedestrians who may be in conflict with their turning maneuver.


**Figure 79.** Novel Sign Tested as a Countermeasure to Reduce RTOR Violations and Pedestrian Conflicts (Zegeer and Cynecki, 1986)

Zegeer and Cynecki (1986) found that offsetting the stop line—moving the stop line of adjacent stopped vehicles back from the intersection by 6 to 10 ft—was effective in providing better sight distance to the left for RTOR motorists. It also reduced the RTOR conflicts with other traffic and resulted in more RTOR vehicles making a full stop behind the stop line. The offset stop line was recommended as a countermeasure for consideration at RTOR-allowed sites that have two or more lanes on an approach and heavy truck or bus traffic, or unusual geometrics.

Zegeer and Cynecki (1986) also found that a novel sign (circular red symbol with NO TURN ON RED, shown in Figure 79) was more effective than the standard black-and-white NO TURN ON RED (R10-11a) sign, especially when implemented near the signal. This countermeasure resulted in an overall reduction in RTOR violations and pedestrian conflicts. They offered that the circular red symbol on the sign helps draw drivers' attention to it, particularly as intersections are associated with a preponderance of signs and information, and recommended that it should be added to the *MUTCD* as an alternate or approved as a replacement to the current R10-11a design. Increasing the size of the standard NO TURN ON RED sign from its present size of 24 x 30 in to 30 x 36 in reduced the proportion of violations at most of the test sites. Finally, Zegeer and Cynecki (1986) found that an electronic NO TURN ON RED blank-out sign was found to be slightly better than the standard *MUTCD* sign in terms of reducing violations, and it was effective in increasing RTOR maneuvers when RTOR was appropriate, thereby reducing vehicle delay. Although the sign is more expensive than standard signs and pavement markings, the authors concluded it may be justified in situations where pedestrian protection is critical during certain periods (i.e., school zones) or during a portion of the signal cycle when a separate, opposing left-turn phase may conflict with an unsuspecting RTOR motorist.

# 10 Street Name Signs

The *MUTCD* (2009) specifies that the lettering on street name signs should be at least 6 in for upper-case letters and 4.5 in for lower-case letters, and that larger letters should be used for street name signs that are mounted overhead. It provides an option for using 4-in upper-case lettering and 3-in lower-case lettering on street name signs that are posted on local roads with speed limits 25 mph or less. Burnham (1992) noted that the selection of letter size for any sign must evaluate the needs of the user, which are continuously changing as a function of changes in automotive technology, the roadway system, and the population itself. For example, Phoenix, Arizona, a city with a large aging driver population, has been using "jumbo" street name signs at signalized intersections since 1973. These signs are 16 in high and use 8 in capital letters (*Rural and Urban Roads*, 1973). It is estimated that by the year 2020, 17 percent or more of the population will be older than 65 years of age, and by the year 2030, 1 in 5 Americans will be older than age 65 (U.S. Bureau of the Census, 1996). The ability to read street signs is dependent on visual acuity as well as divided attention capabilities, both of which decline significantly with advancing age.

Aging drivers participating in focus groups and completing questionnaires for traffic safety researchers over the past two decades have consistently stated that larger street signs with bigger lettering and standardization of sign placement overhead would make driving an easier task (Yee, 1985; Gutman and Milstein, 1988; Cooper, 1990; Staplin, Lococo, and Sim, 1990; Benekohal, et al., 1992; Knoblauch, et al., 1995). Problems with placement included signs that were either obstructed by trees, telephone poles, billboards, or large trucks, or placed too close to or across the intersection rather than on the near side. Aging drivers stated that they needed more advance notice regarding upcoming cross streets and larger street-name signs placed overhead, to give them more time to make decisions about where to turn. Also noted were difficulties reading traffic signs with too much information in too small an area, and/or with too small a typeface, which results in the need to slow down or stop to read and respond to the sign's message. May (1992) noted that providing sufficient time to allow motorists to make appropriate turning movements when approaching cross streets can improve safety and reduce congestion, and that consistent street signing across political jurisdictions can be helpful in this regard, as well as presenting an orderly, predictable picture of the region to tourists, business people, and residents.

A decade later, Eck and Winn (2002) conducted a survey of 172 individuals between the age of 50 and 91 (mean age of 73.3). The overall objective was to assess the understanding

**Table 22.** Cross-References Of Related Entries For Street-Name Signs.

| Applications in Standard Reference Manuals | | |
|---|---|---|
| *MUTCD* (2009) | AASHTO *Green Book* (2011) | NCHRP 500–Volume 9 (2004) |
| Sect. 1A.14, Abbreviations<br>Sects. 2A.07, 2A.08, 2A.11, 2A.14, 2A.17, 2D.01 through 2D.06, 2D.43 & 2E.29 | Pg. 2-39, Para. 3<br>Pg. 3-176, Paras. 1-2 | Pgs. V-8-V-16, Sects. on Strategy 3.1 B1 through Strategy 3.1 B3 |

by West Virginia's aging drivers of traffic control devices and roadway design features associated with unsignalized at-grade intersections on high speed divided roadways. A survey was administered in 15 senior centers in counties with high-speed roads within their boundaries. One of the survey items asked participants to pick from a list the factor that presented the greatest difficulty for them in trying to find a side road when traveling on a divided highway. Just over 20 percent indicated that finding a side road was not a problem for them. The most frequent factor was "fast moving traffic on my rear bumper," by 24 percent of the respondents, followed by "road sign name that is too small to read" by just over 20 percent of the participants. This finding underscores the need for larger lettering on street name signs, the use of overhead street name signs, and advance placement of street name signs.

Taoka (1991) discussed "spare glance" duration in terms of how drivers allocate their visual search time among different tasks/stimuli. The tasks ranged from side/rearview mirror glances during turning to reading roadway name signs. Although specific results were not differentiated by age, Taoka asserted that 85th percentile glance times at signs (about 2.4 s) were likely too long, as 2.0 s is the maximum that a driver should divert from the basic driving task. Since aging drivers are more apt to be those drivers taking longest to read signs, these results imply that they will commonly have problems dividing attention between searching for/reading signs and the basic driving task. Malfetti and Winter (1987) observed that aging drivers exhibited excessive vehicle-braking behavior whenever a signal or road sign was sighted. This was categorized as an unsafe behavior, because it is confusing and disruptive to following traffic when the lead vehicle brakes for no apparent reason. These researchers obtained many descriptions of aging drivers who stopped suddenly at unexpected times and in unexpected places, frequently either within the intersection or 40 ft before the intersection to read street signs.

The visibility of retroreflective signs must be considered with regard to their dual requirements of detection and legibility. The sign components affecting detection are sign size, color, shape, brightness, and message or content design. External factors affecting sign detection include its placement (e.g., left, right, or overhead), the visual complexity of the area, and the contrast of the sign with its background. The component parts of retroreflective signs that determine legibility fall into two major classes of variables: character and message. Character variables include the variables related to brightness—i.e., contrast, luminance, color, and contrast orientation—as well as font, letter height, letter width, case, and stroke width. Message variables address the visibility issues of spacing and include interletter, interword, interline, and copy-to-border distances.

Most studies of sign legibility report legibility distance and the letter height of the stimulus; dividing the former measure by the latter defines the "legibility index" (LI), which can serve as a common denominator upon which to compare different studies. Forbes and Holmes (1939) used the LI to describe the relative legibility of different letter styles. Under daytime conditions, series B, C, and D were reported to have indexes of (33 ft/in, 42.5 ft/in, and 50 ft/in), respectively. Forbes, Moskowitz, and Morgan (1950) found the wider, Series E letters to have an index of 55 ft/in. Over time the value of 50 ft/in of letter height became the nominal, though arbitrary and disputed, standard. The LI is important to the size requirement determination for a sign in a specific application. Based on the physical attributes of the aging driver population, the then-standard of

50 ft of legibility for every 1 in of letter height (corresponding to a visual acuity of 20/25) exceeded the visual ability of approximately 40 percent of the drivers between ages 65 and 74. The *MUTCD* (2009) section 2A.13, which provides guidance for determining sign letter heights, indicates that sign letter heights should be determined based on 1 inch of letter height per 30 ft of legibility distance; this shift is certainly desirable considering the human factors issues addressed in this chapter.

Mace (1988), in his work on minimum required visibility distance (MRVD) for highway signs, noted the following relationships:

**Required letter size = MRVD / LI** ***or*** **Required LI = MRVD / letter size**

Either the letter size or the LI may be manipulated to satisfy the MRVD requirement, which specifies the minimum distance at which a sign should be read for proper driver reaction.

Olson and Bernstein (1979) suggested that aging drivers should not be expected to achieve a LI of 50 ft/in under most nighttime circumstances. The data provided by this report gives some expectation that 40 ft/in is a reasonable goal under most conditions. A 40 ft/in standard can generally be effective for aging drivers, given contrast ratios greater than 5:1 (slightly higher for guide signs) and luminance greater than 10 cd/m$^2$ for partially reflectorized signs. With regard to the effect of driver age on legibility, Olson, Sivak, and Egan (1983) concluded that older drivers require more contrast between the message and the sign's background than younger drivers to achieve the same level of comprehension. They also noted that legibility losses with age are greater at low levels of background luminance. A reduction in legibility distance of 10 to 20 percent should be assumed when signs are not fully reflectorized. (It should be noted that the *MUTCD* (2009) includes text in section 2A.07 that states that regulatory, warning, and guide signs shall be retroreflective or illuminated to show the same shape and color by both day and night, unless specifically stated otherwise in the *MUTCD* text discussion of a particular sign or group of signs. Section 2D.03 further states that all messages, borders, and legends on guide signs shall be retroreflective, and all backgrounds shall be retroreflective or illuminated.) Also, higher surround luminance improved the legibility of signs more for aging drivers and reduced the negative effects of excessive contrast. In general, the LI for aging drivers is 70 to 77 percent of the LI for younger drivers. The average LI for aging drivers is clearly below the nominal value of 50 ft/in of letter height. The means for aging drivers are generally between 40 ft/in and 50 ft/in; however, the 85th percentile values reported are between 30 ft/in and 40 ft/in (Sivak, Olson, and Pastalan, 1981; Kuemmel, 1992; Mace, Garvey, and Heckard, 1994). Mace (1988) concluded that a most conservative standard would provide drivers with 2 minutes of arc, which corresponds to 20/40 vision and a 30 ft/in LI.

In a laboratory simulation study, Staplin et al. (1990) found that older drivers (ages 65–80) demonstrated a need for larger letter sizes to discern a message on a guide sign, compared with a group of younger drivers (ages 19–49). To read a one-word sign, older drivers required a mean letter size corresponding to 2.5 minutes of visual angle (or a Snellen acuity of 20/50), compared with the mean size required by younger drivers of 1.8 minutes of visual angle (or Snellen acuity of 20/35). Character size requirements increased for both age groups when the message contained four words, to 3.78 minutes of visual angle (acuity equivalent of 20/75) for the older drivers, and to 2.7 minutes of visual angle (acuity equivalent of 20/54) for the younger drivers. The main effect of age for the word and message legibility measure was highly significant. Staplin et al. (1990) concluded that for standard highway signing, an increase in character size in the range of 30 percent appears necessary to accommodate age-related acuity differences across the driving population.

Tranchida, Arthur, and Stackhouse (1996) conducted a field study using aging drivers who drove the research laboratory's vehicle at nighttime, to determine the legibility distances of street-name signs as a function of sheeting type. The subjects included nine males ages 68 to 74, and nine females ages 62 to 83. The four sheeting types were: Type IX, Type VII, Type III, and Type I (American Society for Testing and Materials, 2001). Intersections of three levels of complexity were used: high complexity/ high traffic activity (e.g., large intersection in downtown business area); intermediate complexity/ intermediate traffic activity (e.g., small intersection area in suburban small business/ apartment area); and low complexity/low traffic activity (e.g., residential area of single-family homes). All intersections were lighted. Street-name signs with invented names (Strike, Strong, Stress, Straw, Story, and Storm) were created using Series C letters, with a 6-in uppercase "S", followed by 4.5-in lowercase letters. There were no borders on the street name signs. The signs were placed on the far side of the intersection, either on the right or the left side, and the drivers' task was to read aloud the street name as soon as it was legible to them, as they approached at a speed of 20 mph. The vehicle was a two-door sedan with automatic transmission, power steering, and power brakes.

The mean legibility distances across the three intersections and two street sides were as follows for the four sheeting types: Type VII=170 ft; Type IX=172 ft; Type III=142 ft; and Type I=130 ft. Legibility distances were always longer for signs placed on the right side of the street than for those placed on the left. The mean legibility distances for the signs mounted on the right side of the road and corresponding luminances of the sheeting at the legibility distances are as follows: Type VII=205 ft) and 4.392 cd/m$^2$; Type IX=201 ft and 7.369 cd/m$^2$; Type III=177 ft and 1.1314 cd/m$^2$; and Type I=174 ft and 0.9671 cd/m$^2$. Sheeting Types VII and IX performed similarly, and produced significantly longer legibility distances than both Type III and Type I sheeting. However, Types VII and Type IX provided significantly longer legibility distances only for the intersections with high complexity viewing conditions. There was no significant benefit in legibility distance for Type VII and Type IX sheeting at the two streets making up the low complexity intersection and on one street that was less traveled and less visually complex than the other in the intermediate complexity intersection.

These results suggest that at visually complex intersections with exaggerated demands for divided attention, the use of retroreflective sheeting that provides increased legibility distance would be of clear benefit to aging drivers. Sheeting that provides for high retroreflectance overall, and particularly at wide observation angles typical when viewing street-name signs, would best meet this need. The anticipated benefit is that fewer glances will need to be directed toward the sign to determine the legend, and more effort can be devoted to vehicle control and visual search for traffic and pedestrian conflicts.

The use of mixed-case letters on overhead street name signs was studied by Garvey, Gates, and Pietrucha (1997). Based on this research, it was recommended that for any approach with a 35 mph or lower speed limit, an overhead street name sign should have 8-in uppercase and 6-in lowercase letters. For approaches with a speed limit above 35 mph, an overhead street name sign should contain 10-in uppercase and 8-in lowercase letters. This recommendation is based on the need for street name signs to be legible for 5.5-s before the intersection, which allows for a 1.5-s alerted perception-reaction time to read a sign and initiate a response (Johannson and Rumar, 1971), plus a 4.0-s interval to complete a combined speed reduction and tracking task (McGee, et al., 1979). Street name signs should therefore be readable at 300 ft at speeds of 35 mph, and at 450 ft at 55 mph.

In an earlier study, Garvey, Meeker, and Pietrucha (1996) found a 12 to 15 percent increase in recognition distance for mixed-case text over all upper case legends under both daytime and nighttime conditions. However, this result was for recognition of words that drivers already knew would appear on the signs. Because the reading of street name signs is often a recognition task, rather than a pure legibility task, the reading distance of street name signs will be higher than would be predicted on driver visual acuity alone. At the same time, street name legends provide useful information only when they can be read and understood by motorists. This fact underscores the focus on manipulations of those characteristics of sign legends that can increase reading distance. The rationale for mixed-case letters is reported above; the case for enhancements of street name letter fonts follows. Another obvious manipulation, of course, is simply the size of the letters themselves.

Garvey, Pietrucha, and Meeker (1997) investigated an experimental font in two controlled field studies, using drivers ages 65 to 83. To accurately describe this research, it is necessary to use a trademarked name; however, this does not imply an endorsement of this product by the U.S. Government. Also, until this font undergoes the procedures required for *MUTCD* approval (rule making process), a recommendation cannot be made to use a non-standard font on standard highway signs. Garvey at al. (1997) compared the recognition distances and legibility distance of words displayed in mixed-case Clearview® font with those displayed in Standard Highway Series D uppercase font, and mixed-case Standard Highway Series E(M) font. The Clearview® font was developed to have open, wider spaces within a letter, to eliminate the effects of irradiation/halation that is caused by bright, bold stroke widths that "bleed" into a character's open spaces, rendering it illegible. Since each Clearview® character has more openness than the Standard Highway font, the intercharacter spacing is smaller. Clearview® spacing results in words that take up 10.8 percent less space than Standard Highway fonts, such that a 12 percent increase in Clearview® character height results in words equal in sign space to words presented in the Standard fonts. The Clearview® font was produced in a regular version, with visual proportions similar to the Standard FHWA Series E(M) font, as well as in a condensed version, with visual proportions similar to the Standard FHWA Series D font. Two sizes of the Clearview® font were displayed: Clearview® 100 (fonts matched to Standard Highway font height) and Clearview® 112 (fonts 112 percent of Standard Highway font letter height, but equal in overall sign size to Standard Highway font). The fonts tested are described in Table 23. The Clearview® fonts will be referred to as Clear Condensed 100, Clear Condensed 112, Clear 100, and Clear 112 throughout the remainder of this section. White words were created with either encapsulated lens (ASTM Type III: $R_A$=250 cd/lux/m$^2$) material or microprismatic sheeting designed for

**Table 23.** Fonts Tested by Garvey, Pietrucha, and Meeker (1997).

| Font Name | Case | Letter Height |
|---|---|---|
| Clear Condensed 100 | mixed case | Upper Case: 5 in |
| | | Lower Case: 3.9 in loop height |
| Clear Condensed 112 | mixed case | Upper Case: 5.6 in |
| | | Lower Case: 4.4 in |
| Standard Highway Series D | Uppercase | 5 in |
| Standard Highway Series E(M) | mixed case | Upper Case: 5 in |
| | | Lower Case: 3.9 in loop height |
| Clear 100 | mixed case | Upper Case: 5 in |
| | | Lower Case: 3.9 in loop height |
| Clear 112 | mixed case | Upper Case: 5.6 in |
| | | Lower Case: 4.4 in |

short-distance brightness ($R_A$=430 cd/lux/m$^2$), and were displayed on a green sign panel measuring 4 ft$^2$. Each sign contained three place names, each containing six letters (from the same font). The study was conducted using one subject at a time, who was seated in the front passenger's seat of a vehicle driven by the experimenter. For each test run, the vehicle was started at a point 1,000 ft from the sign.

For the word recognition study, the experimenter read aloud the place name that the subject was to look for on a sign. As the experimenter drove toward the sign at approximately 5 to 10 mph, the subject's task was to tell the experimenter when he or she could determine where the place name was located on the sign: top, middle, or bottom. The distance from the sign at which the subject answered correctly was recorded as the recognition distance. Twelve aging drivers (mean age = 70.9 years) completed the word recognition study during the day, and another 12 aging drivers (mean age = 74.8 years) completed the study at nighttime.

A new set of 24 subjects was recruited for the legibility study, with half completing the study during daytime (mean age = 71.3 years) and half at nighttime (mean age = 73.9 years).

For the word legibility study, subjects were presented with only one word on a sign, and were required to read the word. Legibility distance was recorded at the point where subjects correctly read the word.

Results of the word recognition study indicated that during the daytime, there were no significant differences between either the Clear 100 or Clear 112 and the Series E(M) fonts. However, when comparing the Clear Condensed 100 and Clear Condensed 112 to the Series D font, the mixed-case fonts produced significantly longer recognition distances (14 percent greater) than the all uppercase Standard Highway font. At nighttime, the Clear 100 font did not produce recognition distances significantly different from those obtained with the Standard E(M) font, however, the Clear 112 font produced significantly greater recognition distances (16 percent greater) than the Standard E(M) font. The Clear 112 and Clear Condensed 112 fonts produced significantly longer recognition distances than the all-uppercase Series D font. Under both daytime and nighttime, there were no significant effects of material brightness, for the word recognition study. The mean daytime and nighttime recognition distances for the six fonts are displayed in Table 24.

**Table 24.** Daytime and Nighttime Recognition Distances for Fonts Studied by Garvey, Pietrucha, and Meeker (1997).

| Font Name | Daytime Recognition Distance (ft) | Nighttime Recognition Distance (ft) |
|---|---|---|
| Clear Condensed 100 | 394 | 282 |
| Clear Condensed 112 | 440 | 344 |
| Standard Highway Series D | 384 | 282 |
| Clear 100 | 433 | 338 |
| Clear 112 | 472 | 387 |
| Standard Highway Series E(M) | 449 | 331 |

The results of the word legibility study conducted during the daytime indicated that the microprismatic sheeting produced a 4 percent improvement in legibility distance, compared to the encapsulated lens sheeting. There was no significant interaction between font and material, however. Looking at the effects of font on legibility distance, there was no significant difference in the daytime legibility distances obtained with the Series E(M) font and the Clear 100 and Clear 112 fonts. There was also no significant difference in legibility distance between the Series D font and the Clear 112 and Clear Condensed 112 fonts. However, the all uppercase Series D font showed significantly longer legibility distances than the Clear Condensed 100 font.

At nighttime, there was a significant interaction effect between font and sheeting material, such that the Clear 112 font produced significantly longer legibility distances (22 percent longer) than the Series E(M) font, using the encapsulated lens sheeting. The microprismatic sheeting showed the same trend (although not significant), with the Clear 112 font producing 11 percent longer legibility distances than the Series E(M). There were no differences between the all uppercase Series D font and the same-size, mixed-case Clear fonts (i.e., Clear 112 and Clear Condensed 112). However, the Series D font produced significantly longer legibility distances than the Clear Condensed 100 font at night. The legibility distances obtained for the six fonts studied under daytime and nighttime are shown in Table 25.

**Table 25.** Daytime and Nighttime Legibility Distances for Fonts Studied by Garvey, Pietrucha, and Meeker (1997).

| Font Name | Daytime Legibility Distance (ft) | Nighttime Legibility Distance (ft) |
|---|---|---|
| Clear Condensed 100 | 187 | 148 |
| Clear Condensed 112 | 220 | 194 |
| Standard Highway Series D | 223 | 207 |
| Clear 100 | 220 | 197 |
| Clear 112 | 230 | 246 |
| Standard Highway Series E(M) | 223 ft | 197 ft |

Garvey, Pietrucha, and Meeker (1997) state that guide signs are read using both legibility and recognition criteria, depending on the familiarity of a traveler with the location words used on the signs. A driver who is looking for a particular word on a sign will be able to read it at a farther distance that a driver who has no idea of what might be on the sign. In the legibility task, the larger letters used with the all-uppercase Series D font produced greater legibility distances than the smaller mixed case Clear 100 Condensed font. But when the mixed-case font was increased to take up the same sign area as the Series D font (Clear Condensed 112), the legibility distances for the mixed-case and uppercase fonts were the same. In the recognition task, for which Garvey, Pietrucha, and Meeker (1998) state more closely represents real-world behavior, the same-size, mixed-case fonts performed significantly better than the all uppercase Series D font. And, even the mixed-case font that took up less sign space performed as well as the all-uppercase, Series D font, in terms of word recognition. The authors explain that uppercase words look like blurry rectangles when viewed from a distance. Mixed-case font, on the other hand, produces words with a recognizable overall shape, due to the ascending and descending elements in each letter. The data from this study indicate that if the size of mixed-case words on a sign is matched to the size of words presented in all uppercase font, the mixed-case font provides equal legibility distance and superior recognition distance.

Next, the *MUTCD* states that street-name signs should be placed at least on diagonally opposite corners so that they will be on the far right-hand side of the intersection for traffic on the major street. Burnham (1992) noted that signs located over the highway are more likely to be seen before those located on either side of the highway. In this regard, Zwahlen (1989) examined detection distances of objects in the peripheral field versus line-of-sight detection and found that average detection distances decrease considerably as the peripheral visual detection angle increases. Placement of street-name signs overhead places the sign in the driver's forward line of sight, eliminating the need for the driver to take his/her eyes away from the driving scene, and reduces the visual complexity of the sign's surround, but under some sky conditions (e.g., backlit by the sun at dawn and dusk) the sign may be unreadable. Thus, overhead street-name signing should be a supplement to standard roadside signing.

The use of an advance street name plaque (W16-8) with an advance warning crossroad, side road, or T-intersection sign (W2-1, W2-2, W2-3, and W2-4) provides the benefit of additional decision and maneuver time prior to reaching the intersection. Section 2C.46 of the *MUTCD* (2009) indicates the use of such supplemental street-name signs on intersection warning signs as an option (e.g., an advance street name plaque may be installed above or below an Intersection Warning Sign). The use of advance street name plaques on advance warning signs has been successful in Phoenix, AZ (*Rural and Urban Roads*, 1973); the size of the lettering on these signs is 8 in (200 mm). Midblock street-name signs provide the same benefit, and are described as an option in section 2D.36 of the *MUTCD*.

Finally, noting Mace's (1988) conclusions supporting a legibility index as conservative as 30 ft/in to accommodate aging drivers, and the practical limitations of increasing sign panel size, a justification emerges for eliminating the border on street name signs to permit the use of larger characters. The *MUTCD* (2009) section 2A.14 states that, "Unless otherwise provided, each sign illustrated in this Manual shall have a border of the same color as the legend, at or just inside the edge." In section 2D.43 (Street Name Signs), the *MUTCD* states that, "Regardless of whether green, blue, or brown is used as the background color for Street Name (D3-1 or D3-1a) signs, the legend (and border, if used) shall be white. For Street Name signs that use a white background, the legend (and border, if used) shall be black." The border on street name signs is presumed to enhance the conspicuity of the sign panel at intersections, where visual complexity and driving task demands may be relatively high. However, the aspect of conspicuity at issue here is "search conspicuity" rather than "attention conspicuity;" as demonstrated by Cole and Hughes (1984), a sign is noticed at significantly greater distance when a driver expects its presence and knows where to look for it. This is the case with street name signs at intersections. Detecting the presence of street name signs isn't the problem—reading them is. Thus, a strong argument can be made that any marginal reduction in conspicuity that may result from eliminating sign borders will be more than offset by the resultant gains in legibility produced by larger characters in the sign legend.

## 11 Stop and Yield Signs

Drivers approaching an unsignalized intersection must be able to detect the presence of the intersection and then detect, recognize, and respond to the intersection traffic control devices present at the intersection. Next, drivers must detect potential conflict vehicles, pedestrian crosswalk locations, and pedestrians at or near the intersection. Proper allocation of attention has become more difficult, as drivers are overloaded with more traffic, more signs, and more complex roadway configurations and traffic patterns, as well as more complex displays and controls in newer vehicles (Dewar, 1992). The presence of large commercial signs near intersections has been associated with a significant increase in crashes at stop-controlled intersections (Holahan, 1977).

Age-related deficits in vision and attention are key to developing recommendations for improved stop control and yield control at intersections. Researchers examining the State crash records of 53 aging drivers found that those with restrictions in their "useful field of view," a measure of selective attention and speed of visual processing, had 15 times more intersection crashes than those with normal visual attention (Owsley, et al., 1991). A follow-up study with a sample of 300 drivers demonstrated that visual attention deficits could account for up to 30 percent of the variance in intersection crash experience (Ball, et al., 1993). Additional relevant findings may be cited from a simulator study of peripheral visual field loss and driving impairment which also examined the actual driving records of the study participants (Szlyk, Severing, and Fishman, 1991). It was found that visual function factors, including acuity as well as visual field measures, could account for 26 percent of the variance in real-world crashes. Also, greater visual field loss was associated in the simulator data with greater distance traveled ("reaction distance") before responding to a peripheral stimulus (e.g., a STOP sign).

A considerable body of evidence exists documenting the difficulties of aging driver populations in negotiating stop-controlled intersections. Specifically, analyses of crash and violation types at these sites highlight the aging driver's difficulty in detecting, comprehending, and responding to signs within an appropriate timeframe for the safe completion of intersection maneuvers.

Statistics on Iowa fatal crashes show that during 1986–1990, running STOP signs was a contributing circumstance in 297 fatal crashes which killed 352 people; drivers age 65 and older accounted for 28 percent of the fatal crashes, and drivers younger than age 25 were involved in 27 percent of the fatal crashes (Iowa Department of Transportation, 1991). Stamatiadis, Taylor, and McKelvey (1991) found that at stop-controlled urban intersections, the percentage of drivers age 75 and older involved in right-angle crashes was more than double that of urban signalized intersections. Malfetti and Winter (1987), reporting on the unsafe driving performance of drivers age 55 and older, noted that aging drivers frequently failed to respond properly or respond at all to road signs and signals; descriptions of their behavior included running red lights or STOP signs and rolling through STOP signs. Some aging persons' behavior at STOP signs and signals seemed to indicate that they did not understand why they needed to wait when no other traffic was coming. Brainan (1980) used in-car observation to gain firsthand knowledge and insight into aging people's driving behavior. Drivers in the 70 and older age group showed difficulty at two of the STOP signs on the test route; their errors were in failing to make complete stops, poor vehicle positioning at STOP signs, and jerky and abrupt stops. Campbell, Wolfe, Blower, Waller, Massie, and Ridella (1990), looking at police reports of crossing crashes at unsignalized intersections, found that aging drivers often stopped and then pulled out in front of oncoming traffic, whereas younger drivers more often failed to stop at all. Further evidence of unsafe behaviors by aging drivers was provided in a study by McKnight and Urquijo (1993). Their data consisted of 1,000 police referral forms from the motor vehicle departments of California, Maryland, Massachusetts, Michigan, and Oregon; the forms included observations of incompetent behavior exhibited by aging

**Table 26.** Cross-References Of Related Entries For Stop And Yield Signs.

| Applications in Standard Reference Manuals | | | | |
|---|---|---|---|---|
| ***MUTCD*** **(2009)** | **AASHTO** *Green Book* **(2011)** | **NCHRP 500 – Volume 9 (2004)** | **NCHRP 279 Intersection Channelization Design Guide (1985)** | **Traffic Engineering Handbook (2009)** |
| *Sect. 1A.13, regulatory sign*<br>*Tables 2B-1 & 2C-4*<br>*Sects. 2B.03 through 2B.12, 3B.16 & 2C.36* | Pgs. 3-2 through 3-6, Sect. 3.2.2 *Stopping Sight Distance*<br>Pg. 9-30, Fig.9-15<br>Pgs. 9-36 through 9-50, Sects. on *Case B-Intersections with Stop Control on the Minor Road & Case C—Intersections with Yield Control on the Minor Road*<br>Pg. 9-180, Para. 2<br>Pg. 10-90, Sect. on *At-grade terminals*<br>Pg. 10-105, Para. 1 | Pgs. V-8-V-11, Sect. on *Strategy 3.1 B1: Provide Advance Warning Signs (T)* | Pg. 9, Figs. 2-5 & 2-7<br>Pg. 10, Table 2-4, 4th bullet<br>Pg. 21, Fig. 3-1 | Pgs. 357, Sects. on *Regulatory Signs*<br>Pg. 381, Sect. on *Stop and Yield Lines*<br>Pgs. 629-630, Sects. on *Yield Control and Stop Control*<br>Pgs. 110-111, Sect. on *Traffic Characteristics at Unsignalized Intersections*<br>Pg. 391-392, Sect. on *Older Drivers and Pedestrians* |

drivers who were stopped for a violation by law enforcement personnel or were involved in a crash. The specific behaviors contributing to the contact between the aging driver and the police officer included failing to yield right-of-way or come to a complete stop at a STOP sign, and failing to stop or yield to other traffic; taken together, these behaviors contributed to significant numbers of crashes (74) and violations (114).

Data from 124,000 two-vehicle crashes (54,000 crashes at signalized intersections and 70,000 crashes at unsignalized intersections) showed that drivers younger than age 25 and older than age 65 were overinvolved in crashes at both types of intersections (Stamatiadis et al. 1991). However, the overinvolvement of aging drivers in unsignalized intersection crashes was more pronounced than it was for signalized intersection crashes. Although the total number of crashes was reduced at unsignalized intersections that contained signs when compared with unsigned intersections, the crash involvement ratios of aging drivers were higher at signed intersections than at unsigned intersections. At unsignalized intersections, the highest percentage of fatalities resulted from right-angle collisions (25 percent). In terms of the frequency of injury at unsignalized intersections, rear-end crashes were the most frequent cause (35 percent), followed by right-angle crashes (18 percent), other-angle crashes (10 percent), and head-on/left-turn crashes (8 percent). The leading violation types for all aging drivers in descending order were failure to yield right-of-way, following too closely, improper lane usage, and improper turning. At unsignalized intersections, aging drivers showed the highest crash frequency on major streets with two lanes in both directions (a condition most frequently associated with high-speed, low-volume rural roads), followed by roads with four lanes, and those with five lanes in both directions. These configurations were most often associated with low-speed, high-volume urban locations, where intersection negotiation involves more complex decisions involving more conflict vehicles and more visually distracting conditions.

Cooper (1990) utilized a database of all 1986 police-attended crashes in British Columbia, in an effort to compare the crash characteristics of aging drivers with those of their younger counterparts. While 66.5 percent of crashes involving drivers ages 36–50 occurred at intersections, the percentage increased to 69.2 percent, 70.7 percent, and 76.0 percent for drivers ages 55–64, 65–74, and 75 and older, respectively. Overall, the two oldest groups identified in this analysis were significantly more crash involved at STOP/YIELD sign locations and less involved at either uncontrolled or signal-regulated locations. In follow-on questionnaires administered to a sample of drivers in each age group studied, intersection negotiation was mentioned by the aging drivers as second in difficulty to problems changing lanes. About 20 percent of the aging drivers mentioned not stopping properly at STOP signs. Vehicle maneuvering prior to the crash was a key variable for drivers over age 65, and in particular, for left turns at uncontrolled or STOP/YIELD sign-controlled intersections. Drivers ages 36–50 experienced only 10.9 percent of their crashes while turning left at this type of intersection, compared with 13.0, 15.4, and 19.5 percent of drivers ages 55–64, 65–74, and 75 and older, respectively.

Council and Zegeer (1992) conducted an analysis of intersection crashes occurring in Minnesota and Illinois for the time period of 1985–1987 to highlight crash types, situations, and causes of crashes, in an effort to increase the knowledge of how aging drivers react at intersections. For all the analyses, comparisons were made between a "young-old" group (ages 65–74), an "old-old" group (age 75 or older), and a "middle-aged" comparison group (ages 30–50). Their findings regarding driver age differences in collision types, pre-crash maneuvers, and contributing factors are described below.

With respect to collision type at stop-controlled intersections, analysis of the data showed little difference in the proportion of crashes involving left-turning vehicles at either urban or rural locations when the older groups were compared with the middle-aged group. There was, however, a significant over-involvement for both groups of older drivers in right-angle collisions, both in urban and in rural locations. At urban intersections, right-angle collisions accounted for 56.1 percent of the middle-aged driver crashes, compared with 64.7 percent of the young-old, and 68.3 percent of the old-old driver crashes. These percentages increase for all groups at rural intersections—61.3, 68.6, and 71.2 percent, respectively for middle-aged drivers, young-old drivers, and old-old drivers. Data for yield-controlled intersections showed older drivers over-contributing to left-turn collisions in urban areas and to angle collisions in both urban and rural areas.

Regarding pre-crash maneuvers at stop-controlled intersections, for both rural and urban locations, right-angle collisions were the most frequent collisions, and middle-aged drivers were more likely to be traveling straight or slowing/stopping than the two older groups. The older drivers were more likely to be turning left or starting from a stop than their younger counterparts. The pattern is similar for left-turning crashes. For rear-end collisions, the old-old drivers were more likely to be going straight (thus being the striking vehicle), and the middle-aged and young-old drivers were more likely to be stopped or slowing. For the few right-turning collisions at urban stop-controlled intersections, the middle-aged drivers were going straight and the old-old drivers were more likely to be turning left or right or starting from a stop. Rural stop-controlled locations showed the same patterns of pre-crash maneuvers among the three age groups.

Finally, breakdowns of contributing factors for the urban and rural stop-controlled intersections showed that the middle-aged drivers exhibited a higher proportion of no improper driving behavior, while the young-old and old-old drivers were more often cited for failure-to-yield, disregarding the STOP sign, and driver inattention. When starting from a stop, however, the old-old drivers had a lower probability of being cited for improper driving. When cited, the old-old group was more likely to have disregarded the STOP sign than the other two driver groups. The young-old drivers as well as the old-old drivers more frequently failed to yield than the middle-aged drivers.

For left turns, the middle-aged drivers again were more frequently found to have exhibited "no improper driving." The two older driver groups were most frequently cited with failure-to-yield. There was no difference in the number of drivers in each age group who disregarded the STOP sign. For going-straight situations, the middle-aged driver was found to have exhibited no improper driving behavior twice as often as the young-old driver and almost three times as often as the old-old driver. Failing to yield, disregarding the STOP sign, and inattention were most often cited as the contributing factor for the two older groups.

Signing countermeasures to improve safe operation by aging drivers at stop- and yield-controlled intersections follow.

Greene, et al. (1996) noted that the *MUTCD* provides for the possibility of enlarging STOP signs where greater emphasis or visibility is required. They proposed an enlargement from 30 x 30 in to 36 x 36 in at well-traveled intersections or at intersections of small country lanes with State highways. This would also be appropriate at intersections where there is a high incidence of STOP-sign running. Further, Swanson, Dewar, and Kline (1994) reported that aging drivers participating in focus group discussions in Calgary, Alberta, Canada; Boise, Idaho; and San Antonio, Texas indicated a need for bigger and brighter STOP signs.

Mace and Pollack (1983) noted that conspicuity is not an observable characteristic of a sign but a construct which relates measures of perceptual performance with measures of background, motivation, and driver uncertainty. In this regard, conspicuity may be aided by multiple treatments or advance signing as well as changes in size, contrast, and placement. They noted that STOP signs following a STOP AHEAD (W3-1a) sign are more conspicuous not only to aging drivers but to everyone, because expectancy has been increased.

The need for appropriate levels of brightness to ensure conspicuity and timely detection by drivers of highway signs, including STOP and YIELD signs, was addressed in FHWA-sponsored research to establish minimum retroreflectivity requirements for these devices (minimum maintained levels, as opposed to new or in-service levels). Mace developed a model to derive the retroreflectivity levels necessary for adequate visibility distance, taking into account driver age and visual performance level, as well as the driver's response requirements (action versus no action) to the information presented on a given sign when encountered in a given situation (city, highway) with an assumed operating speed (ranging from 10 mph to 65 mph), for signs of varying size and placement (shoulder, overhead). This work is reported by Ziskind, et al. (1991), who conducted laboratory and controlled field studies using 200 younger and older drivers (ages 16 to 70+) to determine the minimum visibility requirements for traffic control devices. Taking speed and sign application into account, the recommended (minimum maintained, below which the sign should be replaced) retroreflectivity for STOP signs resulting from this research ranged between 10 cd/lux/ m² up to 24 cd/lux/ m² for the sign background (red) area, with significantly higher values for the sign legend. For the YIELD sign, the recommended minimum maintained levels ranged between 24 and 39 cd/lux/ m². These units, in cd/lux/m², or coefficient of retroreflection ($R_A$) express the efficiency with which the material is able to return incident light at a given geometry between the sign, the vehicle, and the driver. A retroreflectometer is used to obtain these data in the field; reflectivity of a material is measured at specific angles. The observation angle is the angle between the headlamps, the sign, and the driver's eye. The $R_A$ measurements provided by FHWA are all measured at a 0.2 degree observation angle, which corresponds roughly to a viewing distance of 700 ft, for a right shoulder-mounted sign on a straight road viewed from a passenger sedan. This is important, because in general, as a vehicle approaches a sign, the observation angle becomes larger, reaching 1.0 degrees at 300 ft, which is roughly legibility distance. Knowing the $R_A$ of a material at 0.2 degrees does not automatically predict its reflectivity at a closer distance (larger observational angle). Because both the STOP and YIELD signs are so extensively overlearned by drivers, their comprehension is believed to be associated with the icon, i.e., their unique shape and coloration. Thus, the brightness of the sign's background area is most critical, because these devices will typically be recognized and understood as soon as they are detected (the conspicuity distance), rather than closer in (legibility distance).

Mercier, et al. (1995) conducted a laboratory study using younger and older drivers to measure the minimum luminance thresholds for traffic sign legibility, to accommodate varying percentages of the driving population. The purpose of the study was to evaluate the proposed minimum retroreflectivity values derived using CARTS (Computer Analysis of the Retroreflectance of Traffic Signs) that uses a mathematical model to study the relationships between driver variables, vehicle variables, sign variables, and roadway variables (Paniati and Mace, 1993). This model uses MRVD (Minimum Required Visibility Distance), which is the shortest distance at which a sign must be visible to enable a driver to respond safely and appropriately, and includes the distance required for a driver to detect the sign, recognize the message, decide on a proper action, and make the appropriate maneuver before the sign moves out of the driver's view. Paniati and Mace's minimum in-service values (below which sign replacement is indicated) were reported to accommodate an unknown level between 75 to 85 percent of all drivers (see Table 27).

The subjects in the Mercier et al. (1995) study included 10 drivers ages 16 to 34; 10 drivers ages 35 to 44; 10 drivers ages 45 to 54; 10 drivers ages 55 to 64; 13 drivers ages 65 to 74; and 10 drivers age 75 or older. All subjects had a visual acuity of at least 20/40. Subjects viewed 25 scaled signs at two distances to simulate minimum required visibility distances (MRVD) traveling at 30 mph and 55 mph. Among the signs tested were white-on-red regulatory signs. Illumination levels were manipulated using 20 neutral density filters ranging from 0.02 to 3.0. Type I engineering grade sheeting was used for all signs.

Retroreflectance values were calculated based on the luminance levels needed to accommodate 67, 85, and 95 percent of the population of U.S. drivers. Mercier et al.

**Table 27.** Minimum (Maintained) Retroreflectivity Guidelines for White on Red Signs Specified by Paniati and Mace (1993) to Accommodate 75 to 85 Percent of all Drivers.

| Sign Size (in) | Speed (mph) | Minimum Retroreflectivity (cd/lux/m$^2$) |
|---|---|---|
| 30 | ≥45 | 70 (white)<br>14 (red) |
| 30 | ≤40 | 40 (white)<br>8 (red) |
| 36 | ≥45 | 60 (white)<br>12 (red) |
| 36 | ≤40 | 35 (white)<br>7 (red) |
| 48 | ≥45 | 50 (white)<br>10 (red) |
| 48 | ≤40 | 30 (white)<br>6 (red) |

(1995) concluded that the values recommended by Paniati and Mace (1993), reproduced in Table 27 for the white on red signs, are sufficient to accommodate a high percentage of drivers, with the exception of a few signs, which includes the YIELD sign. The 95th percentile driver could not be accommodated by the minimum retroreflectivity suggested for the YIELD sign measuring 30 in, for MRVD at both 30 and 55 mph. The authors point out that increasing brightness for this sign does not increase legibility for aging drivers; instead, a redesign of the sign or an enlargement would be needed to enable aging drivers to resolve the level of detail required for recognition.

Next, there has been increasing interest in the use of durable fluorescent sheeting for highway signs, because of its increased conspicuity over standard highway sign sheeting, under daytime conditions. Highway signs with fluorescent sheeting have been found to be more conspicuous and can be detected at a further distance than signs with standard sheeting of the same color. In addition, the color of fluorescent signs is more frequently recognized correctly at farther distances than standard sheeting of the same color (Jenssen, et al., 1996; Burns and Pavelka, 1995). Of particular interest, however, are findings reported by Burns and Pavelka (1995) for a field study conducted at dusk (15 min after sunset), without the use of vehicle headlights. In this study, 14 drivers ages 19 to 57 (median age = 40 years) viewed signs with fluorescent red sheeting and signs with standard red sheeting at a distance of 98 ft. The signs with fluorescent red sheeting were detected by 90 percent of the participants; only 23 percent were able to detect the standard red signs. In terms of correct color recognition, 49 percent were able to correctly recognize the color of the fluorescent red signs at dusk from a distance of 90 ft, compared to 12 percent who correctly identified the standard red signs as red. Luminance measurements of the targets and the background were taken for these north-facing signs at dusk, so that luminance contrast ratios could be calculated. The luminance contrast ratio (Lt-Lb/Lb, or the luminance of the target minus the luminance of the background, divided by the luminance of the background) for the fluorescent red signs was 0.7, and the luminance contrast ratio for the standard red signs was 0.3. The results of this study suggest that the use of fluorescent red sheeting on STOP signs would serve to increase their conspicuity both under daytime and low luminance conditions, and would be of particular benefit to aging drivers, who suffer from decreases in contrast sensitivity and have greater difficulty quickly isolating and attending to the most relevant targets in a cluttered visual background. When additional studies quantify the performance gains for aging road users, recommendations for relatively widespread use of fluorescent sheeting keyed to specific characteristics of stop- and yield-controlled intersections are likely to emerge. Present recommendations for applications of fluorescent sheeting are limited to the special cases of controlling prohibited movements on freeway ramps (see Chapter 3) and for passive control systems at highway-rail grade crossings (see Chapter 6).

A two-way stop requires a driver to cross traffic streams from either direction; this poses a potential risk, because cross traffic may be proceeding rapidly and drivers may be less prepared to accommodate to errors made by crossing or turning drivers. Most critically, drivers proceeding straight through the intersection must be aware of the fact that the cross-street traffic does not stop, and that they must yield to cross-street vehicles from each direction before proceeding through the intersection. Aging drivers are disproportionately penalized by the late realization of this operating condition, due to the various sources of response slowing noted earlier. Studies of cross-traffic signing to address this problem have shown qualified but promising results in a number of jurisdictions (Gattis, 1996). Although findings indicate that conversion of two-way to four-way stop operations may be more effective in reducing intersection crashes than the use of cross-traffic signing, there are obvious tradeoffs for capacity from this strategy. However, data from crash analyses in Arkansas, Oregon, and Florida reported by Gattis (1996) showed significant reductions in right-angle crashes after cross-traffic signing was installed at problem intersections. Until fairly recently, there was no standard sign design to convey this message; Ligon, Carter, and McGee (1985) identified a number of alternate wordings used in different States. In addition, a warrant for use of a cross-traffic sign applied in the State of Illinois may be reviewed in the Gattis (1996) article. The *MUTCD* (2009) indicates in section 2C.59 that a CROSS TRAFFIC DOES NOT STOP plaque (W4-4p) may be used in combination with a STOP sign when engineering judgment indicates that conditions are present that are causing or could cause drivers to misinterpret the intersection as an all-way stop.

Picha, et al. (1996) conducted a survey of 2,129 drivers in five States (California, Minnesota, Mississippi, Pennsylvania, and Texas) to evaluate driver understanding of right-of-way conditions and preference for supplemental signs at two-way, stop-controlled intersections. The majority of the respondents (59 percent) were between ages 25 and 54; however, 22 percent were age 65 or older. The mail survey presented nine supplemental sign designs (three word messages, three symbol messages, and three word-plus-symbol messages), and respondents were asked to choose the preferred sign in each category that best conveyed the right of way conditions at a two-way, stop-controlled intersection, and then to choose the most preferred design of the three. The sign most often preferred (by 84 percent of the sample) was the CROSS TRAFFIC DOES NOT STOP word message with a horizontal double-headed arrow symbol. When asked whether a supplemental sign was needed at all two-way, stop-controlled intersections to tell drivers who has the right-of-way (a diagram was provided with the question), 44 percent of the drivers responded "yes," 50 percent "no," and 6 percent "not sure." Picha et al. (1996) provided a list of conditions that may lead a driver to misinterpret an intersection to be all-way stop controlled, which would justify a supplemental sign treatment. In addition to intersections converted from four-way to two-way stop control, these include:

- The intersection of two single-jurisdictional roadways (e.g., two state-maintained roadways) in a rural or isolated area.
- Intersections with similar average daily traffic (ADT) volumes on all approaches, but less than the minimum volumes that would warrant the installation of a traffic signal. Typical volumes ranging from 5,000 to 10,000 ADT will not likely meet signal warrants, but could justify a supplemental treatment.
- Intersections with a high conflict frequency and rate, i.e., 20 to 25 conflicts per day (all conflicts combined) or a rate of at least 4 conflicts per 1,000 entering vehicles.
- Intersections with a right-angle crash frequency in the range of three to five (or more) per year. Such a condition may not necessarily meet traffic signal warrants.

- A system of roadway intersections (at-grade) that is not consistent with respect to traffic control schemes.
- Intersections with similar high speeds (i.e., greater than 50 mph on all approaches.
- Intersections with similar cross-sectional elements (number and width of lanes, shoulders, grades, drainage) on all approaches.

The issue of driver expectancy, a key predictor of performance for aging motorists, was addressed in a study by Agent (1979) to determine what treatments would make drivers more aware of a stop-ahead situation. Agent concluded that at rural sites, transverse pavement striping should be applied approximately 1,200 ft in advance of the STOP sign to significantly reduce approach speeds. Later research (Agent, 1988) recommended the following operational improvements at intersections controlled by STOP signs: (1) installing additional advance warning signs; (2) modifying warning signs to provide additional notice; (3) adding stop lines to inform motorists of the proper location to stop, to obtain the maximum available sight distance; (4) installing rumble strips, transverse stripes, or post delineators on the stop approach to warn drivers that they would be required to stop; and (5) installing beacons. Although Agent emphasized that beacons do not eliminate the problem of drivers who disregard the STOP sign, flashing beacons used in conjunction with STOP signs at isolated intersections or intersections with restricted sight distance have been consistently shown to be effective in decreasing crashes by increasing driver awareness and decreasing approach speeds (California Department of Public Works, 1967; Cribbins and Walton, 1970; Goldblatt, 1977; King, et al., 1978; Lyles, 1980).

With regard to the crash reduction effectiveness of rumble strips placed on intersection approaches, Harwood (1993) reported that rumble strips can provide a reduction of at least 50 percent in the types of crashes most susceptible to correction, including crashes involving running through a STOP sign. They can also be expected to reduce vehicle speed on intersection approaches and to increase driver compliance with STOP signs. In an evaluation conducted by the Virginia Department of Highways and Transportation (1981a) where rumble strips were installed at stop-controlled intersections, the total crash frequency was reduced by 37 percent, fatal crashes were reduced by 93 percent, injury crashes were reduced by 37 percent, and property-damage-only crashes were reduced by 25 percent. In this study, 39 of the 141 crashes in the before period were classified as being types susceptible to correction by rumble strip installation, particularly rear-end crashes and ran-STOP-sign crashes. The crash rate for these crash types was reduced by 89 percent. Carstens and Woo (1982) found that primary highway intersections where rumble strips were installed experienced a statistically significant reduction in the crash rate in the first year or two following their installation, both at four-way and T-intersections. The crash rate at the 21 study intersections decreased by 51 percent for total crashes and by 38 percent for ran-STOP-sign crashes. Carstens and Woo found no statistically significant change in crash rate at 88 intersections on secondary roads where rumble strips were installed. They concluded that rumble strips are more effective at primary highway intersections than secondary road intersections for the following reasons: (1) primary highways serve a higher proportion of drivers who are unfamiliar with the highway; (2) trips tend to be longer on primary highways so that fatigue and the monotony of driving may play a more important role than on secondary roads; (3) traffic volumes are higher on primary highways, so the number of potential conflicts is greater; and (4) the geometric layout of primary highway intersections is often more complex than that of secondary road intersections. These researchers also found that rumble strips may be more effective in reducing nighttime crashes at unlighted intersections than at lighted intersections. Harwood (1993) reported that several highway agencies commented that it was important to avoid the temptation to use rumble strips where they are not needed; if every intersection had rumble strips on its approach, rumble strips would soon lose their ability to focus the attention of the motorist on an unexpected hazard.

Before concluding this discussion, certain aspects of YIELD sign operations deserve mention. A YIELD sign facilitates traffic flow by preventing unnecessary stops and allowing drivers to enter the traffic flow with minimum disruption of through traffic. Most YIELD signs are posted where right-turning drivers can approach the cross street at an oblique angle. Such configurations benefit elderly drivers in carrying out the turning maneuver by avoiding the tight radii that characterize right-angle turns. However, in several respects, intersections regulated by YIELD signs place greater demands upon drivers than those employing other controls, in terms of gap selection, difficulty with head turning, lane-keeping, and maintaining or adjusting vehicle speed. The angle of approach to the street or highway being entered ranges from the near perpendicular to the near parallel. The closer the angle is to the parallel, the further the driver must turn his/her head to detect and to judge the speed and distance of vehicles on the road to be entered. Many elderly drivers are unable to turn their heads far enough to get a good look at approaching traffic, while the need to share attention with the road ahead necessarily limits the gap search to 1 or 2 s. Some drivers are reduced to attempting to judge distance and gaps by means of the outside mirror. The inability to judge gaps in this manner often results in the driver reaching the end of the access lane without having identified an appropriate gap. The driver in this situation comes to a complete stop and then must enter the cross street by accelerating from a stopped position. The difficulty in judging gaps may lead to aborted attempts to enter the roadway, leaving the aging driver vulnerable to following drivers who direct their attention upstream and fail to notice that a vehicle has stopped in front of them. The need to share attention between two widely separated points results in eyes being off the intended path for lengthy periods. The diversion of attention, along with movement of the upper torso, hampers the aging driver's ability to maintain directional control.

McGee and Blankenship (1989) reported that intersections converted from stop to yield control are likely to experience an increase in crashes, especially at higher traffic volumes, at the rate of one additional crash every 2 years. In addition, converted yield-controlled intersections have a higher crash rate than established yield-controlled intersections. They note that while yield control has been found to be as safe as stop control at very low volumes, the safety impacts are not well established for higher volume levels. Agent and Deen (1975) reported that rural road crash types at yield-controlled intersections are different from those at stop-controlled intersections. At YIELD signs, more than half of the crashes were rear-end collisions, while more than half of the crashes at STOP signs were angle collisions.

# 12 Lane Assignment on Intersection Approach

As a driver approaches an intersection with the intention of traveling straight through, or turning onto an intersecting roadway, he/she must first determine whether the currently traveled lane is the proper one for executing the intended maneuver. This understanding of the downstream intersection geometry is accomplished by the driver's visual search and successful detection, recognition, and comprehension of pavement markings (including stripes, symbols, and word markings); regulatory and/or advisory signs mounted overhead, in the median, and/or on the shoulder in advance of the intersection; and other geometric feature cues such as curb and pavement edge lines, pavement width transitions, and surface texture differences connoting shoulder or median areas. Uncertainty about downstream lane assignment produces hesitancy during the intersection approach; this in turn decreases available maneuver time and diminishes the driver's attentional resources available for effective response to potential traffic conflicts at and near intersections.

Aging drivers' decreased contrast sensitivity, reduced useful field of view, increased visual search and decision times—particularly in response to unexpected events—and slower vehicle control during movement execution combine to put these highway users at greater crash risk when approaching and negotiating intersections. Contrast sensitivity and visual acuity are the visual/perceptual requirements necessary to detect pavement markings and symbols and to read lane control signs and word and symbol pavement markings. The early detection of lane control devices, by cueing the driver in advance that designated lanes exist for turning and through maneuvers, promotes safer and more confident performance of any required lane changes. This is because the traffic density is lighter, there are more available gaps, and there are fewer potential conflicts with other vehicles and pedestrians the farther away from the intersection the maneuver is performed. Of course, even the brightest delineation and pavement markings will not be visible to an operator unless an adequate sight distance (determined by horizontal and vertical alignment) is available.

In an effort to analyze the needs and concerns of aging drivers, the Illinois Department of Transportation sponsored a statewide survey of 664 drivers, followed up by focus group meetings held in rural and urban areas (Benekohal, et al. 1992). Within this sample, the following four age categories were used for statistical analyses: ages 66–68, ages 69–72, ages 73–76, and age 77 and older. Comparisons of responses from drivers ages 66–68 and age 77 and older showed that the older group had more difficulty following pavement markings, finding the beginning of the left-turn lane, driving across intersections, and driving during daytime. Similarly, the level of difficulty for reading street signs and making left turns at intersections increased with increasing driver age. Turning left at intersections was perceived as a complex driving task, made more difficult when channelization providing visual cues was absent and only pavement markings designated which lane ahead was a through lane and which was a turning lane. The processes of lane location, detection, and selection must be made upstream at a distance where a lane change can be performed safely. Late detection by aging drivers will result in erratic maneuvers such as lane weaving close to the intersection (McKnight and Stewart, 1990).

More than half of 81 aging drivers participating in another set of focus group discussions stated that quite often they suddenly find themselves in the wrong lane, because (1) they have certain expectations about lane use derived from intersections encountered earlier on the same roadway, (2) the advance signing is inadequate or lacking, or (3) the pavement markings are covered by cars at the intersection (Staplin, et al., 1997). The biggest problem with turn-only lanes reported by group participants was that there is not enough warning for this feature. The appropriate amount of advance notice, as specified by these drivers, ranged from 5 car lengths to 1 mi. Sixty-four percent of the participants said that multiple warning signs are necessary when the right lane becomes a turn-only lane, with the need for an initial sign 20 to 30 s away, and a second sign 10 s away from the turn location. The remaining participants said that these distances should be increased.

**Table 28.** Cross-References of Related Entries for Lane Assignment on Intersection Approach.

| Applications in Standard Reference Manuals | | | |
|---|---|---|---|
| *MUTCD* (2009) | AASHTO *Green Book* (2011) | NCHRP 279 Intersection Channelization Design Guide (1985) | Traffic Engineering Handbook (2009) |
| Sect. 1A.13, approach<br>Table 2B-1<br>Sects. 2B.19 through 2B.27, 2B.42 through 2B.48,Sects. 2B.51 through 2B.55,<br>Fig. 2B-4<br>Sects. 3A.01, 3A.02, 3A.06, & 3B.05<br>Figs. 3B-13<br>Sect. 3B.20<br>Figs. 3B-18, 3B-23, 3B-24, & 3B-27 | Pgs. 5-13 through 5-14, Sects. on *Width of Traveled Way & Parking Lanes*<br>Pg. 6-13, Para. 5<br>Pg. 7-31, Para. 6<br>Pgs. 9-10 through 9-19, Sects. 9.3.1 and 9.3.2 *Three-Leg Intersections & Four-Leg Intersections*<br>Pg. 9-131 through 9-133, sect. on *Guidelines for Design of Left-Turn Lanes*<br>Pgs. 9-11 and 9-13, Figs. 9-4 and 9-5<br>Pgs. 9-124 through 9-125, Sect. 9.7.1 *General Design Considerations*<br>Pgs. 9-124 through 9-40, Sect. 9.7 Auxiliary Lanes Pgs. 9-176 through 9-179, Sect. 9.11.1 *Intersection Design Elements with Frontage Roads*<br>Pgs. 9-180 through 9-181, Sect. 9.11.3 *Bicycles*<br>Pgs. 9-182 through 9-183, Sect. 9.11.7 *Midblock Left Turns on Streets with Flush Medians* | Pg. 1, Item 2, 3rd bullet<br>Pg. 19, Middle fig.<br>Pg. 21, 2nd col., item 1<br>Pg. 24, Para. 1 & top fig.<br>Pg. 32, Bottom fig.<br>Pg. 34, Para. 1 & two figs.<br>Pg. 35, Top right fig.<br>Pg. 36, Para. 1 & top & bottom figs.<br>Pg. 37, Para. 2 & top two figs.<br>Pgs. 47-48, Sect. on *Warrants/ Guide-lines For Use of Left-Turn Lanes*<br>Pg. 51, Fig. 4-12<br>Pg. 57, Sects. on *Double Left-Turn Lanes—Guidelines for Use & Guidelines for Implementation of COTWLTL*<br>Pg. 59, Fig. 4-20<br>Pgs. 61-63, Sect. on *Exclusive Right-Turn Lanes*<br>Pgs. 92-97, Intersct. Nos. 2 & 4<br>Pgs. 99-119, Intersct. Nos. 6-16<br>Pgs. 132-139, Intersct. Nos. 22-24 & 29<br>Pgs. 142-144, Intersct. Nos. 31-33<br>Pgs. 146-153, Intersct. Nos. 34-37 | Pg. 243, 2nd & 7th Principles<br>Pg. 391-392, Sect. on *Older Drivers and Pedestrians* |

Even greater consensus was shown in this study regarding sign location for lane assignment. Seventy-nine percent of the group reported that overhead lane-use signs are far more effective than roadside-mounted signs for this type of warning. Several participants suggested that a combination of roadside and overhead signs, in addition to roadway markings, would be beneficial. Although roadway markings were deemed helpful, 84 percent of all participants stated that they are useless in isolation from signs, because they are usually at the intersection and are obscured by traffic, and they are frequently worn and faded. The result is that drivers end up in the wrong lane and must go in a direction they had not planned for, or they try to change lanes at a point where it is not safe to do so. Thus, a general conclusion from this study is that overhead signing posted in advance of, as well as at, an intersection provides the most useful information to drivers about movement regulations which may be difficult to obtain from pavement marking arrows when traffic density is high or when pavement markings are obscured by snow or become faded, or where sight distance is limited.

In an early study conducted by Hoffman (1969), the installation of overhead lane-use control signs in advance of six intersections in Michigan contributed to a reduction in the total number of crashes by 44 percent in a 1-year period, and a reduction in the incidence of crashes caused by turning from the wrong lane by 58 percent. Later, older drivers (as well as their younger counterparts) were shown to benefit from redundant signing (Staplin and Fisk, 1991). In addition to redundant information about right-of-way movements at intersections, drivers should be forewarned about lane drops, shifts, and merges through advance warning signs, and ideally these conditions should not occur close to an intersection. Advance route or street signing as well as reassurance (confirmatory) signing/route marker assemblies across the intersection will aid drivers of all ages in deciding which lane will lead them to their destination, prior to reaching the intersection.

The 2009 *MUTCD* specifies in section 2B.19 that Intersection Lane Control signs should be mounted overhead, except where the number of through lanes for an approach is two or less, where the Intersection Lane Control signs (R3-5 through R3-8) may be overhead or ground mounted. The Mandatory Movement Lane Control signs (R3-5, R3-5a, R3-7, and R3-20) are required to be located where the regulation applies. The Optional Movement Lane Control Sign (R3-6) is required to be located in advance of and/or at the intersection where the regulation applies. The section on Advance Intersection Lane Control signs (sign series R3-8, section 2B.22), states that when used, these signs should be placed at an adequate distance in advance of the intersection so that road users can select the appropriate lane (e.g., in advance of the tapers or at the beginning of the turn lane). Where three or more approach lanes are available to traffic, Advance Intersection Lane Control signs, if used, shall be post-mounted in advance of the intersection and shall not be mounted overhead. Section 3B.20 indicates that where through lanes become mandatory turn lanes, lane-use arrow markings shall be used and shall be accompanied by standard signs.

Although pavement markings have obvious limitations (e.g., limited durability when installed in areas exposed to heavy traffic, poor visibility on wet roads, and obscuration by snow in some regions), they have the advantage of presenting information to drivers without distracting their attention from the roadway.

Finally, the Institute of Transportation Engineers identified several features to enhance the operation of urban arterial trap lanes (through lanes that terminate in an unshadowed mandatory left- or right-turn regulation): (1) signing that gives prominent advance notice of the unexpected mandatory turn regulation, followed by a regulatory sign at the point where the mandatory turn regulation takes effect, followed by a third sign at the intersection itself if there are intervening driveways from which motorists might enter the lane; (2) supplemental pavement markings which consist of a double-width broken lane line beginning at the advance warning sign and extending to the first regulatory sign; (3) a pavement legend in the trap lane; and (4) overhead signing. Candidates for these remedial treatments include left-turn trap lanes on roadways with high volumes, high speeds, poor approach visibility, and complex geometrics (Foxen, 1986).

# 13 Traffic Signals

Traffic signals are power-operated signal displays used to regulate or warn traffic. They include displays for intersection control, flashing beacons, lane-directional signals, ramp-metering signals, pedestrian signals, railroad-crossing signals, and similar devices. Warrants for traffic signals are thoroughly described in the *MUTCD*. The decision to install a traffic signal is based on an investigation of physical and traffic flow conditions and data, including traffic volume, approach travel speeds, physical condition diagrams, crash history, and gap and delay information (Wilshire, 1992). The *MUTCD* incorporates the intensity, light distribution, and chromaticity standards from the following Institute of Transportation Engineers (TEH) standards for traffic signals: *Vehicle Traffic Control Signal Heads*, TEH Standard No ST-008B (TEH, 1985b); *Pedestrian Traffic Control Signal Indications*, TEH Standard No. ST-011B (TEH, 1985a); *Traffic Signal Lamps*, TEH Standard No. ST-010 (TEH, 1986); *Lane-Use Traffic Control Signal Heads* (TEH,

**Table 29.** Cross-References of Related Entries for Traffic Signals.

| Applications in Standard Reference Manuals | | | |
|---|---|---|---|
| *MUTCD* (2009) | AASHTO *Green Book* (2011) | NCHRP 500 – Volume 9 (2004) | Traffic Engineering Handbook (2009) |
| *Sect. 1A.13, flashing & traffic control signal (traffic signal)*<br>*Sects. 4A.02, 4D.01, 4D.04, through 4D.31, 4E.03 through 4E.13, 4I.02, 4J.02, 4M.03, & 4L.01*<br>*MUTCD references to TEH standards ST-008B, ST-011B, ST-010 & Lane-Use Traffic Control Signal Heads* | Pg. 2-62, Para. 2<br>Pgs. 3-76, Paras. 2-4<br>Pg. 6-19, Sect. on *Traffic Control Devices*<br>Pgs. 7-43 through 7-44, Sect. on *Traffic Control Devices*<br>Pg. 9-19, Paras. 2 & 3 & Fig. 9-9 on pg. 9-18<br>Pg. 9-51, Sect. on *Case D-Intersections with Traffic Signal Control*<br>Pg. 9-180, Paras. 3 & 4<br>Pg. 10-38, Para. 1<br>Pg. 10-105, Para. 1 | Pgs. V-17-V-18, Sect. on *Strategy 3.1 B4: Provide All-Red Clearance Interval at Signalized Intersection (T)* | Chapter 12 |

1980); *Vehicle Traffic Control Signal Heads: Light Emitting Diode (LED) Circular Signal Supplement*, TEH Standard No. ST-052 (TEH, 2005); and *Vehicle Traffic Control Signal Heads: Light Emitting Diode Vehicle Arrow Traffic Signal Supplement*, TEH Standard No. ST-054 (TEH, 2008). Standards for traffic signals are important because it is imperative that they attract the attention of every driver, including aging drivers and those with impaired vision who meet legal requirements, as well as those who are fatigued or distracted, or who are not expecting to encounter a signal at a particular location. It is also necessary for traffic signals to meet motorists' needs under a wide range of conditions including bright sunlight, nighttime, in adverse weather, and in visually cluttered surroundings.

To date, studies of traffic signal performance have not typically included observer age as an independent variable. Available evidence suggests, however, that aging individuals have reduced levels of sensitivity to intensity and contrast, but not to color. Fisher (1969) reported that as a person ages, the ocular media yellows and has the effect of enhancing the contrast between a red signal and a sky background. However, this effect is more than offset by increasing light scatter within the eye, which diminishes contrast. Aging drivers need increased levels of signal luminance and contrast in certain situations to perceive traffic signals as efficiently as 20- to 25-year-old drivers; however, higher signal intensities may cause disability glare. Fisher and Cole (1974), using data from Blackwell (1970), suggested that aging drivers may require 1.5 times the intensity at 50 years of age and 3 times the intensity at 70 years of age, and protanopes (individuals with a color-vision deficiency resulting in partial or full insensitivity to red light) may require a fourfold increase. They noted that while increased intensity will ensure that aging observers see the signal, the reaction time of aging drivers will be longer than for younger drivers. To compensate for this, it would appear necessary to assume a longer required visibility distance, which would result in an increase in the signal intensity required. However, Fisher (1969) also suggested that no increase in signal intensity is likely to compensate for increasing reaction time with age. It therefore deserves emphasis that the goal of increased response times for aging drivers, requiring longer visibility distances, can also be provided by ensuring that the available signal strength (peak intensity) is maintained through a wide, versus a narrow, viewing angle. This makes signal information more accessible over longer intervals.

It is generally agreed that the visibility issues associated with circular signals relate to the following factors: minimum daytime intensity, intensity distribution, size, nighttime intensity, color of signals, backplates, depreciation (light loss due to lamp wear and dirt on lenses), and phantom (apparent illumination of a signal in a facing sun). To place this discussion in context, it should also be noted that traffic signal recommendations for different sizes, colors, and in-service requirements have, in large part, been derived analytically from one research study conducted by Cole and Brown (1966).

In establishing minimum daytime intensity levels for (circular) traffic signals, the two driver characteristics that are considered with regard to the need to adjust peak intensity requirements are color anomalies and driver age. Cole and Brown (1968) determined that the optimum red signal intensity is 200 cd for a sky luminance of 10,000 cd/m$^2$, and an adequate signal intensity for this condition would be 100 cd. Cole and Brown (1966, 1968) defined "optimum" as "a signal intensity that provides a very high probability of recognition and which also evokes the shortest response times from the observer." In their research, very high probability was defined as 95 to 100 percent probability of detection. An "adequate signal," although not likely to be missed, results in driver reaction time that is slower than for a signal of "optimum" intensity.

The number of foreign and domestic highway organizations that specify a minimum standard for peak daytime traffic signal intensity is larger than the number of research studies upon which those standards are based. In fact, all of the standards including those for 8-in (200-mm) and 12-in (300-mm) signals, those for red, yellow, and green signals, and those for new and in-service applications are derived from a single requirement for a red traffic signal, established from the work of Cole and Brown (1966). The conclusion of this laboratory study was that a red signal with an intensity of 200 cd should invoke a "certain and rapid response" from an observer viewing the signal at distances up to 328 ft even under extremely bright ambient conditions. This conclusion was based on experiments in which the background luminance was 5,142 cd/m$^2$. The results were linearly extrapolated to a background luminance of 10,000 cd/m$^2$ which yielded the 200-cd recommendation. Janoff (1990) concluded that a value of 200 cd minimum intensity for a red signal will suffice for observation distances up to 328 ft and vehicle speeds up to 50 mph, based on analytic, laboratory, and controlled field experiments performed by Adrian (1963); Boisson and Pages (1964); Rutley, Christie, and Fisher (1965); Jainski and Schmidt-Clausen (1967); Cole and Brown (1968); Fisher (1969); and Fisher and Cole (1974). Fisher and Cole (1974) cautioned against using a value less than 200 cd, to ensure that aging drivers and drivers with abnormal color vision will see the signal with certainty and with "reasonable speed."

For green signals, Fisher and Cole (1974) indicated that the ratio of green to red intensity should be 1.33:1, based on laboratory and controlled field research by Adrian (1963), Rutley et al. (1965), Jainski and Schmidt-Clausen (1967), and Fisher (1969), and the ratio of yellow to red should be 3:1, based on research performed by Rutley et al. (1965) and Jainski and Schmidt-Clausen (1967). Janoff (1990) noted that the evidence to support these ratios is somewhat variable, and support of these recommendations is mixed. Table 30, from Janoff (1990), presents the peak intensity requirements of red, green, and yellow traffic signals for 200-mm (8-in) signals for normal-speed roads and for 12-in signals for high-speed roads; the values presented exclude the use of backplates and ignore depreciation. A normal-speed road, in this context, includes speeds up to 50 mph, distances up to 328 ft, and sky luminances up to 10,000 cd/m$^2$. A high-speed road is defined as one with speeds up to 62 mph, distances up to 787 ft, and sky luminances up to 10,000 cd/m$^2$. Janoff also noted that although signal size is included, research performed by Cole and Brown (1968) indicated that signal size is not important because traffic

**Table 30.** Peak (Minimum) Daytime Intensity Requirement (CD) For Maintained Signals with no Backplate (Janoff, 1990).

| Signal Size | Signal Color | | |
|---|---|---|---|
| | Red | Green | Yellow |
| 8 in (200 mm) | 200 | 265 | 600 |
| 12 in (300 mm) | 895 | 1,190 | 2,685 |

signals are point sources rather than area sources and only intensity affects visibility. Thus, the required intensity can be obtained by methods other than increasing signal size (i.e., by using higher intensity sources in 8-in signals).

The specification of standard values for peak intensity is important because the distribution of light intensity falls off with increasing horizontal and vertical eccentricity in the viewing angle. Janoff (1990) summarized the peak intensity standards of TEH, Commission Internationale de l'Éclairage (CIE), the British Standards Organization, and standards organizations of Australia, Japan, and South Africa. The U.S. (TEH) standard provides different recommendations for each of the three colors for each signal size. The recommendations are as follows: for red, 157 cd for 8-in signals and 399 cd for 12-in signals; for green, 314 cd for 8-in signals and 798 cd for 12-in signals; and for yellow, 726 cd for 8-in signals and 1,848 cd for 12-in signals. Australia recommends the same peak intensity for red and green (200 cd for 8-in signals and 600 cd for 12-in signals), and a yellow intensity equal to three times the red intensity. The CIE recommends the same peak intensity for all three colors (200 cd for 8-in signals and 600 cd for 12-in signals), but acknowledges that actual intensity differences between colors result due to the differential transmittance of the colored lenses (1:1.3 for red to green and 1:3 for red to yellow). Japan recommends 240 cd for all three colors. Great Britain recommends a peak intensity of 475 cd for 8-in red and green signals, and 800 cd for 12-in red and green signals. The range for red signals among all of these standards is from 157 cd (TEH) to 475 cd (British Standards Organization). The 157 cd is from research by Cole and Brown. The modal value of 200 cd, specified by Australia, South Africa, and the CIE, is based upon a depreciation factor of 33 percent.

Only two research reports provide intensity requirements for green and/or yellow signals based upon empirical data. Adrian (1963) used a subjective scale and threshold detection criteria in a study that tested red and green signals at different background luminances. He concluded that the intensity requirements for green were 1.0 and 1.2 times that of red for the subjective and threshold studies, respectively. Jainski and Schmidt-Clausen (1967) tested the ability of observers to detect the presence of a red, amber, or green spot, which was either 2 minutes or 1 degree, against varying background luminances. Their results found that green required 1.0 and 2.5 times that of red, and yellow required 2.5 and 3.0 times that of red, for 1 degree and 2 minutes, respectively. Using these results, most standards set requirements for green and yellow to be 1.3 and 3.0 times that of red, respectively. The CIE standard discusses the fact that the ratios of 1.3 and 3.0 for green and yellow appear to reflect the differences in the transmissivity of the varying color lenses.

Information on signal intensity requirements that will accommodate road users with age-related vision deficiencies is provided by NCHRP Project 5-15, Visibility Performance Requirements for Vehicular Traffic Signals. This investigation includes a series of laboratory and field studies to determine performance-based signal requirements for traffic signal intensity, intensity distribution, and related photometric parameters using a subject population that oversamples aging drivers (Freedman, Flicker, Janoff, Schwab, and Staplin, 1997). What NCHRP 5-15 makes clear is that the 200 cd intensity requirement for red 200 mm (8-in) signals that appears most prominently in the literature cited above (e.g., Janoff, 1990) is the maintained, in-service performance level for signals in visually simple to moderately complex environments. For more highly complex visual environments, the intensity recommendation for the red signal is approximately doubled. The NCHRP 5-15 recommendation for maintained intensity levels also establishes a need for in-service intensity performance measurement.

Holowachuk, Leung, and Lakowski (1993) conducted a laboratory study to evaluate the effects of color vision deficiencies and age-related diminished visual capability on the visibility of traffic signals. Subjects ranged in age from 18 to 80 and older, and included 64 individuals with normal color vision and 51 subjects who were color-vision deficient. A laboratory simulation apparatus was used to present photographs taken of seven signal head assemblies at intersections at distances of 164 and 328 ft. The photographs were taken at intersections in the Vancouver area within simple and complex environments. Each subject viewed 48 photographs shot during daylight conditions and 38 photographs shot at nighttime. Subjects' reaction times to recognize the color of the "on" signal were measured, as was the accuracy of response. The basic highway signal head used by the Ministry of Transportation and Highways in British Columbia consists of a 12-in red light, a 8-in amber light, and a 8-in green light arranged vertically with a yellow backplate. This "standard highway" signal plus six other off-the-shelf signal-head designs were used in the study (see Table 31).

Results indicated that color-vision-deficient drivers had significantly longer reaction times than drivers with normal color vision, and aging drivers had longer reaction times compared to younger drivers. Of particular importance is that the reaction times of the normal color vision drivers over age 50 (n=15) compared closely to those of color-vision-deficient drivers (n=50). Regarding signal design, for daytime conditions, the no backplate assembly produced the longest reaction times for both the normal color vision and the color-vision deficient drivers. Reaction times for the larger and brighter lenses (shape coded and 12 RYG) were the shortest, for both groups of subjects. For nighttime conditions, the signal assemblies showed few differences in reaction time for subjects with normal color vision. Reaction times were shortest for the shape coded and 12 RYG assemblies; however the baseline assembly and the No Backplate assemblies produced the longest reaction times. For the color-vision-deficient group, the reaction times for the shape-coded, 12 RYG, and the Modified Backplate assemblies were distinctly shorter than

**Table 31.** Signal Head Designs Evaluated by Holowachuk et al. (1993, 1994).

| Name | Abbreviation | Lens Size (in)* | Backplate | Other Features |
|---|---|---|---|---|
| No Backplate | NO BP | Red 8, Amber 8, Green 8 | No | N/A |
| Base Line | Baseline | Red 8, Amber 8, Green 8 | Yes | N/A |
| Modified Backplate | Mod BP | Red 8, Amber 8, Green 8 | Yes | Backplate with 2-in reflective border |
| Standard Highway | Std Hwy | Red 12, Amber 8, Green 8 | Yes | N/A |
| 12-in LED | LED | Red 12 (LED), Amber 8, Green 8 | Yes | 12-in red LED signal |
| 12-in Red, Green, Amber | 12 RYG | Red 12, Amber 12, Green 12 | Yes | N/A |
| 12-in Shape Coded | Shape Coded | Red 12, Amber 12, Green 12 | Yes | Red Square<br>Amber Diamond<br>Red Circle |

**Note: 12-in lens uses 150-Watt bulb; 8-in lens uses 69-Watt bulb.*

those for the Baseline and No Backplate assemblies. Nighttime reaction times were much longer than daytime reaction times for the subjects with color vision deficiencies. Signal light colors were identified more incorrectly for night conditions than for day conditions. This difference was greatest for the aging color-vision-deficient drivers (n=22).

Overall, findings indicated that the reaction times for all subjects were the shortest for signal designs with larger 12- in lenses and higher luminances (150-W bulbs). There was no significant difference in reaction times between the shape-coded and the 300 RYG, for the normal subjects or for the color-vision deficient subjects. The next-best performing signal design was the Modified Backplate. The signal assembly with no backplate produced the longest reaction times. Based on these findings, a before and after safety evaluation was conducted with the larger signal head, consisting of a 12-in red light, a 12-in amber light, and a 12-in green light, all with 150-W lamps and a yellow backboard with an additional 2-in reflective border (Sayed, Abdelwahab, and Nepomuceno, 1998). The signal head design was tested at 10 urban intersections in British Columbia, that were originally equipped with the standard signal head design consisting of a 12-in 150-W red light, an 8-in 69-W amber light, and an 8-in 69-W green light, with a yellow backboard. Crash frequency and severity were analyzed at the treatment sites 1 year before the treatment and 2 years after the treatment. Another 10 sites similar to the treatment sites were selected as comparison sites, to adjust for time trend effect. An empirical Bayes before and after safety analysis indicated that the improved signal head design had a significant effect in reducing the overall frequency and severity of crashes at the treatment sites. Crashes were reduced by approximately 24 percent, and injury and fatal crashes were reduced by approximately 16 percent. These results indicated that increasing traffic signal visibility through the improvement of signal head design is an effective countermeasure in reducing both the frequency and severity of traffic crashes at signalized intersections.

Some research has indicated that the dimming of signals at night may have advantages, while also reducing power consumption. Freedman, Davit, Staplin, and Breton (1985) conducted a laboratory study and controlled and observational field studies to determine the operational, safety, and economic impact of dimming traffic signals at night. Results indicated that drivers behaved safely and efficiently when signals were dimmed to as low as 30 percent of TEH recommendations. Previously, however, Lunenfeld (1977) cited the considerable range of night background luminances that may occur in concluding that in some brightly lit urban conditions, or where there is considerable visual noise, daytime signal brightness is needed to maintain an acceptable contrast ratio. The TEH standard does not differentiate between day and night intensity requirements. The CIE has recommended that intensities greater than 200 cd or less than 25 cd be avoided at night and advises a range of 50 to 100 cd for night, except for high-speed roads where the daytime values are preferred. While the option for dimming on a location-by-location basis should not be excluded, from the standpoint of aging driver needs, there is no compelling reason to recommend widespread reduction of traffic signal intensity during nighttime operations.

It is common practice to try to enhance the visibility of signals by placing a large, black backplate around the signals. The backplate, rather than the sky, becomes the background of the signals, enhancing the contrast. Regarding backplate size, no recommendation is contained in the TEH standard. The CIE (1988), however, recommends that all signals use backplates of a size (width) of three times the diameter of the signal.

Researchers have postulated further safety gains by adding a 1-inch to 3-inch yellow retroreflective strip around the perimeter to "frame" the backplate. In theory, by drawing drivers' attention to the backplate, their attention to the signal will be similarly enhanced. In other words, this represents an attempt to heighten signal conspicuity, while the backplate itself improves signal visibility. Sayed, de Leur, and Pump (2005) conducted a before-after study of crash experience at 17 signalized intersections in British Columbia, Canada, using auto insurance claims data. An empirical Bayes analysis, which included a comparison group to control for trend effects and a reference group to adjust for regression to the mean, indicated a nearly 15% drop in the number of crash claims following introduction of the enhanced-conspicuity backplates. The types of collisions (either before or after the backplate treatment was introduced) were not revealed in this report (i.e. it is unknown whether rear end crashes or more injurious angle crashes figured more prominently in these data). In addition, there is no discussion of driver age in the study results. Thus, while this practice has gained adherents in a number of jurisdictions, reliable evidence of its benefit for aging road users is still pending. However, FHWA has named backplates with retroreflective borders as a Proven Safety Countermeasure to reduce red-light-running crashes for all drivers (Office of Safety, 2012). Retroreflective backplate borders are included as an option in the 2009 MUTCD and have been implemented statewide in Ohio and Nebraska.

As a practical matter, the use of a backplate also serves to compensate, in part, for the effects of depreciation, since a backplate reduces the required intensity by roughly 25 percent (Cole and Brown, 1966) while depreciation increases the requirement by the same amount. Guidelines published by the CIE (1988) include an allowance of 25-percent transmissivity for depreciation due to dirt and aging (a 33-percent increase in intensity for new installations). The 200-cd requirement for red signals, as noted earlier, must be met after the depreciation factor has been taken into account.

Regarding signal size, section 4D.07 of the *MUTCD* specifies that the two nominal diameter sizes for vehicular signal lenses are 8 in and 12 in, and requires that 12-in lenses be used at all new signal locations with only a few exceptions. Existing 8-inch circular signal indications may be retained for the remainder of their useful service life. Researchers at the Texas Transportation Institute proposed that the larger 12-in lens should be used to improve the attention-getting value of signals for aging drivers (Greene, et al., 1996). Use of the large lens also provides motorists with more time to determine the signal color and to make the correct response.

A final issue with respect to signal performance and aging drivers is the change intervals between phases, and the assumptions about perception-reaction time (PRT) on which these calculations are based. At present, a value of 1.0 s is assumed to compute change intervals for traffic signals, a value which, according to Tarawneh (1991), dates back to a 1934 Massachusetts Institute of Technology study on brake-reaction time. Tarawneh examined findings published by proponents of both "parallel" and "sequential" (serial) models of driver information processing, seeking to determine the best estimator for aging individuals of a PRT encompassing six different component processing operations:

(1) latency time (onset of stimulus to beginning of eye movement toward signal); (2) eye/head movement time to fixate on the signal; (3) fixation time to get enough information to identify the stimulus; (4) recognition time (interpret signal display in terms of possible courses of action); (5) decision time to select the best response in the situation; and (6) limb movement time to accomplish the appropriate steering and brake/accelerator movements.

Tarawneh's (1991) review produced several conclusions. First, the situation of a signal change at an intersection is among the most extreme, in terms of both the information-processing demand and subjective feelings of stress that will be experienced by many aging drivers. Second, the most reasonable interpretation of research to date indicates that the best "mental model" to describe and predict how drivers respond in this context includes a mix of concurrent and serial-and-contingent information-processing operations. In this approach, the most valid PRT estimator will fall between the bounds of values derived from the competing models thus far, also taking into account age-related response slowing for recognition, decision-making, and limb movement. After a tabular summary of the specific component values upon which he based his calculations, Tarawneh (1991) called for an increase in the current PRT value used to calculate the length of the yellow interval (derived from tests of much younger subjects) from 1.0 s to 1.5 s to accommodate aging drivers.

A contrasting set of results was obtained in a FHWA-sponsored study of traffic operations control for older drivers (Knoblauch, et al., 1995). This study compared the decision/response times and deceleration characteristics of older drivers (ages 60–71 and older) with those of younger drivers (younger than age 60) at the onset of the amber signal phase. Testing was conducted using a controlled field test facility, where subjects drove their own vehicles. Subjects were asked to maintain speeds of 30 mph and 20 mph for certain test circuits. The duration of the yellow signal was 3.0 s before turning to red. On half of the trials, the signal changed from green to yellow when the subject was 3.0 to 3.9 s from the signal, and on the remaining trials, when the subject was 4.0 to 4.9 s away from the signal. For three of the circuits, subjects were asked to brake as they normally would and to stop before reaching the intersection, if they chose to do so. During a fourth circuit, they were asked to brake to a stop, if they possibly could, if the light changed from green to yellow. Response times were measured for the drivers who stopped, from the onset of the yellow phase to the time the brake was applied.

Results of the Knoblauch et al. (1995) study showed no significant differences in 85th percentile decision/response times between younger and older drivers when subjects were close to the signal at either approach speed. The 85th percentile decision time of younger subjects was 0.39 s at 20 mph and 0.45 s at 30 mph. For older drivers, these times were 0.51 and 0.53 s, for 20 mph and 30 mph, respectively. When subjects were further from the signal at amber onset, older drivers had significantly longer decision/response times (1.38 s at 20 mph and 0.88 s at 30 mph) than the younger drivers (0.50 s at 20 mph and 0.46 s at 30 mph). The authors suggested that the significant differences between older and younger drivers occurred when the subjects were relatively far from the signal, and that some older subjects will take longer to react and respond when additional time is available for them to do so. Thus, they concluded that the older drivers were not necessarily reacting inappropriately to the signal. In terms of deceleration rates, there were no significant differences, either in the mean or 15th percentile values, between the older and younger subjects. Together, these findings led the authors to conclude that no changes in amber signal phase timing are required to accommodate aging drivers.

Taking the review and study findings of Tarawneh (1991) and Knoblauch et al. (1995) into consideration, an approach that retains the 1.0-s PRT value as a minimum for calculating the yellow change interval seems appropriate; but, to acknowledge the significant body of work documenting age-related increases in PRT, the use of a 1.5-s PRT is well justified when engineering judgment determines a special need to take aging drivers' diminished capabilities into account. A treatment for an all-red clearance interval logically follows, with length determined according to the TEH (1992).

# 14 Intersection Lighting

One of the main purposes of lighting a roadway at night is to increase the visibility of the roadway and its immediate environment, thereby permitting the driver to maneuver more safely and efficiently. The visibility of an object is that property which makes it discernible from its surroundings. This property depends on a combination of factors; principally, these factors include the differences in luminance, hue, and saturation between the object and its immediate background (contrast); the angular size of the object at the eye of the observer; the luminance of the background against which it is seen; and the duration of observation.

Of all the highway safety improvement projects evaluated by FHWA (1996), using data

**Table 32.** Cross-References of Related Entries for Intersection Lighting.

| Applications in Standard Reference Manuals | | | |
|---|---|---|---|
| ***MUTCD* (2009)** | **AASHTO *Green Book* (2011)** | **NCHRP 500 – Volume 9 (2004)** | **Roadway Lighting Handbook (1978)** |
| *Sect. 1A.13, sign illumination*<br>*Sects. 2A.07, 2D. 03, 2E.06, & 3I.04*<br>*Sect. 4B.04*<br>*Sects. 6D.01 & 6D.03*<br>*Sect. 6F.81 and 6F. 82*<br>*Sect. 6G.14 and 6G. 19*<br>*Table 6H-2*<br>*Figs. 6H-12, 6H-40, 6H-41*<br>*Sects. 8A.06* | Pgs. 3-172 through 3-173, Sect. 3.6.3 *Lighting*<br>Pg. 3-176, Para. 3<br>Pgs. 5-22, Sect. 5.3.8 *Street and Roadway Lighting*<br>Pg. 6-19, Sect. 6.3.8 on *Roadway Lighting*<br>Pg. 7-52, Sect. 7.3.17 *Lighting*<br>Pg. 9-181, Sect. 9.11.5 *Lighting at Intersections* | Pgs. V-21-V-22, Sect. on *Strategy 3.1 B7:Improve Lighting at Intersections, Horizontal Curves, and Railroad Grade Crossings (T)* | Pgs. 16-27, Sects. on *Analytical Approach to Illumination Warrants, Informational Needs Approach to Warrants, & Warrants for Rural Intersection Lighting*<br>Pgs. 29-30 Sect. on *Adverse Geometry and Environment Warrant*<br>Pgs. 42-45, Sect. on *Summary of Light Sources*<br>Pgs. 53-56, Sect. on *Classification of Luminaire Light Distributions*<br>Pg. 71, 5th bullet<br>Pg. 94, Sect. on *Coordination of the Arterial Lighting System and Traffic Controls*<br>Pg. 96, Sect. on *Intersection Lighting*<br>Pgs. 98-99, Sect. on *Rural Intersection Lighting*<br>Pgs. 120-129, Sect. on *Illumination Design Procedure*<br>Pgs.187-200, Sect. on *Maintaining the System* |

from 1974 to 1995 where before- and after-exposure data were available, intersection illumination was associated with the highest benefit-cost ratio (26.8) in reducing fatal and injury crashes. The link between reduced visibility and highway safety is conceptually straightforward. Low luminance contributes to a reduction in visual capabilities such as acuity, distance judgment, speed of seeing, color discrimination, and glare tolerance, which are already diminished capabilities in aging drivers.

A recent NCHRP report shows that intersection lighting can reduce total nighttime crashes by 21 percent and nighttime injury crashes by 27 percent. On the basis of day-night crash distributions, this translates into a 4 percent reduction in total crashes at an intersection where lighting is added and a 5 percent reduction in all injury crashes. (Harkey et al., 2008) These results are based on a meta-analysis of 38 studies, including 14 conducted in the U.S. (Elvik and Vaa, 2004) and review by an expert panel as part of the referenced NCHRP study.

The Commission Internationale de l'Éclairage (1990) reports that road crashes at night are disproportionately higher in number and severity compared with crashes during the daytime. Data from 13 Organization for Economic Cooperation and Development countries showed that the proportion of fatal nighttime crashes ranged between 25 and 59 percent (average value of 48.5 percent). In this evaluation of 62 lighting and crash studies, 85 percent of the results showed lighting to be beneficial, with approximately one-third of the results statistically significant.

In 1990, drivers (without regard to age) in the United States experienced 10.37 fatal involvements per 100 million mi at night and 2.25 fatal involvements per 100 million mi during the day (Massie and Campbell, 1993). In their analysis, the difference between daytime and nighttime fatal rates was found to be more pronounced among younger age groups than among older ones, with drivers ages 20–24 showing a nighttime rate that was 6.1 times the daytime rate, and drivers age 75 and older showing a nighttime rate only 1.1 times the daytime rate. The lower percentage of nighttime crashes of aging drivers may be due to a number of factors, including reduced exposure—aging drivers as a group drive less at night—and a self-regulation process whereby those who do drive at night are the most fit and capable to perform all functional requirements of the driving task (National Highway Traffic Safety Administration, 1987).

A specific driving error with high potential for crash involvement is wrong-way movements. Analyses of wrong-way movements at intersections frequently associate these driving errors with low visibility and restricted sight distance (Vaswani, 1974, 1977; Scifres and Loutzenheiser, 1975) and note that designs that increase the visibility of access points to divided highways and treatments that improve drivers' understanding of proper movements at these locations have been found to reduce the potential for crashes.

Inadequate night visibility, where the vehicle's headlights are the driver's primary light source, was reported by Vaswani (1977) as a factor that makes it more difficult for drivers to determine the correct routing at intersections with divided highways. Similarly, Woods, Rowan, and Johnson (1970) reported that locations where highway structures, land use, natural growth, or poor lighting conditions reduce the principal sources of information concerning the geometry and pavement markings are associated with higher occurrences of wrong-way maneuvers. Crowley and Seguin (1986) reported that drivers over the age of 60 are excessively involved in wrong-way movements on a per-mile basis. Suggested countermeasures include increased use of fixed lighting installations. Lighting provides a particular benefit to aging drivers by increasing expectancy of needed vehicle control actions, at longer preview distances. It has been documented extensively in this *Handbook* that an aging driver's ability to safely execute a planned action is not significantly worse than that of a younger driver. The importance of fixed lighting at intersections for aging drivers can therefore be understood in terms of both the diminished visual capabilities of this group and their special needs to prepare farther in advance for unusual or unexpected aspects of intersection operations or geometry. Targets that are especially critical in this regard include shifting lane alignments; changing lane assignments (e.g., when a through lane changes to turn-only operation); a pavement width transition, particularly a reduction across the intersection; and, of course, pedestrians.

Detectability of a pedestrian is generally influenced by contrast, motion, color, and size (Robertson, Berger, and Pain, 1977). If a pedestrian is walking at night and does not have good contrast, color contrast, or size relative to other road objects, an increase in contrast will significantly improve his/her detectability. This is one effect of street lighting. Extreme contrasts as well as dark spots are reduced, giving the driver and the pedestrian a more "even" visual field. The effectiveness of fixed lighting in improving the detectability of pedestrians has been reported by Pegrum (1972); Freedman, et al. (1975); Polus and Katz (1978); and Zegeer (1991).

While age-related changes in glare susceptibility and contrast threshold are currently accounted for in lighting design criteria, there are other visual effects of aging that are currently excluded from visibility criteria. Solid documentation exists of age-related declines in ocular transmittance (the total amount of light reaching the retina), particularly for the shorter wavelengths (cf. Ruddock, 1965); this suggests a potential benefit to aging drivers of the "yellow tint" of high-pressure sodium highway lighting installations. The aging eye experiences exaggerated intraocular scatter of light—all light, independent of wavelength (Wooten and Geri, 1987)—making these drivers more susceptible to glare. Diminished capability for visual accommodation makes it harder for aging observers to focus on objects at different distances. Pupil size is reduced among aging individuals through senile miosis (Owsley, 1987), which is most detrimental at night because the reduction in light entering the eye compounds the problem of light lost via the ocular media, as described above.

The loss of static and dynamic acuity—the ability to detect fine detail in stationary and moving targets—with advancing age is widely understood. Although there are pronounced individual differences in the amount of age-related reduction in static visual acuity, Owsley (1987) indicated that a loss of about 70 percent in this capability by age 85 is normal. Among other things, declines in acuity can be used to predict the distance at which text of varying size can be read on highway signs (Kline and Fuchs, 1993), under a given set of viewing conditions.

There are a number of other aspects of vision and visual attention that relate to driving. In particular, saccadic fixation, useful field of view, detection of motion in depth, and detection of angular movement have been shown to be correlated with driving performance (see Bailey and Sheedy, 1988, for a review). As a group, however, these visual functions do not appear to have strong implications for highway lighting practice, with the possible exception of the "useful field of view." It could be argued that it would be advantageous to provide wider angle lighting coverage to increase the total field of view of aging drivers. High-mast lighting systems can increase the field of view from 30 degrees to about 105 degrees (Hans, 1993). Such wide angles of coverage might have advantages for aging drivers in terms of peripheral object detection. However, because high-mast lighting systems tend to sacrifice target contrast for increased field of view, opinion is divided about their application at intersections. Traditionally, field of view has not been considered as a parameter that needs to be optimized in lighting system design for intersection applications.

Rockwell, Hungerford, and Balasubramanian (1976) studied the performance of drivers approaching four intersection treatments, differentiated in terms of special reflectorized delineators and signs versus illumination. A significant finding from observing 168 test approaches was that the use of roadway lighting significantly improved driving performance and earlier detection of the intersection, compared with the other treatments (e.g., signing, delineation, and new pavement markings), which showed smaller improvements in performance.

Finally, it must be emphasized that the effectiveness of intersection lighting depends upon a continuing program of monitoring and maintenance by the local authority. Guidelines published by AASHTO (1984) identify depreciation due to dirt on the luminaires and reduced lumen output from the in-service aging of lamps as factors that combine to decrease lighting system performance below design values. Maintained values in the range of 60 to 80 percent of initial design values are cited as common practice in this publication. With a particular focus on the needs of aging drivers for increased illumination relative to younger motorists, to accommodate the age-related sensory deficits documented earlier in this discussion, a recommendation logically follows that lighting systems be maintained to provide service at the 80 percent level—i.e., the upper end of the practical range—with respect to their initial design values.

# 15 Pedestrian Crossings

A nationwide review of fatalities during the year 1985, and injuries during the period of 1983–1985, showed that 39 percent of all pedestrian fatalities and 9 percent of all pedestrian injuries involved persons age 64 and older (Hauer, 1988). While the number of injuries is close to the population distribution (approximately 12 percent), the number of fatalities far exceeds the proportion of aging pedestrians. The percentages of pedestrian fatalities and injuries occurring at intersections were 33 percent and 51 percent, respectively (Hauer, 1988). People age 70 and older have the highest pedestrian death rate – 2.7 per 100,000 people vs. 1.5 per 100,000 people for those younger than 70 (IIHS,

**Table 33.** Cross-References Of Related Entries For Pedestrian Crossings.

| Applications in Standard Reference Manuals | | | | |
|---|---|---|---|---|
| *MUTCD* (2009) | AASHTO *Green Book* (2011) | Roadway Lighting Handbook (1978) | NCHRP 279 Intersection Channelization Design Guide (1985) | Traffic Engineering Handbook (2009) |
| Sect. 1A.13, *crosswalk, crosswalk lines, & pedestrian*<br>Tables 2A-1 & 2C-2 through 2C-3<br>Sects. 1A.15, 2B.51 through 2B.54, 2C.50, 3B.15 & 3B.18<br>Figs. 3B-17, 3B-19, 3B-20, Sect. 3B.20<br>Sect. 3G.01<br>Sect. 4A.02<br>Sects. 4C.05 & 4D.03<br>Sect. 4D.07 through 4D.11<br>Sects. 4E.01 through 4E.13<br>Fig. 4E-1<br>Sect. 7A.03<br>Fig. 7A-1<br>Table 7B-1<br>Sects. 7B.11 & 7B.12<br>Fig. 7B-1<br>Sects. 7C.02, 7D.01 through 7D.05 | Pgs. 2-78 through 2-81, Sect. 2.6 *The Pedestrian* Pg. 4-49, Para. 2<br>Pg. 5-15, Sect. on *Bicycle/ Pedestrian Facilities*<br>Pg. 6-16, Sect. on *Bicycle/ Pedestrian Facilities*<br>Pgs. 7-41 through 7-42, Sect. 7.3.9 *Bicycle and Pedestrian Facilities*<br>Pgs. 9-83 through 9-92, Sects. on *Effect of Curb Radii on Turning Paths and Effect of Curb Radii on Pedestrians*<br>Pg. 9-98, Sect. on *Refuge Islands*<br>Pg. 9-181, Sect. 9.11.4 *Pedestrians* | Pg. 2, 2nd col., Para. 1<br>Pg. 9, Sect. on *Contrast*<br>Pg. 18, Form 2<br>Pgs. 21-22, Tables 1-2<br>Pgs. 27-30, Sect. on *Warrants for Application of Specialized Crosswalk Illumination*<br>Pg. 45, Para. 3<br>Pg. 71, 3rd bullet<br>Pgs. 94-9, Sects. on *Coordination of the Arterial Lighting System and Traffic Controls & Pedestrian Lighting on Arterials* | Pg. 1, Item 3, 2nd bullet<br>Pg. 6, Table 2-2<br>Pg. 9, Fig. 2-4<br>Pg. 11, Bottom left photo<br>Pg. 21, Item 9 & Fig. 3-1<br>Pg. 27, Bottom left fig.<br>Pg. 33, Bottom right fig.<br>Pg. 38, Para. 1 & top two figs.<br>Pg. 39, Entire pg.<br>Pg. 40, Fig. 4-1<br>Pg. 42, 2nd col., item 3<br>Pg. 61, 2nd col, Paras. 2-3 & item 2<br>Pg. 66, Paras. 1 & 4 & item 4<br>Pg. 67, 2nd col, Paras. 1-2<br>Pg. 68, Fig. 4-26<br>Pg. 69, 2nd col., Para. 4<br>Pgs. 70-72, Figs. 4-27 & 4-28<br>Pg. 75, Paras. 4-5, Table 4-10, & 2nd col, Para. 1<br>Pg. 76, Item 4 & Table 4-11<br>Pgs. 96-97, Intersct. No. 4<br>Pgs. 104-105, Intersct. No. 9<br>Pgs. 150-151, Intersct. No. 36 | Pgs. 18-23, Sect. on *Pedestrians*<br>P. 29, Para. 5<br>Pgs. 252-254, Sect. on *Pedestrian Facilities*<br>Pg. 404, Para. 1<br>Pgs. 369-370, Sect. on *Crossing Warning Signs*<br>Pg. 153, Sect. on *Non-Motorist Safety*<br>Pgs. 381-382, Sect. on *Crosswalks*<br>Pgs. 421-422, Sect. on *Pedestrian Signal Heads*<br>Pg. 450, Sect. on *Pedestrian Countdown Signals* |

2007). Crash types that predominantly involve aging pedestrians at intersections are as follows (Blomberg and Edwards, 1990):

- **Vehicle turn/merge**—The vehicle turns left or right and strikes the pedestrian.
- **Intersection dash**—A pedestrian appears suddenly in the street in front of an oncoming vehicle at an intersection.
- **Multiple threat**—One or more vehicles stop in the through lane, usually at a crosswalk at an unsignalized intersection. The pedestrian steps in front of the stopped vehicle(s) and into the path of a through vehicle in the adjacent lane.
- **Bus-stop related**—The pedestrian steps out from in front of a stopped bus and is struck by a vehicle moving in the same direction as the bus.
- **Pedestrian trapped**—At a signalized intersection, a pedestrian is hit when a traffic signal turns red (for the pedestrian) and cross-traffic vehicles start moving.
- **Nighttime**—A pedestrian is struck at night when crossing at an intersection.

Earlier analyses of over 5,300 pedestrian crashes occurring at urban intersections indicated that a significantly greater proportion of pedestrians age 65 and older were hit at signalized intersections than any other group (Robertson, Berger, and Pain, 1977).

Age-related diminished capabilities, which may make it more difficult for aging pedestrians to negotiate intersections, include decreased contrast sensitivity and visual acuity, reduced peripheral vision and "useful field of view," decreased ability to judge safe gaps, slowed walking speed, and physical limitations resulting from arthritis and other health problems. Aging pedestrian problem behaviors include a greater likelihood to delay before crossing, to spend more time at the curb, to take longer to cross the road, and to make more head movements before and during crossing (Wilson and Grayson, 1980).

Older and Grayson (1972) reported that although aging pedestrians involved in crashes looked more often than the middle-aged group studied, over 70 percent of the adults struck by a vehicle reported not seeing it before impact. Job, et al. (1992) found that pedestrians over age 65 looked less often during their crossings than did younger pedestrians. In a survey of aging pedestrians (average age of 75) involved in crashes, 63 percent reported that they failed to see the vehicle that hit them, or to see it in time to take evasive action (Sheppard and Pattinson, 1986). Knoblauch, et al. (1995) noted that difficulty seeing a vehicle against a (complex) street background may occur with vehicles of certain colors, causing them to blend in with their background. This is especially problematic for aging persons with reduced contrast sensitivity, who require a higher contrast for detection of the same targets than younger individuals, and who also have greater difficulty dividing attention between multiple sources and selectively attending to the most relevant targets. In addition, the loss of peripheral vision increases an aging pedestrian's chances of not detecting approaching and turning vehicles from the side.

Reductions in visual acuity make it more difficult for aging pedestrians to read the crossing signal. In a survey of aging pedestrians in the Orlando, Florida area, 25 percent of the participants reported difficulty seeing the crosswalk signal from the opposite side of the street (Bailey, et al., 1992). Aging pedestrians wait for longer gaps between vehicles before attempting to cross the road. In one study, approximately 85 percent of the pedestrians age 60 and older required a minimum gap of 9 s before crossing the road, while only 63 percent of all pedestrians required this minimum gap size duration (Tobey, Shungman, and Knoblauch, 1983). The decline in depth perception may contribute to aging persons' reduced ability to judge gaps in oncoming traffic. It may be concluded from these studies that aging pedestrians do not process information (presence, speed, and distance of other vehicles) as efficiently as younger pedestrians, and therefore require more time to reach a decision. Other researchers have observed that aging pedestrians do not plan their traffic behavior, are too trusting about traffic rules, fail to check for oncoming traffic before crossing at intersections, underestimate the speed of approaching vehicles, and follow other pedestrians without first checking for conflicts before crossing (Jonah and Engel, 1983; Mathey, 1983).

With increasing age, there is a concurrent loss of physical strength, joint flexibility, agility, balance, coordination and motor skills, and stamina. These losses contribute to slower walking speeds and difficulty negotiating curbs. In addition, aging persons often fall as a result of undetected surface irregularities in the pavement and misestimation of curb heights. This results from a decline in contrast sensitivity and depth perception. In an assessment of 81 aging residents (ages 70–97) to examine susceptibility to falling, 58 percent experienced a fall in the year following clinical assessment (Clark, Lord, and Webster, 1993). Impaired cognition, abnormal reaction to any push or pressure, history of palpitations, and abnormal stepping were each associated with falling. Knoblauch, et al. (1995) reported that locating the curb accurately and placing the foot is a matter of some care, particularly for the elderly, the very young, and those with physical disabilities.

The studies discussed below define the types of crashes in which aging pedestrians are most likely to be involved, and under what conditions the crashes most frequently occur. In addition, the specific geometric characteristics, traffic control devices (including signs, signals, and markings), and pedestrian signals that seem to contribute to aging pedestrians' difficulties at intersections are discussed. Zegeer and Zegeer (1988) stressed the importance of "tailoring" the most appropriate traffic control measures to suit the conditions at a given site. The effect of any traffic control measure is highly dependent on specific locational characteristics, such as traffic conditions (e.g., volumes, speeds, turning movements), pedestrian volumes and pedestrian mix (e.g., young children, college students, aging adults, persons with physical disabilities), street width, existing traffic controls, area type (e.g., rural, urban, suburban), site distance, crash patterns, presence of enforcement, and numerous other factors.

Harrell (1990) used distance stood from the curb as a measure of pedestrian risk for intersection crossing. Observations of 696 pedestrians divided among three age groups (age 30 and under, ages 31–50, and age 51 and older) showed that the oldest group stood the farthest from the curb, that they stood even farther back under nighttime conditions, and that aging females stood the farthest distance from the curb. The author used these data to dispel the findings in the literature that aging pedestrians are not cognizant of the risks of exposure to injury from passing vehicles. Similarly, it may be argued that this behavior keeps them from detecting potential conflict vehicles and makes speed and distance judgments more difficult for them, while limiting their conspicuity to approaching drivers who might otherwise slow down if pedestrians were detected standing at the curbside at a crosswalk.

A study of pedestrian crashes conducted at 31 high-pedestrian crash sections in Maryland between 1974 and 1976 showed that pedestrians age 60 and older were involved in 53 (9.6 percent) of the crashes, and children younger than age 12 showed the same proportions. The pedestrians age 60 and older accounted for 25.6 percent of the fatal crashes. Compliance with traffic control devices was found to be poor for all pedestrians at all study locations; it was also found that most pedestrians keyed on the moving vehicle rather than on the traffic and pedestrian control devices. Only when the traffic volumes were so high that it was impossible to cross did pedestrians rely on traffic control devices (Bush, 1986).

Garber and Srinivasan (1991) conducted a study of 2,550 crashes involving pedestrians that occurred in the rural and urban areas of Virginia to identify intersection geometric characteristics and intersection traffic control devices that were predominant in crashes involving aging pedestrians. Crash frequency by location and age for the crashes within the cities showed that while the highest percentage of crashes involving pedestrians age 59 and younger occurred within 150 ft from the intersection stop line, the highest percentage of crashes for pedestrians age 60 years and older (51.8 percent) occurred within the intersection.

Knoblauch, et al. (1995) reported that, compared with younger pedestrians, aging adults are overinvolved in crashes while crossing streets at intersections. In their earlier analysis of the national Fatal Analysis Reporting System (FARS) data for the period 1980–1989, 32.2 and 35.3 percent of the deaths for pedestrian ages 65–74 and age 75 and older, respectively, occurred at intersections (Reinfurt, et al., 1992). This compared with 22 percent or less for the younger age groups. Analysis of the North Carolina motor vehicle crash file for 1980–1990 displayed somewhat smaller percentages, but showed the trend of increasing pedestrian crashes at intersections as age increased. Further analysis of the North Carolina database showed that pedestrians age 65 and older as well as those ages 45–64 experienced 37 percent of their crashes on roadways with four or more lanes. This compares with 23.7 percent for pedestrians ages 10–44 and 13.6 percent for those age 9 and younger. The highest number of pedestrian-vehicle crashes occurred when the vehicle was going straight (59.7 percent), followed by a vehicle turning left (17.2 percent), and a vehicle turning right (13.3 percent). Right-turn crashes accounted for 18.9 percent of crashes with pedestrians ages 65–74, compared with 14.2 percent for pedestrians age 75 and older. The oldest pedestrian group was the most likely to be struck by a left-turning vehicle; they accounted for 23.9 percent of the crashes, compared with 18.1 percent of those ages 65–74 and 15.8 percent of those ages 45–64.

Knoblauch, et al. (1995) conducted a study to determine if pedestrian comprehension of and compliance with pedestrian signals could be improved by installing a placard that explained the three phases of pedestrian signals. They used findings from: (1) a focus group and workshop conducted in Baltimore, Maryland, with 13 participants ages 19–62 and (2) questionnaires administered to 225 individuals ages 19–80 and older at four Virginia Department of Motor Vehicles offices to determine the most effective message content and format for a pedestrian signal education placard. The newly developed placard was installed at six intersections in Virginia, Maryland, and New York. Observational studies of more than 4,300 pedestrians during 600 signal cycles found no change in pedestrian signal compliance. However, results from questionnaires administered to 92 subjects at Departments of Motor Vehicles in Virginia, Maryland, and New York indicated a significant increase in understanding of the phases of the pedestrian signal. The authors concluded that although pedestrian crossing behavior is more influenced by the presence or absence of traffic than the signal indication, the wording on the placard was based on quantitative procedures using a relatively large number of subjects and should be used where signal educational placards are installed. The wording of the educational placard recommended by Knoblauch, et al. (1995) for one-stage and two-stage crossings is shown in Figure 80. The *MUTCD* has adopted similar wording, which is shown as part of Recommendation C of Design Element 16.

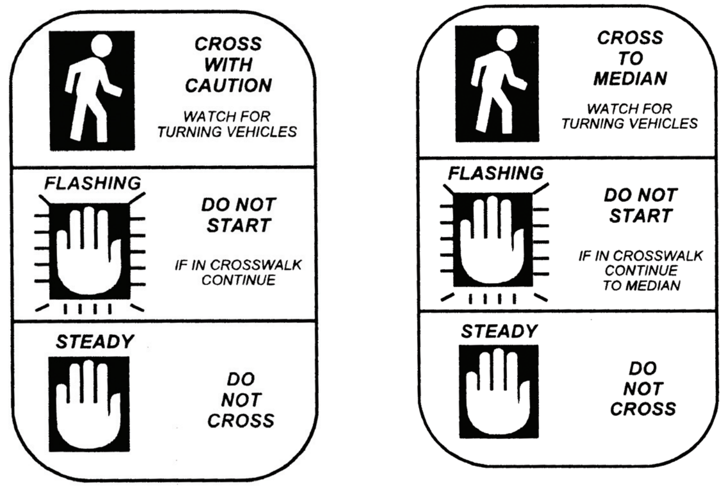



**Figure 80.** Recommended Wording For Educational Placards For One-Stage And Two-Stage Crossings (Knoblauch et al., 1995)

Zegeer and Cynecki (1986) tested a LOOK FOR TURNING VEHICLES pavement marking in a crosswalk, as a low-cost countermeasure to remind pedestrians to be alert for turning vehicles, including right-turn-on-red (RTOR) vehicles. Results showed an overall reduction in conflicts and interactions for RTOR vehicles and also for the total number of turning vehicles. Even with an RTOR prohibition, approximately 20 percent of motorists committed an RTOR violation when given the opportunity (Zegeer and Cynecki, 1986). Of those violations, about 23.4 percent resulted in conflicts with pedestrians or vehicles on the side street.

Zegeer, Opiela, and Cynecki (1982) conducted a crash analysis to determine whether pedestrian crashes are significantly affected by the presence of pedestrian signals and by different signal timing strategies. They found no significant differences in pedestrian crashes between intersections that had standard-timed (concurrent walk) pedestrian signals compared with intersections that had no pedestrian signals. Concurrent or standard timing provides for pedestrians to walk concurrently (parallel) with traffic flow on the WALK signal. Vehicles are generally permitted to turn right (or left) on a green light while pedestrians are crossing on the WALK interval. Other timing strategies include early release timing, late release timing, and exclusive timing. In early release timing—also termed a "leading pedestrian interval"—the pedestrian WALK indication is given before the parallel traffic is given a green light, allowing pedestrians to get a head start into the crosswalk before vehicles are permitted to turn. In late release timing, the pedestrians are held until a portion of the parallel traffic has turned. Exclusive timing is a countermeasure where traffic signals are used to stop motor vehicle traffic in all directions simultaneously for a phase each cycle, while pedestrians are allowed to cross the street. "Barnes Dance" or "scramble" timing is a type of exclusive timing where pedestrians may also cross diagonally in addition to crossing the street. Exclusive timing is intended to virtually eliminate turning traffic or other movements that conflict with pedestrians while they cross the street. In the Zegeer et al. (1982) analysis, exclusive-timed locations were associated with a 50 percent decrease in pedestrian crashes for intersections with moderate to high pedestrian volumes when compared with both standard-timed intersections and intersections that had no pedestrian signals. However, this timing strategy causes excessive delays to both motorists and pedestrians. Aging road users (age 65 and older) recommended the following pedestrian-related countermeasures for pedestrian signs and signals, during focus group sessions held as a part of the research conducted by Knoblauch, et al. (1995): (1) reevaluate the length of pedestrian walk signals due to increasingly wider highways, (2) implement more Barnes Dance signals at major intersections, and (3) provide more YIELD TO PEDESTRIANS signs in the vicinity of heavy pedestrian traffic.

Several studies have been conducted to determine whether regulatory signing aimed at turning motorists could reduce conflicts with pedestrians. Zegeer, Opiela, and Cynecki (1983) found that the regulatory sign YIELD TO PEDESTRIANS WHEN TURNING was effective in reducing conflicts between turning vehicles and pedestrians. They recommended that this sign be added to the *MUTCD* as an option for use at locations with a high number of pedestrian crashes involving turning vehicles. Zegeer and Cynecki (1986) found that the standard NO TURN ON RED sign with the supplementary WHEN PEDESTRIANS ARE PRESENT message was effective at several sites with low to moderate right-turn vehicle volumes. However, it was less effective when RTOR volumes were high. It was therefore recommended that the supplemental message WHEN PEDESTRIANS ARE PRESENT be added to the *MUTCD* as an accepted message that may be used with an NTOR sign when right-turn volume is light to moderate and pedestrian volumes are light or occur primarily during intermittent periods, such as in school zones. The supplemental message when added to the NTOR sign with the circular red symbol reduced total pedestrian conflicts at one site and increased RTOR usage (as desired, from 5.7 percent to 17.4 percent), compared with full-RTOR prohibitions. It was recommended that the supplemental message be added to the *MUTCD* for the NTOR sign with the circular red symbol, under low to moderate right-turn vehicle volumes and light or intermittent pedestrian volumes.

In the late 1990s, Abdulsattar, Tarawneh, and McCoy (1996) found that the TURNING TRAFFIC MUST YIELD TO PEDESTRIANS sign was effective in significantly reducing pedestrian-vehicle conflicts during right turns. The sign was installed at six marked crosswalks in Nebraska, where right-turn vehicle-pedestrian conflict data were collected before and after its installation in an observational field study. For the six study crosswalks combined, a conflict occurred in 51 percent of the observations in the before period, but in only 38 percent of the observations during the after period. The reductions in pedestrian-vehicle conflicts across the observation sites ranged from 15 to 30 percent, and were statistically significant.

The type of markings used to define a crosswalk can also make a difference in driver compliance. Fitzpatrick, et al (2010) investigated the relative daytime and nighttime visibility of three crosswalk marking patterns: transverse lines, continental, and bar pairs. The conclusions from their study were as follows:

- The detection distances to continental and bar pairs are statistically similar. The detection distances to continental and bar pairs are statistically different from transverse markings.

- For the existing midblock locations, a general observation is that the continental marking was detected at about twice the distance upstream as the transverse marking during daytime conditions. This increase in distance reflects 8 s of increased awareness of the crossing for a 30-mph operating speed.
- The results of the appearance ratings of the markings on a scale of A to F mirrored the findings from the detection distance evaluation. Participants preferred the continental and bar pairs markings over the transverse markings.
- Participants gave the continental and bar pairs markings similar ratings during both the day and night. However, the transverse marking ratings differed based on the light level. The participants gave slightly better ratings, although still worse than continental or bar pairs markings, for transverse markings during the nighttime as compared to the daytime. The lower ratings during daylight conditions could be due to sun glare or shadow issues mentioned by the participants.

Considering pedestrian walking times, section 4E.06 of the *MUTCD* (2009) indicates that a pedestrian change interval consisting of a flashing UPRAISED HAND (symbolizing DONT WALK) signal indication shall begin immediately following the WALKING PERSON (symbolizing WALK) signal indication. The pedestrian clearance time should be sufficient to allow a pedestrian crossing in the crosswalk who left the curb or shoulder at the end of the WALKING PERSON (symbolizing WALK) signal indication to travel at a walking speed of 3.5 feet per second to at least the far side of the traveled way or to a median of sufficient width for pedestrians to wait. The *MUTCD* further states that, "where pedestrians who walk slower than 3.5 ft per second, or pedestrians who use wheelchairs, routinely use the crosswalk, a walking speed of less than 3.5 ft per second should be considered in determining the pedestrian clearance time."

Aging pedestrian walking speed has been studied by numerous researchers. TEH (1999) reports walking speeds obtained by Perry (1992) for physically impaired pedestrians. Average walking speeds for pedestrians using a cane or crutch were 2.62 ft/s; for pedestrians using a walker, 2.07 ft/s; for pedestrians with hip arthritis, 2.24 to 3.66 ft/s; and for pedestrians with rheumatoid arthritis of the knee, 2.46 ft/s. Sleight (1972) determined that there would be safety justification for use of walking speeds between 3.0 to 3.25 ft/s, based on the results of a study by Sjostedt (1967). In this study, average adults and the elderly had walking speeds of 4.5 ft/s; however, 20 percent of the aging pedestrians crossed at speeds slower than 4.0 ft/s. The 85th percentile aging pedestrian walking speed in that study was 3.4 ft/s. A 1982 study by the Minnesota Department of Transportation found that the average walking speed of aging pedestrians was 3.0 ft/s. In a study conducted in Florida, it was found that a walking speed of 2.5 ft/s would accommodate 87 percent of the aging pedestrians observed (TEH, undated). Weiner (1968) found an average rate for all individuals of 4.22 ft/s, and of 3.7 ft/s for women only. A Swedish study by Dahlstedt (undated), using pedestrians age 70 and older, found that the 85th percentile comfortable crossing speed was 2.2 ft/s.

Interviews and assessments were conducted with 1,249 persons age 72 and older from the New Haven, CT community of Established Populations for Epidemiologic Studies of the Elderly, to determine walking speeds and self-reported difficulty with crossing the street as pedestrians (Langlois, et al., 1997). The study population excludes persons in nursing homes or hospitals. In a telephone interview, 11.4 percent indicated that they had difficulty crossing the street. Reasons provided included insufficient time to cross and difficulty with right-turning vehicles. The mean walking speed for those reporting difficulty crossing the street was 1.25 ft/s, and for those reporting no difficulty was 1.94 ft/s. Only 7.3 percent of the population had measured walking speeds 3 ft/s, and less than 1 percent had walking speeds of 4.0 ft/s.

Hoxie and Rubenstein (1994) measured the crossing times of older and younger pedestrians at a 71.69-ft wide intersection in Los Angeles, CA, and found that aging pedestrians (age 65 and older) took significantly longer than younger pedestrians to cross the street. In this study, the average walking speed of the older pedestrians was 2.8 ft/s, with a standard deviation of 0.56 ft/s); the average speed of the younger pedestrians was 4.2 ft/s, with a standard deviation of 0.56 ft/s). Of the 592 older pedestrians observed, 27 percent were unable to reach the curb before the light changed to allow cross traffic to enter the intersection, and one-fourth of this group were stranded at least a full traffic lane away from safety. A study of crossing speeds by Coffin and Morrall (1995) limited to 15 pedestrians age 60 or older, at each of six crosswalk locations in Calgary, Canada, documented an 85th percentile walking speed of 3.28 ft/s for midblock crosswalks and 4.0 ft/s for crosswalks at signalized intersections. The authors noted that the walking speed of aging pedestrians varies according to functional classification, gender, and intersection type, and stated that approximately 95 percent of pedestrians in this study would be accommodated using a design walking speed of 2.62 ft/s.

Much more extensive observations of pedestrian crossing behavior were conducted at two crosswalk locations at two intersections in Sydney, Australia (a major 6-lane divided street, and a side street), where the design crossing speed was changed from 4.0 ft/s to 3.0 ft/s (Job, et al., 1994). Observations were made during 3,242 crossings during a baseline period (4.0 ft/s design crossing speed) and 2 and 6 weeks after the flashing DONT WALK interval was extended to allow for the slower crossing speed under study. This study was conducted to evaluate countermeasures to address the over-representation of pedestrians age 70 and older in crashes in the greater Sydney metropolitan area. At all crosswalk locations, the WALK phase remained a constant 6 s, and the clearance interval was extended from 14 s to 20 s at one intersection 59.7 ft wide, and from 18 to 20 s at the other intersection measuring 79.4 ft wide. Observations were conducted for 2,377 pedestrians ages 20-59, 511 pedestrians ages 60-65, and 354 pedestrians age 66 and older. The number of males and females was approximately equal. For both intersections, a general trend showed that the older the pedestrian, the longer the crossing time. Also, females crossed more slowly than males in all age groups. At the wider intersection, mean crossing speeds were 4.9 ft/s for pedestrians ages 20-59; 4.27 ft/s for pedestrians ages 60-65, and 3.6 ft/s for pedestrians age 66 and older. The mean walking speed for females age 66 and older was 3.28 ft/s. The authors note that the assumed walking speed of 4.0 ft/s leaves almost 15 percent of the total population walking below the assumed speed. Extending the clearance interval resulted in a decrease in the percentage of pedestrian-vehicle conflicts, from 4 percent in the baseline period to 1 percent in the experimental period at 2 weeks and also 1 percent at 6 weeks, at the wider intersection. This difference was significant at the $p \leq .001$ level. Observed changes in pedestrian-vehicle conflicts at the smaller intersection were contaminated by an increase in the proportion of pedestrians (in the young and young/middle age groups only) who crossed illegally (i.e., began to cross during the flashing DONT WALK phase); consequently, sustained differences between the baseline and experimental phases were not demonstrated. At the conclusion of this research, the authors recommended a reduction in the design walking speed from 4.0 ft/s to 3.0 ft/s at locations where there is significant usage by aging pedestrians.

Knoblauch, et al. (1995) conducted a series of field studies to quantify the walking speed, start-up time, and stride length of pedestrians younger than age 65 and pedestrians 65 and older under varying environmental conditions. Analysis of the walking speeds of 3,458 pedestrians younger than age 65 and 3,665 pedestrians age 65 and older crossing at intersections showed that the mean walking speed for younger pedestrians was 4.95 ft/s and 4.11 ft/s for older pedestrians. The 15th percentile speeds were 4.09 ft/s and 3.19 ft/s for younger and older pedestrians, respectively. These differences were statistically significant. Among the many additional findings with regard to walking speed were the following:

- pedestrians who start on the WALK signal walk slower than those who cross on either the flashing DONT WALK or steady DONT WALK;
- the slowest walking speeds were found on local streets while the faster walking speeds were found on collector-distributors;
- sites with symbolic pedestrian signals had slower speeds than sites with word messages;
- pedestrians walk faster where RTOR is not permitted, where there is a median, and where there are curb cuts;
- faster crossing speeds were found at sites with moderate traffic volumes than at sites with low or high vehicle volumes.

For design purposes, a separate analysis was conducted by Knoblauch, et al. (1995) for pedestrians who complied with the signal, as they tended to walk more slowly than those who crossed illegally. The mean crossing speed for the young compliers was 4.79 ft/s and for the older compliers was 3.94 ft/s. The 15th percentile speed for the young compliers was and was 3.08 ft/s for the older compliers. Older female compliers showed the slowest walking speeds, with a mean speed of 3.74 ft/s and a 15th percentile of 2.97 ft/s. One of the slowest 15th percentile values (2.94 ft/s) was observed for older pedestrians crossing snow-covered roadways. It was concluded from this research that a mean design speed of 4.0 ft/s is appropriate, and where a 15th percentile is appropriate, a walking speed of 3.0 ft/s is reasonable. It was also determined by Knoblauch, et al. (1995) that the slower walking speed of older pedestrians is due largely to their shorter stride lengths. The stride lengths of all older pedestrians are approximately 86 percent of those of younger pedestrians.

Knoblauch, et al. (1995) also measured start-up times for younger and older pedestrians who stopped at the curb and waited for the signal to change before starting to cross. The mean value for younger pedestrians was 1.93 s compared with 2.48 s for older pedestrians. The 85th percentile value of 3.06 s was obtained for younger pedestrians, compared with 3.76 s for older pedestrians. For design purposes, the authors concluded that a mean value of 2.5 s and an 85th percentile value of 3.75 s would be appropriate.

These data specifically did not include pedestrians using a tripod cane, a walker, or two canes; people in wheelchairs; or people walking bikes or dogs. The *MUTCD* (2009) states that the walk interval should be at least 7 s long so that pedestrians will have adequate opportunity to leave the curb or shoulder before the pedestrian clearance time begins (where pedestrian volumes and characteristics do not require 7 s, walk intervals as short as 4 s may be used). Parsonson (1992) noted that the reason this much time is needed is because many pedestrians waiting at the curb watch the traffic, and not the signals. When they see conflicting traffic coming to a stop, they will then look at the signal to check that it has changed in their favor. If they are waiting at a right-hand curb, they will often take time to glance to their left rear to see if an entering vehicle is about to make a right turn across their path. Parsonson reported that a pedestrian reasonably close to the curb and alert to a normal degree can be observed to require up to 4 or 5 s for this reaction, timed from when the signal changes to indicate that it is safe to cross, to stepping off the curb. It may be remembered that aging pedestrians stand farther away from the curb, and may or may not be alert. In addition, there are many drivers who run the amber and red signals, and it is prudent for pedestrians to "double-check" that traffic has indeed obeyed the traffic signal, and that there are no vehicles turning right on red or (permissive) left on green before proceeding into the crosswalk. Because aging persons have difficulty dividing attention, this scanning and decision-making process requires more time than it would for a younger pedestrian. Parsonson (1992) reported that the State of Delaware has found that pedestrians do not react well to the short WALK and long flashing DON'T WALK timing pattern. They equate the flashing with a vehicle yellow period. The Florida Department of Transportation and the city of Durham, Ontario, provide sufficient WALK time for the pedestrian to reach the middle of the street, so that the pedestrian will not turn around when the flashing DONT WALK begins.

Fitzpatrick, et al (2006) studied characteristics of walking speed associated with different roadway conditions and pedestrian characteristics. Data on pedestrian crossings were grouped into "young" (between the ages of 15 and 60) and "old" (older than 60). A total of 3,155 pedestrian crossings were recorded during the study. Of that, 81 percent (2,552 pedestrians) were observed as "walking." The remaining 19 percent of the pedestrians (603) were observed to be running, both walking and running during the crossing, or using some form of assistance (e.g., skates or bicycles). Those 603 data points were not included in the analyses, nor were 107 walking pedestrians whose ages could not be estimated and six pedestrians whose genders could not be determined. For the remaining crossings, they determined that the walking speed values for older pedestrians were lower than those for younger people. For young pedestrians, the 15th percentile walking speed was 3.77 ft/s (1.15 m/s). Older pedestrians had a slower walking speed with the 15th percentile being 3.03 ft/s (0.9 m/s). The average walking speed was 4.25 and 4.74 ft/s (1.3 and 1.45 m/s) for old and young pedestrians, respectively.

Most recently, TEH and AAA Foundation for Traffic Safety (Stollof, McGee, and Eccles, 2007) published a study on pedestrian walking rates of aging persons and the effects of slower rates on signal timing operations. The study included a review of past studies (many of which were previously discussed) and the collection of additional observational data in six cities throughout the U.S. The results showed the 15th percentile of aging pedestrians to range between 3.4 and 3.8 ft/s. The study recommended a walking speed of 3.5 ft/s. However, additional guidance was provided to use a walking speed of 3.0 ft/s at locations where pedestrians are routinely crossing at a slower pace. Under those conditions, it is also recommended that the crossing distance used in the calculation of the WALK and pedestrian clearance interval be measured from 6 ft back of the edge of curb (starting location assumption) to the far side of the travel way being crossed. Recommendation A of this Design Element 16 reflects the guidance for accommodating slower pedestrians.

One strategy that has appeared to offer promise in assisting pedestrians who are slower or more reluctant to cross when there is a perceived likelihood of conflict with turning vehicles is the leading pedestrian interval (LPI). A LPI is a brief, exclusive signal phase dedicated to pedestrian traffic. Van Houten, et al. (1997) investigated the effects of a 3-s LPI on pedestrian behavior and conflicts with turning vehicles at three urban intersections in St. Petersburg, FL. In the study, pedestrian-vehicle conflicts were observed during a baseline period, where the signal phasings at each intersection provided the onset of the pedestrian WALK signal and the onset of the green signal for turning vehicles concurrently. During the experimental phase, a 3-s LPI was installed to release pedestrian traffic three seconds before turning vehicles. The LPI was implemented using a modified, solid-state plug-in signal load switch that had the capacity to delay the change of the traffic signal phase from red to green. Pedestrians estimated to be age 65 and older were scored separately from those estimated to be age 12 and older. A total of 1,195 seniors and 3,680 nonseniors were observed across all three sites during the baseline condition. During the LPI condition, 860 seniors and 4,288 nonseniors were observed.

Observers collected data between 8:30 a.m. and 5:00 p.m., and scored the number of pedestrians who left the curb within 2 s before the start of the WALK indication, within 3 s after onset of the WALK indication, during the remainder of the WALK cycle, and during the flashing DON'T WALK indication. The number of conflicts was scored for each of these intervals, defined as any situation where a driver engaged in abrupt braking or either the driver or pedestrian took sudden evasive action to avoid a collision. Conflicts were scored separately for right-tuning and left-turning vehicles. Other data of interest included the number of times that a pedestrian yielded to a turning vehicle by stopping or waving the vehicle through, and the distance covered by the pedestrian during the LPI condition. The intersection geometries included the following: (1) one-way traffic with four northbound lanes by two-way traffic with one lane in each direction and diagonal parking (north and west crosswalks were observed because both included left-on-green conflict potential); (2) one-way traffic with four southbound lanes by two-way traffic with one lane in each direction and diagonal parking (south and east crosswalks were observed because both included left-on-green conflict potential); and (3) two-way traffic with two lanes in each direction by two-way traffic with two lanes in each direction (all four crosswalks were observed).

The number of conflicts per 100 pedestrians who started crossing during a defined 5-s begin-walk period (which began 2 s before and ended 3 s after the onset of the WALK indication) showed that during the baseline period, the number of conflicts averaged 3.0, 2.1, and 3.3 for the three sites. After the introduction of the LPI, the number of conflicts averaged 0.1, 0.1, and 0.2 for the three sites. The likelihood of conflict was significantly lower during the LPI condition than during the baseline condition for both left- and right-turning vehicles; the odds of conflict for pedestrians leaving the curb during the begin-walk period were reduced by approximately 95 percent. The reduction in odds conflict for seniors as a function of an LPI phase (89 percent reduction) was not significantly different from that of their younger counterparts (97 percent reduction). There was no significant effect of LPI on the odds of conflict for pedestrians leaving the curb after the begin-walk period, indicating that an LPI does not move conflicts to a later phase in the WALK interval.

The LPI also had the effect of significantly reducing the number of pedestrians yielding to turning vehicles; the odds of a pedestrian yielding to a turning vehicle were reduced by approximately 60 percent. Van Houten et al. (1997) indicate that once pedestrians were in the crosswalk, drivers acknowledged their presence and were more likely to yield the right of way. Also, they state that pedestrians occupying the crosswalk were more visible to drivers who were waiting for the light to change than they would have been had the drivers and pedestrians been released concurrently. The final measure of interest was the mean distance traveled by the lead pedestrian during the LPI condition, which averaged 8.5 ft. The authors state that this distance (which is greater than one-half of a lane width) appears sufficient for pedestrians to assert their right of way ahead of turning vehicles, and reduces conflicts that may result when pedestrians and vehicles begin to move at the same time.

In terms of research on the countdown pedestrian signal, only one formal study was found which attempted to quantify the effects on pedestrian crashes after converting standard WALK/DONT WALK signals to the countdown signals. A study by Markowitz, et al. (2006) involved installing countdown signals at about 700 of the 1,100 signalized intersections in San Francisco. An initial pilot evaluation was performed at nine sites, which found that pedestrian injury crashes dropped from 27 to 13 after countdown signal installation, a 52% reduction, with a slight decline in pedestrian crashes for the primary untreated comparison group. The authors cited regression-to-the-mean as a factor in this crash reduction, but noted that the decline in pedestrian injury crashes was consistently greater with the countdown sites than the non-countdown sites. The authors further concluded that "…although the 53% reduction in collisions overstates the impact of the countdown, a real reduction did occur."

As a part of that Markowitz article, the authors also conducted a behavioral evaluation of the countdown signals at eight intersections and found that after installing the countdown signals, there was a significant reduction in the percentage of pedestrians still in the crosswalk when the signal turned to red. There was also a significant reduction in the percentage of pedestrians who were running or had an aborted crossing after the countdown signal installation. There was a small increase in the percentage of pedestrians who left early (i.e., on the flashing hand or solid hand) but that increase was not statistically significant.

A follow-up crash-based analysis by the authors was performed which involved a sample of 579 intersections which involved converting traditional pedestrian signal heads with countdown pedestrian heads and the use of 204 untreated control sites. Based on an average of pedestrian crashes in a one-year before period (average for years 2001 and 2002) and a one-year after period (2003), pedestrian crashes dropped by 25% at the "treated" sites, compared to an increase of 16% at the "Untreated" sites. The authors add that: "This provides some statistical support to popular claims that the addition of countdown devices has improved safety."

Numerous other studies have been conducted in recent years to evaluate the effects of countdown signals on pedestrian and motorist behavior, conflicts between pedestrians and motorists, and/or surveys which ask pedestrians their opinions about countdown signals. For example, Eccles, Tao, and Mangum (2003) evaluated countdown pedestrian signals at 5 intersections in Montgomery County, Maryland. The results found that of the 20 intersection approaches, the proportion of pedestrians entering the street during the flashing or steady hand decreased at 13 of the approaches (6 decreases were significant) with a significant increase at 2 approaches. Of the 4 approaches where pedestrian/vehicle conflicts were recorded, pedestrian-vehicle conflicts decreased at all four intersections after installation of the countdown signals (significant at the 0.05 level).

A study by Rousseau and Davis (2003) compared 6 display-timing strategies with the standard *MUTCD* pedestrian signal to gain information on pedestrian understanding. A total of 134 participants were tested in three age groups: 18 to 29, 30 to 59, and 60 and above. A higher percentage of aging pedestrians (compared to other age groups) were found to have difficulties in understanding the conventional pedestrian signal displays. The countdown signal display resulted in a substantial improvement in the understanding of the pedestrian signal display by aging adults.

## 16 Roundabouts

Countermeasures that have been suggested to reduce the occurrence of aging driver crashes at intersections have included changes to intersection operations (e.g., protected left-turn phases, elimination of RTOR, redundant signing, etc.) and geometric design (e.g., full positive offset of opposite left-turn lanes, increases in turning radius for right turns, etc.). One proposed solution to reduce not only the frequency but also the severity of crashes at intersections is the installation of a modern roundabout (Harkey, 1995; Jacquemart, 1998). Modern roundabouts are an intersection design that has been in use in Europe and Australia for decades, but have more recently come into their own in the United States. Over a 10-15 year period beginning in the late 1990s interest in roundabouts has increased exponentially in this country, and more jurisdictions have installed them as their benefits have become better known. FHWA released two Roundabout Guides (Robinson, et al. 2000; Rodegerdts, et al. 2010) during that period of time, and a number of other research projects have explored the various operational and safety benefits of roundabouts. In addition, FHWA considers roundabouts to be a Proven Safety Countermeasure (FHWA Office of Safety 2012).

There are treatments currently within the Handbook that discuss features at roundabout intersections that can benefit aging drivers; however, roundabouts themselves can be a beneficial treatment over a traditional stop- or signal-controlled intersection if properly designed to meet the needs of that location. A great deal of existing research on roundabouts has not been conducted specifically from the perspective of the aging road user, but the benefits apply to drivers and pedestrians of any age. It may be necessary to provide focused educational efforts to aging drivers when roundabouts are introduced into a community, so that unfamiliarities with that design can be at least somewhat mitigated. Indeed, FHWA's Roundabout Outreach and Education Toolbox (FHWA Office of Safety 2013) provides a search feature that includes "older drivers" as a searchable target audience.

This countermeasure, it has been suggested, addresses problems that aging drivers experience in judging speeds and gaps, understanding operational rules at complex intersections, and maneuvering through turns. Specifically, the following advantages of roundabouts for aging road users have been postulated:

- Reductions in the speed of vehicles entering the intersection/circle— this makes it easier to choose an acceptable gap to merge into, removes the need to accelerate quickly which occurs after a conventional right turn, and results in lower severity crashes with less serious injuries.
- The left turn is completely eliminated.
- The larger curb radius improves maneuverability.

**Table 34.** Cross-References of Related Entries for Roundabouts.

| Applications in Standard Reference Manuals | | | | |
|---|---|---|---|---|
| ***MUTCD*** **(2009)** | **AASHTO** *Green Book* **(2011)** | **Highway Capacity Manual (2010)** | **Roundabouts: An Informational Guide, Second Edition (2010)** | |
| *Sect. 2B.43 through 2B.45, 3B.16 Chapt. 3C* | Pgs. 9-167 through 9-176, Sect. 9-10 *Roundabout Design* | Chapter 21 | Pg. 1-7, Exhibit 1-5, Items c & d<br>Pg. 1-11, Exhibit 1-8, Items g and h<br>Pg. 1-11, Exhibit 1-8, Item f<br>Pg. 1-12, Exhibit 1-9<br>Pg. 1-13, Sect. 1.3.2<br>Pgs. 2-3 through 2-4, Sect. 2.2.1<br>Pgs. 2-15 through 2-17, Sect. 2.3.2<br>Pgs. 2-18 through 2-19, Sect. 2.3.4<br>Pg. 3-5, Exhibit 3-1 (Determine Preliminary Lane Numbers, and Determine the Space Requirements)<br>Pg. 3-8, first two bullets on pg.<br>Pgs. 3-21 through 3-24, Sect. 3.5.1<br>Pg. 3-30, third bullet<br>Pg. 3-26, Sect. 3.5.3 and Pg. 3-27, Exhibit 3-17<br>Pgs. 4-4 and 4-5, Sect. 4.2.1<br>Pgs. 4-10 through 4-19, Sects. 4.4 through 4.6<br>Pg. 5-4, 1st Bullet<br>Pgs. 5-6 through 5-7, Sect. 5.2.1 | Pgs. 5-10 through 5-12, Sect. 5.2.3<br>Pg. 5-15, Exhibit 5-9<br>Pg. 5-19, Para. 1<br>Pg. 5-21, last paragraph<br>Pgs. 5-22 through 5-24, Sect. 5.4.1<br>Pg. 6-9, Exhibit 6-2 (*Entry Width, Circulatory Roadway Width, & Inscribed Circle Diameter*)<br>Pgs. 6-11 through 6-13, Sect. 6.2.3<br>Pgs. 6-17 through 6-18, Sect. 6.3.1<br>Pgs. 6-24 through 6-25, Sects. 6.4.2 and 6.4.3<br>Pg. 6-25, Sect. 6.4.4<br>Pgs. 6-22 through 6-24, Sect. 6.4.1<br>Pgs. 6-67 through 6-71, Sect. 6.8.1<br>Pgs. 6-76 through 6-77, Sects. 6.8.5.2 and 6.8.5.3<br>Pgs. 6-46 through 6-47, Sect. 6.6.1<br>Glossary: *Central Island, Circulatory Roadway Width, Entry Width, Inscribed Circle Diameter, Pedestrian Refuge, & Splitter Island* |

- Simplified decision process results from one-way operation, yield-at-entry, and a reduced number of conflict points compared to a conventional intersection.
- A potential for improved pedestrian safety results from shorter crossing distances, fewer possibilities for conflicts with vehicles, and lower vehicle speeds—but, there are many unresolved issues surrounding the use of these facilities by (elderly and visually impaired) pedestrians at this time.

At the same time, there are significant human factors concerns about special driving task demands associated with the geometric and operational characteristics of roundabouts, and their novelty in this country. First, the driver approaching a roundabout must comprehend the prescribed movements, and in particular the yield-on-entry operation, as conveyed by upstream signing. For some years to come, these TCD's will be novel to motorists; and aging persons are at a disadvantage in responding to novel, unexpected stimuli. Upon closer approach, the appropriate speed and heading changes to conform to the splitter island's controlling channelization must be performed; and where increased crash experience has been documented following roundabout installation, as discussed below, excessive entry speeds have been the prevalent contributing factor. Again, vehicle control for smooth entry may be more challenging for aging than for younger drivers. At the point of entry, depending upon the deflection angle of the splitter island, there are critical seconds where confirmation that no conflict exists with a vehicle already in the roundabout requires a glance orientation that well exceeds 90°. The increased difficulty for aging drivers for visual search at skewed intersections has been underscored elsewhere in this *Handbook* (see page 41).

During negotiation of a roundabout, the ability to share attention between path guidance; gap (headway) maintenance; and visual detection, recognition, comprehension, and decision making associated with exit location cues is a near-continuous requirement, even for single-lane facilities. With multiple lanes, the avoidance of conflicts with adjacent vehicles places an exaggerated demand on motorists' attention-sharing abilities; and of course, the increased traffic volumes and speeds associated with these higher-capacity installations pose still greater demands. In the absence of controlled studies in the use of roundabouts by aging drivers, it can only be stated qualitatively that information processing capacity will be exceeded sooner for older than younger persons, and that accommodation by some seniors—probably by reducing their speed while in the roundabout—is likely. This will detract from the operational benefits roundabouts are designed to produce, and may impact safety as well.

A better understanding of the operational and safety issues surrounding the use of roundabouts by aging drivers and pedestrians depends upon crash data analyses from the limited number of existing facilities, and controlled and observational research in this area. This will require time, and more and more of these facilities are expected to come into operation in the immediate future. Thus, recommendations about when and why to use roundabouts to accommodate aging road users remain premature, but an understanding of roundabout task demands that pose special difficulty for seniors allow for certain recommendations regarding preferred practices when a jurisdiction has decided to install a roundabout. The recommendations presented for this design element attempt to balance the human factors considerations above with the accumulating body of information supporting roundabout usage, discussed below.

AASHTO (2011) presents the principles for modern roundabouts and discusses the need to accommodate all modes; the *Green Book* provides some degree of specific design guidance in Section 9.10, but it refers the reader to NCHRP Report 672, which is the second edition of FHWA's *Roundabouts: An Informational Guide* (FHWA, 2010) and provides more detail on specific design parameters. The *Highway Capacity Manual* (2010) includes methodology for estimating capacity and level of service at roundabouts. Presently, several States have design guidelines for roundabouts (Florida, 1996 and Maryland, 1995) based largely on Australian guidelines. Both Florida and Maryland used SIDRA software (Australian methodology) in those guidelines to conduct an analysis of the capacity of a planned roundabout, which is available through McTrans at the University of Florida at Gainesville. A guide written for the California Department of Transportation by Ourston and Doctors (1995) is based on British standards; according to Jacquemart (1998), Caltrans decided not to publish it. However, California DOT has distributed a Design Information Bulletin (No. 80) to provide general guidance to project engineers on appropriate applications, site requirements, geometric elements, and traffic analysis. New York State is developing an *Engineering Instruction* (EI) on roundabouts that will base design guidance on British Guides and software (RODEL). The EI notes that other software programs are permitted (e.g., Highway Capacity, SIDRA, ARCADY), provided that a RODEL analysis is performed for comparison purposes. This EI is to provide interim guidance for current projects, and will be incorporated into the NY State *Highway Design Manual*.

Flannery and Datta (1996) indicate that roundabouts are commonly used in Australia, Great Britain, France, Germany, Denmark, Ireland, Norway, Portugal, Spain, South Africa, Sweden, Switzerland, and the Netherlands. Sarkar, Burden, and Wallwork (1999) state that modern roundabouts are gaining in popularity in cities across the U.S. (in Arizona, California, Colorado, Florida, Kansas, Maryland, Massachusetts, Nevada, Oregon, Texas, and Wisconsin) because of their success in reducing speeds and the number of collisions. Because speeds are reduced, crashes are less severe. Because perpendicular left and right turns are eliminated, a roundabout with one-lane entries has fewer potential conflict points than a conventional intersection (8 vehicle-to-vehicle conflicts and 8 vehicle-to-pedestrian conflicts for a roundabout with 4, 1-lane entries, compared to 32 vehicle-to-vehicle conflicts and 24 vehicle-to-pedestrian conflicts for a conventional four-leg intersection). Jacquemart (1998) reports that as of the middle of 1997, there were fewer than 50 modern roundabouts in the U.S., compared to more than 35,000 in the rest of the world, with France owning the leading number of roundabouts (15,000 modern roundabouts currently, and growing at a rate of 1,000 per year).

Flannery and Datta (1996) highlight the fact that modern roundabouts are different than earlier rotaries and traffic circles common in the early 1900's. First, the modern roundabout requires drivers who are entering the circle to yield to traffic already in the circle (known as "offside priority"). Early roundabout operations gave priority to drivers entering the circle ("nearside priority"), which caused circulating traffic to come to a complete stop resulting in grid-lock. As a result of nearside priority, Flannery and Datta state that the operational performance of traffic circles declined rapidly with the increase in traffic beginning in the 1950's. Because traffic engineers believed that the problem was increased volume as opposed to nearside priority, traffic circles were generally abandoned in the U.S. Studies conducted in the Netherlands, Victoria Australia, and Western Australia have found significant reductions in crashes and casualty rates (from 60 to 90 percent fewer) at roundabouts converted from the old priority to the yield-on-entry priority.

Two other improvements in modern roundabout design are deflection, which helps to slow entering vehicles, resulting in safer merges with the circulating traffic stream, and flared approaches, which helps to increase capacity by increasing the number of lanes on the approach (Flannery and Datta, 1996). Jacquemart (1998) describes deflection as: "No tangential entries are permitted and no traffic stream gets a straight movement through the intersection. Entering traffic points toward the central island, which deflects vehicles to the right, thus causing low entry speeds." The splitter island is the geometric feature that physically separates entering traffic from exiting traffic, and defines the entry angle, which deflects and slows entering traffic. Looking at flared approaches from the viewpoint of accommodating aging driver needs for simplicity, one-lane approaches are likely to be easier to negotiate. In the NCHRP *Synthesis of Roundabout Practice in the United States*, Jacquemart (1998) notes that safety benefits of roundabouts (from studies in Australia and Europe) seem to be greatest for single-lane roundabouts in rural conditions. Generally, safety benefits are related to the reduced speed in the roundabouts, the simplification of conflict points, and the "increased responsibility caused by the slower motion and the need to concentrate and yield, as compared to driver behavior in signalized intersections" (Jacquemart, 1998).

As noted earlier, studies performed to date to evaluate the safety performance of roundabouts have not included driver age as a variable. Flannery and Datta (1996) conducted a safety analysis of six sites in Florida, Maryland, and Nevada that were converted from conventional intersections with traditional control (1-way stop, 2-way stop, or signalized) to roundabouts. All six sites had one-lane entrances and only one lane of circulating traffic. Five roundabouts had a posted speed of 35 mph and one had a posted speed of 45 mph. Four of the sites had four approaches and two sites had three approach legs. Crash data were collected for a period of 1 to 3 years before and after retrofitting the sites (depending on location). Results of chi-squared and normal approximation statistical tests indicated that crash frequencies were significantly reduced in the period after the sites were retrofitted as modern roundabouts. The sites were not stratified by ADT or previous type of traffic control, as the sample size was small; therefore particular crash reduction factors were not identified. However, quick inspection of the crash frequencies provided by site indicate that only the roundabout retrofitted from a signalized intersection showed an increase in crashes in the after period; the other five sites (1-way and 2-way stop controlled) showed decreases in crash frequency in the after period (in the range of 60 to 70 percent). Analyses could only be performed on crash frequencies by group (as opposed to site), because traffic volumes before and after were not characterized, and the six retrofitted roundabouts varied in ADT from 4,069 to 17,825 vehicles.

Rahman (1995) and Jacquemart (1998) provided before and after crash data for the roundabout established in Lisbon, MD in 1993. In the six years prior to the roundabout, there were 45 reported intersection crashes with an average of eight crashes per year.

From 1993 to 1995 (after roundabout installation), there were only two reported crashes. Before the roundabout, the crashes were almost all angle crashes, and after the roundabout was installed, one of the crashes was a single-vehicle crash against a fixed object, and the other crash was a rear-end crash. Injury crashes decreased from 4.3 per year to 0.3. Total delays decreased by 45 percent, from 1.2 vehicle hours to 0.34 vehicle hours in the morning peak hour and from 1.09 vehicle hours to 0.92 vehicle hours in the afternoon peak. This roundabout has four approach legs; it was retrofitted from a 2-way stop-controlled (flashing red beacon) intersection. The ADT was 8,500 vehicles (in March of 1995). The inscribed diameter is 100 ft, there are one-lane entries measuring 18 ft, there is one lane of circulating traffic that is 18-ft wide, and in 1995 the peak hour total approach volume was 630 (Jacquemart, 1998). Rahman (1995) stated that, "the performance of this first experimental roundabout in Maryland demonstrates the safety of roundabouts when properly designed."

Jacquemart (1998) examined the before and after crash data of 11 roundabouts in the U.S. Results are described for large roundabouts with three-lane entries (one in Long Beach, CA and two in Vail, CO) and smaller roundabouts with one- or two-lane entries and inscribed circle diameters of 37 m (121 ft) or less (Santa Barbara, CA; Lisbon, Cearfoss, Lothian, and Leeds, MD; Tampa, FL; Montpelier, VT; and Hilton Head, SC). He states that the small- to moderate- size roundabouts showed significant reductions in total crashes (from an average annual crash frequency 4.8 to 2.4, or 51 percent) and injury crashes (from an average annual crash frequency of 2.0 to 0.5, or 73 percent). There were no statistically significant differences in property-damage-only (PDO) crashes at the smaller roundabouts, although there was a reduction from 2.4 to 1.6 average annual crashes, or 32 percent. Although there was a trend toward crash reduction for the larger roundabouts, there were no statistically significant reductions in total crashes, injury crashes, or PDO crashes. Each roundabout experienced a reduction in injury crashes ranging from 20 to 100 percent. PDO crashes increased at a roundabout in Vail, CO from 15 to 18 per year, and at Leeds, MD from 1.5 to 5.3 per year. At the other 9 roundabouts, however, PDO crashes decreased from 6 to 1 per year. Although PDO crashes at the Leeds, MD site showed an increase, injury crashes decreased from 2.2 to 0.0 per year. The PDO crashes at this site were all single-vehicle crashes that occurred because the vehicles entered the roundabout too fast. Jacquemart (1998) reports findings by Niederhauser, Collins, and Myers (1997) who showed that the average cost per crash decreased by 30 percent across the 5 conventional intersections in Maryland that were retrofitted to roundabouts, from $120,000 before the roundabout to $84,000 after the roundabout.

**Table 35.** Before and After Average Annual Crash History For The Five Intersections In Maryland That Were Converted To Roundabouts (Niederhauser, Collins, And Myers, 1997).

| Site | Average Annual Crashes | |
|---|---|---|
| | Before | After |
| Lisbon | 6.0 | 2.0 |
| Cearfoss | 2.7 | 0.0 |
| Leeds | 3.3 | 4.9 |
| Lothian | 7.7 | 5.1 |
| Taneytown | 5.3 | 0.0 |

Niederhauser, Collins, and Myers (1997) reported the before and after average annual crash history for the five intersections in Maryland that were converted to roundabouts. All sites are single-lane approach and single-lane circulating roundabouts. Overall, the average crash rate was reduced from an average of 5.0 crashes per year to an average of 2.4 crashes per year, which is a reduction of greater than 50 percent. Data for each roundabout is reported in Table 35.

Persuad, et al. (2000) evaluated the change in crashes following conversion of 24 intersections in urban, suburban, and rural environments in 8 States (California, Colorado, Florida, Kansas, Maine, Maryland, South Carolina, and Vermont) from stop-sign or signal control to modern roundabouts. The Bayes procedure was used to account for regression to the mean and to normalize differences in traffic volume between the before and after periods. The number of months of crash data available in the before period ranged from 21 to 66, and the number of months of crash data available in the after period ranged from 15 to 68. Across all sites and crash severities, crashes were reduced by 39 percent in the after-conversion period. A 76-percent reduction was estimated in the after period for injury crashes. For the 20 sites where injury data were available, there were 3 fatal crashes in the before period, and none in the after period. There were 27 incapacitating injury crashes in the before period, and 3 in the after period. Thus, the estimated reduction in fatal and incapacitating injury crashes is 89 percent.

Persuad et al. (2000) looked at the crash reduction rates as a function of operating environment and before-conversion control. For the nine urban single-lane roundabouts converted from stop control, a 61-percent reduction was estimated for all crash severities combined, and a reduction of 77 percent was estimated for injury crashes. For the five rural single-lane roundabouts converted from stop control, a 58-percent reduction was estimated for all crash severities combined, and a reduction of 82 percent was estimated for injury crashes. For the seven urban multilane roundabouts, a 15 percent reduction in crashes of all severities was estimated. Injury data were not available for four these sites in the before-conversion period. For the three roundabouts converted from traffic signal control, all crashes were reduced by 32 percent, and injury crashes by 68 percent. The authors noted that the smaller safety effects for the group of urban multilane roundabouts suggests that there may be differences in safety performance for single-lane designs compared to multi-lane designs. However, they caution that all seven of these roundabouts were located in one State (Colorado) where three of the four in the city of Vail were part of a freeway interchange that also included nearby intersections that were previously four-way stop-controlled. Finally in this research, pedestrian and bicycle crash samples were too small to be meaningful; however, there were three reported pedestrian crashes during the before period and one with minimal injuries in the after period. Four bicyclists were injured in the before period and three during the after period.

Wallwork (1993) notes that crashes do occur at roundabouts, and consist of rear-end or merge-type crashes. Both crash types are low speed and low impact, and result in few – if any – injuries. He stated that with a roundabout, "no one can 'run the red,' and cause a right-angle collision, nor can drivers make a mistake in selecting a gap in the approaching through traffic when making a left turn. The only decision an entering driver needs to make is whether or not the gap in the approaching/circulating traffic is large enough to enter safely." Lower speeds (less than 25 mph) result in shorter braking distances and longer decision making times. Even if a driver makes a mistake and chooses a gap that is too short, a collision is easier to avoid. Thus, the reduction in task difficulty coupled with the low speed environment, results in an overall reduction in the number of crashes, and a reduction in the severity of the crashes that do occur, which should be especially beneficial to aging persons.

The delays before and after eight intersections (seven of which were two-way, or multi-way stop-controlled, and one was signalized) were converted to roundabouts were also described by Jacquemart (1998). The total delay (stopped delay plus move-up time in queue) for eight U.S. roundabouts before retrofit was 13.7 s for morning peak time and 14.5 s for afternoon peak time. This compares to 3.1 s for morning and 3.5 s for afternoon peak times after conversion to roundabouts. Delays were thus reduced by 78 percent in morning peak periods, and by 76 percent in afternoon peak periods, after intersections were converted to roundabouts.

Jacquemart (1998) received information about the design of 38 roundabouts in the U.S., and presented data for four major geometric features: (1) inscribed circle diameter; (2) circulatory roadway width; (3) central island; and (4) entry widths. The inscribed circle diameter is defined as the circle that can be inscribed within the outer curbline of the circulatory roadway. Twenty-eight of the 31 roundabouts for which data were provided on this element have an inscribed circle diameter in the range of 98 to 200 ft, with the majority of these (11) ranging from 98 to 108 ft. Regarding circulatory roadway width, 43 percent of the cases are 15- to 18- ft wide; 21 percent are 20 to 23-ft wide; 25 percent are 24 to 30-ft; and 11 percent are 35 to 36-ft wide. Thus, 36 percent are at least 2 lanes wide. The central island can be raised or flush, or it can be raised with a sloping curb or drivable apron surrounding it. The truck apron is generally included in the central island diameter. Jacquemart reports that approximately 66 percent of the roundabouts for which data were provided have central islands greater than 30 ft diameter. Regarding entry widths, 59 percent of the reported cases have single-lane entries, 30 percent have two-lane entries, and 11 percent have three or more lane entry legs. Studies in other countries help to shed some light on the optimum design characteristics of modern roundabouts.

In the Jacquemart (1998) synthesis, a study by Brilon (1996) of 34 modern roundabouts in Germany concluded that 98 ft seemed to be the ideal inscribed diameter for a single-lane roundabout. Brilon states that smaller diameters result in larger circulatory roadways, which reduces the deflection. Additionally, truck aprons with a rougher pavement are recommended, so that the circulatory roadway remains 13 to 15-ft wide. In a study of 83 roundabouts in France (Centre D'Etudes Techniques de L'Equipment de l'Ouest, 1986) in Jacquemart (1998), it is also concluded that roundabouts with smaller diameters have fewer crashes than larger roundabouts or those with oval circles (see Table 36).

Splitter islands are another geometric feature of modern roundabouts. These are generally raised islands that are placed within a leg of a roundabout to separate entering and exiting traffic, and to deflect entering traffic. They also serve as a safety zone for pedestrians. Only one of the 38 roundabouts has painted (marked) splitter islands. The study conducted in Germany (Brilon, 1996, in Jacquemart, 1998) concluded that splitter islands are important to the safety of pedestrians,

**Table 36.** Roundabout crashes compared to diameter (Jacquemart, 1998)

| Number of Roundabouts | Inscribed Diameter (ft) | Crashes per Roundabout |
|---|---|---|
| 13 | <98 | 0.69 |
| 11 | 98 to 164 | 1.54 |
| 26 | 164 to 230 | 1.58 |
| 16 | 230 to 295 | 1.81 |
| 8 | >295 | 3.80 |
| 9 | Oval | 4.40 |

and should be 5- to 8-ft wide, with pedestrian crossings located 13 to 16 ft back from the circulating roadway. A study conducted in Switzerland by Simon and Rutz, 1988 (in Jacquemart, 1998) also concluded that the distance between the pedestrian crossing and the inscribed circle should be 16 ft as greater distances do not increase pedestrian safety. They recommended the use of splitter islands with safety zones for pedestrians for crossings of more than 300 vehicles per hour. Wallwork (1999) states that a feature of roundabouts that makes them safer for pedestrian than conventional intersections is that pedestrians walk behind the cars. He recommends moving the crosswalk back one car length from the yield line for each lane of entry (i.e., one car length for a one-lane entry, two car lengths for a two-lane entry, or three car lengths for a three-lane entry). Brilon (1996) recommended Zebra-striped crossings only when there were more than 100 pedestrians crossing during the peak hour. Maryland (DOT/SHA, 1995) normally places pedestrian crossings 20 to 25 ft from the yield line. Crosswalk striping is not used, to avoid driver confusion of crosswalk limit lines with yield lines. Special consideration is given in providing priority crossings for pedestrians where pedestrian volumes are high, where there is a high proportion of younger or older pedestrians, or where pedestrians experience particular difficulty in crossing, and are being delayed excessively. The agency believes that it is desirable to place these crossings at least 75 ft downstream of the exit from the roundabout and possibly augment the crossing with a signal. This will reduce the possibility that vehicles delayed at the pedestrian crossing will queue back into the roundabout, and gridlock the whole intersection.

In the survey conducted by Jacquemart (1998) detailing 38 U.S. roundabouts, 56 percent of the sites were reported to have no or very few pedestrians, 22 percent have between 20 and 60 pedestrians during the peak hour, and 22 percent have more than 60 pedestrians per hour. Of particular interest is the Montpelier, Vermont roundabout, which is located next to a senior housing project and is also close to a middle school (400 students), and carries in excess of 260 pedestrians during each rush-hour (morning and afternoon) period on school days (Gamble, 1996; Redington, 1997). This roundabout has 3 legs, an inscribed diameter of 34 m, one-lane entries for each lane and one lane of circulating traffic. The AADT is approximately 11,000 (7,300 AADT for each leg) and carries approximately 40 tractor trailers (WB-62) each day (Redington, 1997). The peak hour total approach volume is 1,000 vehicles (Jacquemart, 1998). Prior traffic control was a one-way stop at a Y-intersection.

Jacquemart (1998) lists criteria to assist visually impaired pedestrians that include: (1) keeping the crossing away from the circle (e.g., 5 to 6 m from the outer circle) lets the blind person distinguish the exiting traffic from the circulating traffic; and (2) the splitter island provides a refuge where the pedestrian can shift his or her attention from one traffic stream to another. Different pavement texture for the walkways will assist the visually impaired pedestrian in locating the crosswalks. Drivers approaching a roundabout approach at speeds slower than they would for an approach to a conventional intersection; thus, they are more likely to stop for pedestrians, and may be more likely to notice a pedestrian on an approach to a roundabout because they are not concentrating on finding a gap in the opposing traffic stream to turn left.

Harkey and Carter (2006) evaluated pedestrian and bicyclist behaviors at single-lane and multilane roundabouts in eight states. The results of the study showed vehicles exiting a roundabout to be less likely to yield (38% non-yield rate) to crossing pedestrians than vehicles approaching a roundabout (23% non-yield rate). There was also less yielding to crossing pedestrians on multilane approaches (43% non-yield rate) compared to single-lane approaches (17% non-yield rates). The authors concluded that roundabouts need to be designed to ensure adequate sight lines and slow vehicle speeds on the exit legs. Multilane roundabouts may also require additional measures to minimize the risk of multiple-threat collisions and create a safe crossing environment.

Jacquemart (1998) also provided a summary of the current lighting, signing, and pavement marking practices at the 38 U.S. roundabouts for which questionnaire data were provided. First, all existing roundabouts were reported to have nighttime lighting. Next, all roundabouts were reported to have the standard YIELD sign, although often it was supplemented by an additional plate with specific instructions, such as "TO TRAFFIC ON LEFT;" "TO TRAFFIC IN ROUNDABOUT;" or " TO TRAFFIC IN CIRCLE;" or with the international roundabout symbol, which is three arrows in a circular pattern. In addition, 90 percent of the roundabouts contain an advance YIELD AHEAD symbol sign and 7 percent use the YIELD AHEAD legend sign. Twenty-four percent included a supplemental plate on the advance YIELD sign that said "AT ROUNDABOUT," presented the roundabout symbol, or displayed a speed limit sign. All roundabouts had either a one-way sign (R6-1 or R6-2) or a large arrow warning sign (W1-6) in the central island. Chevron signs often accompanied the one-way signs at the sites studied (see Figure 81). Regarding pavement markings, approximately 20 percent of the roundabouts supplemented the yield line at the roundabout entrance with the pavement marking legend "YIELD" or "YIELD AHEAD." For multilane roundabouts, only in the case of the Hilton Head, SC, roundabout were lane lines present. Jacquemart (1998) reported that the authorities responsible for the roundabout believe that the large number of senior drivers in the area would be more comfortable with lane markings in the circle. Simon and Rutz, 1988 (in Jacquemart, 1998) recommended that for main roads or national highways, advance directional signs with the roundabout symbol should supplement the roundabout yield sign at the entry, but that other special warning signs—such as roundabout ahead or priority to the left—are not recommended. Wallwork (1999) does not recommend the widespread use of supplemental signs (e.g., posting "TO TRAFFIC IN CROSSWALK" on the YIELD sign), because it constitutes visual clutter. Instead, he recommends their use only as a local measure to educate road users for a short time period after roundabout installation.


**Figure 81.** One Way and Chevron Sign Combination Used in Central Island of Roundabout (Jacquemart 1998)

Molino, Inman, Katz, and Emo (2007) conducted a driving simulator study using 90 participants equally distributed into three age groups: young (ages 18 to 25), middle-aged (26 to 64) and older (age 65 and older). Participants "drove" through double-lane roundabouts marked with five signing and pavement marking schemes:

1. traditional arrow signs and markings;
2. fishhook arrow signs and markings;
3. traditional arrow signs and markings with clarifying words (e.g., "all" and "only");

4. fishhook arrow signs and markings with clarifying words; and
5. destination lane restriction sign with no lane restriction markings.

A sixth condition with no lane restriction signs or markings, served as the control. Except for the destination lane restriction sign condition, all roundabouts had redundant indications of proper lane approach. Participants chose the correct entry lane between 89 and 91 percent of the time, and the percentages did not vary significantly among marking schemes. The overall compliance score across schemes was 89.2 percent; all 5 schemes resulted in successful compliance performance, if the criterion is set to 85 percent. However, the fact that in 11 percent of the scenarios, drivers continued to make left turns from the right lane, even when the signs and markings clearly showed that the right lane must turn right is both an operational and safety concern. The 11 percent compliance failure occurred regardless of the fact that signs/markings were redundantly presented on each approach. Molino et al. (2007) report that in field conditions, where there may be less redundancy in signs and markings, and where traffic may cause drivers to miss some lane restriction indications, overall compliance may be less than 89 percent.

In terms of driver comprehension, participants correctly understood the left and right lane options approximately 90 percent of the time across schemes, but often did not understand markings allowing them to use "either" entry lane to reach their destination. Comprehension for "either" lane entry options was only 44 percent, and was not significantly different across the 5 schemes. Comprehension for the marking schemes ranged from 70 to 78 percent when participants were required to report which, among three lane choices was correct (left, right, or either). Overall comprehension, collapsed across the 5 schemes was 74.9 percent; none of the signing and marking schemes resulted in successful comprehension performance. Poor comprehension that entry from either lane was allowable could interfere with roundabout capacity design calculations. Although comprehension across all schemes was poor, there were no attempts to drive through the roundabout in the wrong direction with any of the schemes.

In terms of age and gender effects, Molino et al. (2007) found that although younger participants had higher percentages of correct responses for both compliance and comprehension than middle-aged participants, who in turn had higher percentages of correct responses than older participants, the differences were not statistically significant. Males had higher percentages of correct responses for both compliance and comprehension than females; however, the difference was significant only for compliance.

Molino et al. (2007) concluded that, based on the simulation results, conventional arrow signs and markings, fishhook signs and markings, or lane restrictions included on diagrammatic navigation signs would be equally effective, however, additional steps may be needed to achieve a higher rate of compliance where lane restriction compliance is deemed important for either operations or safety. The simulation results did not point to what steps would be effective.

Lord, et al. (2007) conducted a laboratory study with aging drivers to evaluate countermeasures that may have the potential to improve the perceived comfort, confidence, and/or safety of aging persons using roundabouts. Structured interviews were conducted in Texas and Arizona with 31 licensed drivers ages 65 and older, in addition to animated video presentations simulating an approach to and traversal of a roundabout. Five design elements were evaluated: (1) advance warning signs; (2) lane control signs; (3) directional signs; (4) yield treatments; and (5) exit sign treatments. For each design element, a base condition (representing existing standards of engineering and design practice as per the 2003 *MUTCD*) was presented along with two countermeasures. The countermeasures were developed using input from focus groups conducted with aging drivers in an earlier phase of the study. Still images were photographed of a roundabout unfamiliar to all participants (in Washington State), every 10 ft during an approach to and going around the roundabout, for a total of 64 images. The images were manipulated with photo-editing software to reflect each of the three alternatives, described in Table 37.

The evaluation was carried out using paired comparisons between the base condition and alternative 1; followed by comparisons between the base condition and alternative 2. Subjects were asked to rate the perceived change in terms of safety, comfort, and confidence. A 7-point Likert scale was used for the ratings, with the endpoints being significantly lower or higher (e.g., 1 = the alternative drive was significantly lower than the baseline, 7= the alternative drive was significantly higher than the baseline) and the midpoint of the scale (4) meaning no change. Study findings are described below for each of the design elements evaluated.

## Advance Warning Sign

Based on the ratings of comfort, confidence, and safety, there was no significant difference between Countermeasures 1 and 2, but both were superior to the baseline. Participants' comment suggested that Countermeasure 2 would best meet their needs. Based on these findings, Lord et al. (2007) recommended the use of the roundabout

**Table 37.** Description of Countermeasures Studied for Roundabout Traffic Control Devices (Lord et al. 2007).

| Traffic Control Device | Baseline | Countermeasure 1 | Countermeasure 2 |
|---|---|---|---|
| Advance Warning Signs | W-2-6 Advance roundabout warning sign | Baseline sign with solid black circle added to center and supplemental plaque "Roundabout" | Countermeasure 1 sign with supplemental plaque (30 mph), but no "Roundabout" plaque |
| Lane Control Signs | Modeled after R3-8 advance intersection lane control signs, where solid lines displayed the 2 possible routes for traveling through the roundabout (one for each entering lane). | A solid black circle representing the central island was added to the left lane's route. | The text "Left Lane" and "Right Lane" were added under the corresponding routes, on the sign used in Countermeasure 1. |
| Directional Signs | A central island without any guide signs or special pavement marking guiding traffic circulating around the roundabout, as per *MUTCD* (2003) guidelines. | One Way (R-6-1) placed on central island, facing centerline of approaching roadway. | One Way (R-6-1) placed on central island, in front of driver's entry point (closer to driver's line of sight. |
| Yield Treatment | Standard R1-2 Yield sign placed on both sides of road at roundabout entrance, per *MUTCD*. | A Yield line consisting of solid white isosceles triangles was added to the base condition. | Yield line from countermeasure 1 plus supplemental signs below Yield sign "TO TRAFFIC IN CIRCLE." |
| Exit Treatment | Street Name exit sign placed between two intersecting streets, prior to the exit. | Same street name exit sign in Baseline, but placed onto splitter island of intended street exit. | Arrow added to street name exit sign and placed as in Countermeasure 1 |

advance warning sign, augmented with a symbol representing the center island, as shown in Figure 82.

Lane Control Signs: Both countermeasures received higher ratings than the base, but Countermeasure #2 received significantly higher ratings. Based on the study findings, Lord et al. (2007) recommended the use of lane control signs designating the intended destinations for each lane (for multilane roundabouts), augmented with a black solid circle for the left lane's route representing the central island, augmented by text under each route, indicating "LEFT LANE" and "RIGHT LANE," as shown in Figure 83.

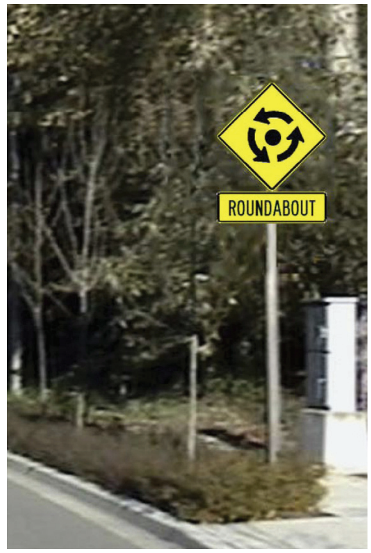



**Figure 82.** Roundabout Advance Warning Sign Recommended by Lord et al. (2007)


**Figure 83.** Lane Control Sign Recommended by Lord et al. (2007)

## Directional Signs

The use of a ONE WAY sign on the center island was associated with increased ratings over the baseline (no signs); there were no significant differences between the countermeasures, however, comments provided by study participants indicated placement to maximize the visibility of a driver just about to enter the roundabout is beneficial. Lord et al. (2007) recommended the use of a ONE WAY sign, shown in Figure 84, placed on the center island in direct view of a driver's entry point, rather than at the centerline of the approaching roadway.

## Yield Treatment

Countermeasure 1 (inverted isosceles triangle pavement markings) did not improve participants' understanding of the yield treatment at the entrance of the roundabout; and some participants thought they were traveling in the wrong direction, given that the triangles were pointed toward the drivers entering. Countermeasure 2 (Yield sign


**Figure 84.** Roundabout Sign Recommended by Lord et al. (2007)

with supplemental plaque "To Traffic in Circle") received significantly higher comfort ratings than the baseline condition. Based on their study findings, Lord et al. (2007) recommended that the supplemental panel bearing the legend "TO TRAFFIC IN CIRCLE" be placed immediately below the R1-2 Yield signs on both sides of the road at the entrance to a roundabout, as shown in Figure 85.

### Exit Treatment

Countermeasure 1 did not significantly improve the perceived comfort, confidence, or safety relative to the baseline. The addition of the arrow on the street name sign pointing toward the exit leg showed significantly improved comfort, confidence, and safety over the baseline. Based on their study findings, Lord et al. (2007) recommended that the name of each intersecting leg on a roundabout be labeled with a sign panel placed on the splitter island for that intersection, facing toward approaching traffic in the roundabout, and that a directional arrow pointing toward the exit leg accompany the street name on the panel, as shown in Figure 86.

As noted by Lord et al., (2007) the findings from the laboratory study should be confirmed through naturalistic field study observations prior to their adoption in Federal


**Figure 85.** Yield Sign Treatment Recommended by Lord et al. (2007)


**Figure 86.** Exit Treatment Recommended by Lord et al. (2007)

and State design manuals. This is particularly important for the lane use control signs and the exit signs evaluated, because misunderstandings about proper lane use, and placement of exit signs at the exit location may result in last-minute, erratic lane-change maneuvers, and crashes. For multilane approaches to roundabouts, signs should be designed to assure that drivers choose the proper lane for their destination before reaching the roundabout, and once in that lane, they should be able to circumnavigate the central roadway of the roundabout and exit to their destination without having to change lanes while in the circular roadway of the roundabout. To ensure that the signs recommended in the laboratory perform as intended, they should be tested in the field, and therefore, no recommendation for their implementation is made for this *Handbook*, and the study findings should be considered as preliminary.

At the same time, providing drivers with more detailed information about what to expect when they reach the roundabout should enhance the operational safety of roundabouts for aging drivers in particular, as well as the general population of drivers, without any unintended consequences. The advanced roundabout sign with the center island symbol advises drivers that traffic flows counterclockwise around an island. The educational plaque on the Yield sign "TO TRAFFIC IN CIRCLE" provides more detail about the right-of-way rules, advising entering drivers that they are the ones who must yield because circulating traffic has the right of way. The ONE WAY sign is a familiar regulatory sign and indicates that the required movement of entering traffic is to the right. Understanding these roundabout operational rules is paramount to avoiding wrong-way maneuvers (and their consequent head-on crashes), panic stops by circulating traffic trying to avoid crashing into a driver who does not yield at entry (resulting in rear-end crashes by following circulating drivers), and angle crashes between entering and circulating drivers when an entering driver fails to yield and an approaching driver does not take evasive action.

The enhanced advanced roundabout warning sign used by Lord et al. (2007) is a novel design, and care must be taken in determining the size of the center island symbol to ensure legibility of the sign. The visual task detail size of the central island symbol should be large enough for detection at a preview distance of at least 5 s, but not so large that it interferes with recognition of the circular intersection arrows. A dimension that satisfies these objectives may be analytically determined; though of course, field validation is desirable. Using principles evidenced in *Standard Highway Signs* (FHWA, 2004), to avoid legibility problems while affording detection for aging drivers at meaningful preview distances, the center island symbol should be centered on the sign and its diameter should range from 2.0 to 2.5 times the stroke width of the arrows.

Jacquemart (1998) lists several location types where it is appropriate to install roundabouts, based on a review of guidelines from abroad and those existing guidelines in the U.S. (e.g., Maryland and Florida). These locations include:

- High crash locations, particularly with high crash rates related to cross movements or left-turn or right-turn movements.
- Locations with high delays.
- Four-way stop intersections.
- Intersections with more than four legs.

- Intersections with unusual geometry (Y or acute angle).
- Intersections with high left-turn flows.
- Intersections with changing traffic patterns.
- Intersections where U-turns are frequent or desirable along commercial corridors.
- At locations where storage capacities for signalized intersections are restricted, or where the queues created by signalized intersections cause operational or safety problems.
- Intersections where the character or speed of the road changes, such as at entry points to a community or at junctions where a bypass road connects to an arterial.

Ourston and Bared (1995) cited the work of Guichet (1992) who investigated 202 crashes at 179 urban roundabouts in France. The crash causes and relative frequencies are presented in Table 38.

**Table 38.** Causes of Crashes at Urban Roundabouts in France (Ourston and Bared, 1995).

| Cause of Crash | Percent of Crashes |
|---|---|
| Entering traffic failing to yield to circulating traffic | 36.6 |
| Loss of control inside the circulatory roadway | 16.3 |
| Loss of control at entries | 10.0 |
| Rear-end crashes at entries | 7.4 |
| Sideswipe, mostly at two-lane exits with cyclists (2 of 3 instances) | 5.9 |
| Running over pedestrians at marked crosswalks, mostly at two-lane entries | 5.9 |
| Pedestrians on the circulatory roadway | 3.5 |
| Loss of control at exits | 2.5 |
| Head-on collision at exits | 2.5 |
| Weaving inside the circulatory roadway | 2.5 |

Guichet (1992) listed the major design recommendations, based on the findings of the crash investigation:

- Ensure that motorists recognize the approach to the roundabout.
- Avoid entries and exits with two or more lanes, except for capacity requirements.
- Separate the exit and entry by a splitter island.
- Avoid perpendicular entries or very large radii.
- Avoid very tight exit radii.
- Avoid oval-shaped roundabouts.

Wallwork (1999) recommends that in areas where there is a high concentration of aging drivers, it is desirable to use the lower end of the speed range that he has determined for roundabouts in a particular roadway class. He states that a roundabout meets drivers' requirements for simple decision making, and low speed is paramount for safe roundabout operation. His design-speed recommendations by roadway class are presented in Table 39.

He states that the best way to control driver behavior is through the use of concrete: the roundabout has a concrete circle in the center, which defines a path to control speed, and a roundabout uses concrete islands to deter wrong-way movements and to control entry speeds. Roundabouts that are not designed for slow speeds result in high crash rates; there are at least two in the U.S. (Boulder, Colorado and Daytona Beach, Florida) that are being removed, because of poor design (e.g., no bulbouts for deflection on the entries allowing for 40-mph speeds).

**Table 39.** Design-Speed Recommendations For Modern Roundabouts By Roadway Class (Wallwork, 1999).

| Roadway Classification | Roundabout Design Speed (mph) |
|---|---|
| Local Road | 12-15 |
| Collector Road | 15-18 |
| Secondary Arterial | 18-21 |
| Major Arterial | 21-23 |
| Rural Roadway | Maximum 25 |

Regarding public opinion about roundabout implementation, Taekratok (1998) indicates that people do not make a clear distinction between modern roundabouts and traffic circles, and therefore public responses to roundabout proposals are negative. Jacquemart (1998) presents copies of media coverage (Howard County Sun Newspaper) about the Lisbon, Maryland roundabout installed in Howard County as an experimental solution to an intersection with a high crash rate. One year before the roundabout opened, most of the Lisbon residents objected to the idea of a roundabout. Four months after the roundabout opened, a local citizen's committee voted overwhelmingly to make the roundabout permanent. Taekratok (1998) reports that the strategies taken by Florida, Maryland, and Vermont have been successful in improving public perception, and include public education through the use of brochures, videotapes, and mass media to provide information during the development stage. This will help the public to understand the differences between circles and roundabouts, and will gradually reduce opposition.

Redington (1997) notes that roundabouts are small (e.g., 91.8 to 180 ft) compared to the old time traffic circles found in New England and New Jersey (e.g., 249 ft or greater), and that drivers strongly dislike traffic circles with their typical operating speeds of 31 to 41 mph. While the Montpelier, VT, Keck Circle Roundabout was under construction, the Roundabout Demonstration Committee prepared educational materials that included a brochure providing safety rules for drivers and pedestrians, as well as news releases and public service announcements in response to negative public reaction during construction, and negative commentary from local morning radio personalities (Redington, 1997). This Committee also conducted a survey of 111 citizens working or living near the roundabout one year after its opening to measure public opinion. Of the 111 respondents, 104 had driven the roundabout, 89 had walked, and 19 had bicycled. "Very favorable" or "favorable" responses were obtained from 57.6 percent of the respondents, 27.9 percent of the responses were "neutral" and 14.4 percent were "unfavorable" or "very unfavorable." The survey contained two open-ended questions to allow respondents to contribute "likes," dislikes," and comments about "what they miss about the old intersection." The 111 respondents contributed 214 comments. The majority of the 65 "like" comments pertained specifically to smoother and better traffic movement. Fifty-six comments were obtained from respondents who "dislike" the roundabout. The majority of these were directed toward poor driver behavior such as drivers failing to yield, failing to follow the rules, and failure to use turn signals.

Finally, Sarkar, Burden, and Wallwork (1999) reviewed driver's manuals for 32 States and the District of Columbia, and concluded that the information on traffic circle and roundabout use was inadequate. Only 10 of the States provided some instruction in their manuals about how to use the circles (i.e., entering drivers should yield to drivers who are already in the circle) and none provided information about how to use roundabouts. Information about types of signs placed near roundabouts and circles was not present, nor was there any explanation about the differences between circles and roundabouts. Only one State had an illustration of a circle, but in the authors' opinion, it was not clear or easy to understand. They recommend that State driver manuals be revised to include information about correct use of traffic circles and roundabouts, as roundabouts are becoming increasingly popular in the U.S.

# PROMISING PRACTICES

## 17 Right-Turn Channelization Design

**Description of Practice:** This practice reflects improved design of the corner island, turning lane width, and turning radii for channelized right turns to discourage high-speed turns while still accommodating large trucks and buses, and also facilitating pedestrians crossing the intersection. Specifically, the triangular corner island should have the "tail" pointing to approaching traffic. This will make the total pedestrian crossing distance of the intersection shorter, as the channelized right-turn is closer to the through lanes. In addition, the crossing of the channelized right-turn lane itself is shorter as pedestrians can cross at a right angle. This design has the additional advantage of the crosswalk being located in an area where the driver is still looking ahead; older designs place the crosswalk in a location where the driver is already looking left for a break in the traffic. The improved channelized right-turn lane design will place a sharper curve at the downstream end of the lane, which will force drivers to negotiate the lane more slowly; and by having the slip lane intersect the destination street at a larger angle, a driver will have better sight lines of approaching traffic on the destination street. Known implementations of this design include an intersection in Charlotte, NC, and several intersections in Florida and Texas.

**Anticipated Benefits to Aging Road Users:** Aging drivers, who as a group experience reduced head/neck mobility, should have a longer time in which to search for conflicts with through traffic before entering the destination street as the result of these design changes. They should also benefit from carrying out this search without dividing their attention to potential conflicts with pedestrians crossing to the corner island. Aging pedestrians, who as a group walk more slowly, should benefit from the shorter crossing distances afforded by this design. The safety of aging pedestrians—and all pedestrians—should also be enhanced to the extent that this design compels turning drivers to enter the turn lane at a lower speed, while permitting them to direct attention to the search for conflicts with pedestrians and conflicts with traffic in separate phases of the turning maneuver.

## 18 Combination Lane-Use/Destination Overhead Guide Signs

**Description of Practice:** Lane use signs indicate the turning movements that can be made from each approach lane of an intersection. This practice is now included in the 2009 MUTCD (the D15-1 sign). A green guide sign is placed over the lane with a street name, route shield, or destination in the top half, and a lane-use regulatory sign in the bottom half. The State of Iowa currently utilizes some examples of overhead lane use signs, though different than the D15-1 series sign found in the 2009 MUTCD. The Iowa signs are on a white background with a route shield and a down arrow pointing to the appropriate approach lane. New York State DOT utilizes examples similar to the 2009 MUTCD D15-1 series sign.

**Anticipated Benefits to Aging Road Users:** The benefits of advance street name signs described above may be amplified by this treatment, which not only provides identification of the receiving leg routes at an intersection but also path guidance for the approaching driver. A driver who is properly positioned for a downstream maneuver will experience reduced demands for divided attention as s/he nears the intersection. Posting the advance signing described in this treatment overhead increases the conspicuity of this guidance information; this is likely to have the greatest benefit for aging drivers who, as a group, do not execute visual search as efficiently as younger persons when concurrent task demands are high.

## 19 Signal Head Visibilty

**Description of Practice:** Traffic signal heads are placed overhead, using one signal head per lane. Several states and municipalities have adopted this signal head placement as policy, including Iowa, Minnesota, Virginia, and the cities of Las Vegas, Nevada and Grand Rapids, Michigan routinely place signal heads centered over each lane. In Kansas City, Missouri, pedestal pole signals were converted to overhead mast arm installations.

**Anticipated Benefits to Aging Road Users:** Increasing the conspicuity of traffic control devices at intersections and reducing any ambiguity about the information they convey may be expected to have the greatest benefits for those with (age-related) visual and cognitive deficits. Physically separating the target stimulus from potentially distracting stimuli in the roadside environment should result in faster and more reliable visual detection, and this performance advantage for an overhead signal (especially with a backplate) compared to a pedestal mount should be disproportionately greater for aging drivers with a reduced ability to "screen out" irrelevant stimuli (selective attention). Similarly, the reduction in decision time that should be realized from centering the signal over the approach lane will be of greatest benefit to aging drivers with reduced speed of processing who face the highest demand for "executive control" when negotiating an intersection.

Reductions in the overall number of crashes and right-angle crashes among drivers 65 and over have been observed in jurisdictions where overhead signals, centered over the approach lane have been introduced (in conjunction with the addition of an all-red clearance interval and/or increasing signal size from 8 to 12 inches).

## 20 High-Visibility Crosswalks

**Description of Practice:** Crosswalk markings provide guidance for pedestrians crossing roadways by defining and delineating paths on approaches. These markings are used in conjunction with signs and other measures to alert road users to a designated pedestrian crossing point. Section 3B.18 of the 2009 MUTCD contains basic information about crosswalk markings; however, some States adopt their own supplement or manual on traffic control devices and some develop policies and practices for subjects not discussed in the MUTCD, so differences in markings occur among States, cities, and other jurisdictions. Some crosswalk markings are more effective than others at drawing attention to the crosswalk and the pedestrians who use it. The traditional set of transverse parallel lines define the boundaries of a crosswalk for the pedestrian, but they are not particularly visible to approaching drivers, especially in dark and/or wet conditions, compared to other marking patterns. More recent crosswalk marking patterns such as continental and bar pairs (see Figures 87 and 88) have shown better recognition among approaching drivers (Fitzpatrick, et al, 2010). Markings commonly called "ladder" crosswalks (see Figure 36) combine the transverse and continental to also increase visibility to approaching drivers.

**Figure 87.** Example of continental crosswalk markings

**Figure 88.** Example of bar pairs crosswalk markings

**Anticipated Benefits to Aging Road Users:** Crosswalk markings not only define a path for the pedestrian to cross the street, but they also call attention to the presence of the crosswalk for approaching drivers. High-visibility crosswalks are beneficial to all drivers, but as eyesight diminishes with age, the increased recognition quality of high-visibility crosswalks becomes even more useful for aging drivers to see and prepare for crossing pedestrians as they approach marked crosswalks.

# 21 Supplemental Pavement Markings for Stop and Yield Signs

**Description of Practice:** Pavement messages in advance of an intersection may be used to supplement critical warning sign messages, such as the stop ahead and yield ahead signs. Such markings are currently in use in many locations in the country, including Irvine, California and Williamston, Michigan. The use of these markings is permitted according to Section 3B.20 of the 2009 MUTCD.

**Anticipated Benefits to Aging Road Users:** As the result of normal aging, drivers may be at higher risk of failing to detect advance stop and yield warning signs posted at the side of the road due to loss of visual sensitivity in the periphery; a narrowing of the attentional (or “useful”) field of view; or a reduced ability to engage in a search of the visual periphery when, for example, road or weather conditions increase demands for path guidance information. To the extent that aging drivers experience any of these limitations, they should derive an extra benefit from advance warning messages presented as pavement markings—if these markings are applied and maintained at contrast levels sufficient to ensure legibility to an "aging design driver."

## 22 Reduced Left-Turn Conflict Intersections

**Description of Practice:** Within the last five years, interest in a set of intersection designs collectively called "innovative" or "alternative" has grown rapidly. These intersection designs use a combination of geometric design features and traffic control devices to mitigate congestion problems at at-grade intersections as an alternative to traditional signalized intersections or grade-separated interchanges. One of the common characteristics of these alternative designs is that they typically accommodate left-turns in unique ways, with the end result that left-turns at the intersection are greatly reduced, if not eliminated. Designs such as the displaced left-turn (DLT) intersection, median U-turn intersection (see Figure 89), and restricted-crossing U-turn (RCUT) intersection (see Figure 90) all have features that minimize the operational delay and potential for crashes due to left turns. More information on the specific design features and traffic control devices used at these intersections can be found in FHWA's Alternative Intersections/Interchanges: Informational Report (Hughes, et al. 2010).

**Figure 89.** Diagram of Median U-Turn Intersection. (Image Credit: Debbie Murillo, Texas A&M Transportation Institute)

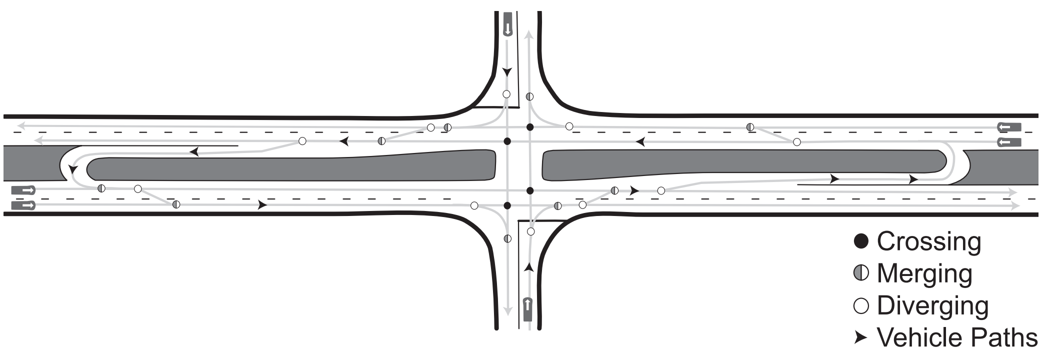
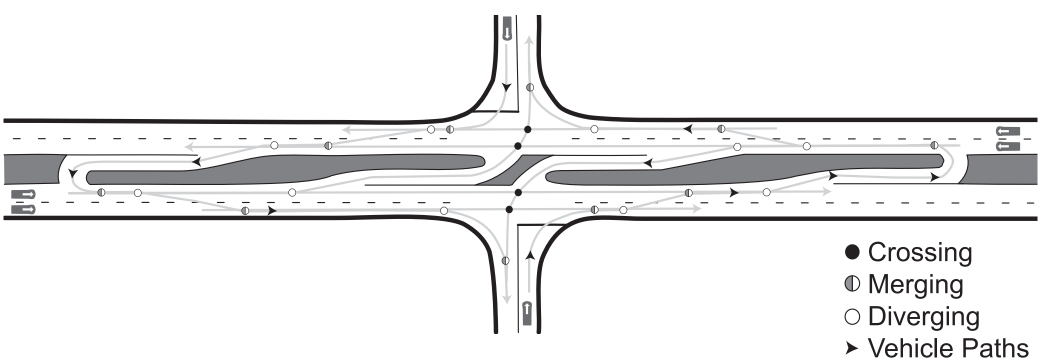



**Figure 90.** Diagram of Restricted Crossing U-Turn Intersection. (Image Credit: Debbie Murillo, Texas A&M Transportation Institute)



**Anticipated Benefits to Aging Road Users:** While modern roundabouts can be found in many parts of the country, these alternative intersections are more isolated and can present some challenges to drivers who have not seen them before, particularly aging drivers. These designs are the subject of a great deal of research at the current time, with studies investigating operational efficiencies and geometric design requirements. Specific benefits for aging drivers are a subject worthy of further exploration, but indications are that they can improve operations and safety for aging drivers as with the driving population as a whole.

As with roundabouts, alternative intersections may require additional outreach and educational efforts to help aging drivers understand what to expect when approaching them, as the geometric patterns of these alternative forms may appear to be complex designs; however, evaluation and observation show that users do find them easy to navigate. FHWA's Every Day Counts 2 initiative has listed "Intersections with Displaced Left-turns or Variations on U-turns" among the treatments for Intersection and Interchange Geometrics that state departments of transportation should consider to reduce conflicts and improve safety. Additional information on these designs and their respective features and benefits can be found at the Alternative Intersections website (www.alternativeintersections.org).

# 23 Accessible Pedestrian Signal (APS) Treatments

## A. Pushbutton-Activated Extended Pedestrian Crossing Phase

**Description of Practice:** A broad range of technologies can be classified as Accessible Pedestrian Signal (APS) treatments (Harkey, et al. 2009). One particular technology is that in which a controller can be programmed to provide extended pedestrian phase timing in response to an extended button press. In most advanced APS devices, these special features are actuated by pressing and holding the pedestrian pushbutton for an additional length of time (Noyce and Bentzen 2005).

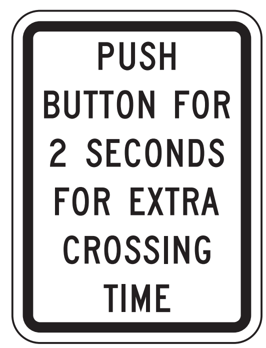



**Figure 91.** Supplemental Plaque Used with Extended Crossing Time Feature for APS. (MUTCD R10-32P)

Paragraph 2 of MUTCD Section 4E.13 states that if an extended pushbutton press is used to provide any additional feature(s), a pushbutton press of less than one second shall actuate only the pedestrian timing and any associated accessible walk indication, and a pushbutton press of one second or more shall actuate the pedestrian timing, any associated accessible walk indication, and any additional feature(s).

Paragraph 3 of Section 4E.13 states that if additional crossing time is provided by means of an extended pushbutton press, a PUSH BUTTON FOR 2 SECONDS FOR EXTRA CROSSING TIME (R10-32P) plaque (see Figure 91) shall be mounted adjacent to or integral with the pedestrian pushbutton.

**Anticipated Benefits to Aging Road Users**: With such a feature, the controller can regularly provide pedestrian timing that is the minimum permissible, while allotting additional crossing time when it is needed by pedestrians who move or react slowly or who do not use visible cues and thus wait to confirm audible or vibrotactile cues before starting a crossing.

**B. Passive Pedestrian Detection**

**Description of Practice**: Another APS treatment is passive detection. Most commonly, this is used in the vicinity of the curb ramp to enable the WALK signal to be requested without the pedestrian needing to use a pushbutton. This feature is particularly useful where site constraints make it difficult for pedestrians with disabilities to approach the pushbutton. However, passive detection also can be used to detect pedestrians within the crosswalk that may need more time to complete their crossing maneuver. According to Harkey, et al. (2010), they were not aware of installations of passive detection in the United States that include audible signals as well as visual signals, but the combination of passive pedestrian detection and audible signals is being used in the United Kingdom, Australia, New Zealand, and the Netherlands. An example of passive pedestrian detection technology is the "Pedestrian User-Friendly Intelligent" (PUFFIN) crossing in use in England (Department of Transport, 2006). PUFFIN crossings employ pedestrian detectors for both the pedestrian waiting area and the crosswalk. Crosswalk detectors at PUFFIN facilities are used to vary the pedestrian clearance times between defined minimum and maximum times; when there are large numbers of pedestrians or if slow-moving pedestrians are crossing, the clearance time is extended to provide ample time for them to complete their crossing. Crosswalk detectors can be infrared or microwave detectors mounted on the signal pole or video cameras serving remote sensor software.

**Anticipated Benefits to Aging Road Users**: Like pushbutton-activated extensions, passive pedestrian detection treatments can help aging pedestrians register their call for a pedestrian phase and receive additional time to cross as needed.

# 24 Flashing Yellow Arrow

**Description of Practice:** Research has been conducted over the previous decade to identify more effective means of indicating permissive (i.e., not protected) left-turn phases at signalized intersections, replacing the traditional circular green (i.e., "green ball") indication. One treatment that has shown promising results is the flashing yellow arrow (FYA). Brehmer, et al (2003) studied a variety of displays for protected/permissive left-turn control, and they found that drivers over the age of 65 had extremely low correct response rates with the permissive circular green indications, as many aging drivers assume right-of-way with circular green permissive left-turn indications. When the permissive circular green indication and the circular red through-movement indication were shown, less than 29 percent of aging drivers correctly responded. Meanwhile, drivers over the age of 65 had a higher correct response rate with flashing circular red indication and flashing yellow permissive indications than all other age groups. Overall, their research indicated an improved response rate for the flashing yellow arrow among users of all ages, as compared to the circular green. Noyce, Bergh, and Chapman (2007) similarly found that the installation of the FYA indication for permissive left-turns provided a safety improvement when added to existing protected/permissive left-turn signal phasing operations. The average annual frequency of total crashes was reduced at 12 of 13 study sites after implementation of the FYA indication, and the average annual frequency of left-turn crashes was reduced at all 13 study sites.

**Anticipated Benefits to Aging Road Users:** The improved recognition and understanding of the flashing yellow arrow increases the likelihood that all drivers, but particularly aging drivers, will wait for an appropriate gap in oncoming traffic before beginning a permissive left-turn maneuver, rather than incorrectly assuming that they have the right-of-way. This, in turn, results in a decrease in the likelihood of right-angle and other crashes (and associated injuries) that are particularly common among aging drivers making unprotected left turns.

# CHAPTER 8
# Interchanges

The following discussion presents the rationale and supporting evidence for *Handbook* recommendations pertaining to these eight proven and promising practices.

## Proven Practices

25. Exit Signs and Markings
26. Freeway Entrance Traffic Control Devices
27. Delineation
28. Acceleration/Deceleration Lane Design
29. Interchange Lighting
30. Restricted or Prohibited Movements

## Promising Practices

31. Route Shield Markings at Major Freeway Junctions
32. Wrong-Way Driving Countermeasures

# PROVEN PRACTICES

## 25 Exit Signs and Markings

A motorist's ability to use highway information from signing and delineation is governed by information acquisition, or how well the source can be seen. It is also governed by information processing, or the speed and accuracy with which the message content can be understood. When either of these key aspects of driver performance is compromised, the result is delayed decision making, erratic behavior, and maneuver errors.

Taylor and McGee (1973) investigated driver behavior at exit gore areas to determine the causes and characteristics of erratic maneuvers. Interviews were also conducted with many drivers whose actions at the gore area were indicative of route choice difficulties. Analyses of the patterns of erratic maneuvers (e.g., cross gore markings, cross gore area, stop in gore, back up, sudden slowing, lane change, swerve, stop on shoulder) and on-site driver interviews were used to determine causative factors of these maneuvers. The most frequent erratic maneuver was crossing the gore marking, which had a 69 percent relative frequency of occurrence for drivers exiting, and a 61 percent relative frequency of occurrence for drivers traveling through the interchange. Most of the motorists who made erratic maneuvers (77 percent) were unfamiliar with the route on which they were traveling. Interviews with exiting motorists who made erratic maneuvers indicated

**Table 40.** Cross-references of Related Entries for Exit Signs.

| Applications in Standard Reference Manuals | | | |
|---|---|---|---|
| ***MUTCD*** **(2009)** | **AASHTO** *Green Book* **(2011)** | **NCHRP 500- Volume 9 (2004)** | **Traffic Engineering Handbook (2009)** |
| Sects. 2A.11, 2A.13, 2A.17, Sects. 2B.03, 2B.37 through 2B.41<br>Tables 2B-1 & 2C-4<br>Sects. 2C.14, 2C.15, 2D.05, 2D.06,<br>Sects. 2E.10 through 2E.12 & 2E.14<br>Tables 2E-2 through 2E-5<br>Sects. 2E.19 through 2E.24<br>Figs. 2E-3 through 2E-16<br>Figs. 2E-22, 2E-26 & 2E-27, 2E-28, 2E-30, 2E-34 through 2E-40<br>Sect. 2E.27<br>Sects. 2E.31 & 2E.33 through 2E.37<br>Sects. 2E-40 through 2E-53<br>Sect. 3B.05<br>Figs. 3B-8, 3B-10, 3B-12, & 3B-23<br>Sects. 3C.01, 3C.03, 3D.01, 3D.02<br>Figs.6H-42 & 6H-43 plus accompanying notes | Pg. 3-146, Final Paragraph<br>Pg. 10-71, Sect. on Signing and Marking<br>Pgs. 10-96 through 10-101, Sect. on Gores<br>Pg. 10-103, Final Paragraph<br>Pg. 10-113, Para. 3 | Pgs. V-15-V-17 Sect. on *Strategy 3.1 B3: Increase Size and Letter Height of Roadway Signs (T)*<br>Pgs. V-22-V-23 Sect. on *Strategy 3.1 B8: Improve Roadway Delineation (T)* | Pgs. 372-373, Sect. on *Sign Sizes*<br>Pg. 391-392, Sect. on *Older Drivers and Pedestrians* |

that more than half of the drivers were not adequately prepared for the exit. These drivers indicated that the signs lacked needed information or that the information was misleading. Interviews with drivers who made erratic maneuvers and continued through, indicated that approximately one-half had difficulty identifying their direction. Approximately 35 percent stated the signing was not clear, 21 percent responded that they could not clearly distinguish the location of the exit ramp, and 34 percent thought the road markings were inadequate.

The following discussion of exit signing issues focuses on the legibility of text, the understandability of diagrammatic guide signs, and the placement of devices to provide needed message redundancy while avoiding information overload.

Prior to the Millennium edition of the *MUTCD*, legibility standards assumed that a 1-in tall letter was legible at 50 ft, which roughly corresponds to a visual acuity of 20/25; as documented in the Transportation Research Board's *Special Report 218* (1988), this "legibility index" value of 50 ft/in exceeds the visual ability of 30 to 40 percent of drivers who are 65 to 74 years of age, even under favorable contrast conditions. The *MUTCD* (2003) section 2A.14 provided guidance for determining sign letter heights, which indicated that sign letter heights should be determined based on 1 inch of letter height per 40 ft of legibility distance. A 40 ft/in standard for signs can accommodate the majority of aging drivers if contrast ratios (between the legend and background) are greater than 5:1 (slightly higher for guide signs) and luminance is greater than 10 cd/$m^2$ (candelas per square meter) for partially reflectorized signs. However, a more conservative standard corresponding to 20/40 vision (i.e., a legibility index of 30 ft/in) would accommodate a greater proportion of aging drivers under a wider range of viewing conditions. The 2009 *MUTCD* (Section 2A.13) has updated the recommendation for letter heights accordingly, stating that a minimum specific ratio of 1 inch of letter height per 30 feet of legibility distance should be used.

Nighttime legibility requirements were addressed by Staplin, Lococo, and Sim (1990), who conducted a laboratory simulation using 28 young/middle-aged subjects (ages 19–49) and 30 older subjects (ages 65–80) to measure age-related differences in drivers' ability to read unique word combinations (of four letters) on green-and-white guide signs. As expected, older drivers required significantly larger letter sizes to read the (unfamiliar) words than younger drivers. Translating the 20-ft subject-to-stimulus distance in the laboratory to a requirement of 600 ft to read a freeway sign, the data showed that older subjects would require a letter height of 24 in, corresponding to an acuity of 20/46. This corresponds to a legibility index of 25 ft/in for positive contrast (lighter characters on darker background) highway guide signs.

In a review of State practices, McGee (1991) reported that Oregon reduced the size of letters on their freeway signs from 13.33 in uppercase and 10 in lowercase to 8 in and 6 in, respectively. They received numerous complaints that the signs were difficult to read at highway speeds and they therefore returned the letter sizes to their original heights (George, 1987). By contrast, North Carolina, in consideration of aging driver needs, increased the Interstate shield size from 36 in to 48 in, the uppercase letter size from 16 in to 20 in, and the lowercase letter size from 12 in to 15 in on guide signs at freeway-to-freeway interchanges (McGee, 1991). No evaluation was planned to determine the effectiveness of this countermeasure.

Garvey, Pietrucha, and Meeker (1997, 1998) conducted daytime and nighttime controlled field studies with aging drivers, to compare word legibility and word recognition distances obtained with the Standard Series E(M) font, and a new font with the proprietary name Clearview®, which was designed to reduce the effects of a phenomenon referred to as "irradiation," "halation," or "overglow." This phenomenon occurs when bright bold strokes bleed into a character's open spaces under headlight illumination, causing the lettering to appear blurry, rendering the text illegible. The study details are presented on page 152 in Chapter 7, Design Element 10 (Street Name Signs). Two versions of this experimental font were employed: one version matched Series E(M) in letter width and height, but because of its smaller intercharacter spacing, it resulted in a smaller word area (referred to in this *Handbook* as Clear 100); and one version contained letters that were increased in size to 112 percent of the standard font, so that the words created with the experimental font (referred to in this *Handbook* as Clear 112) were the same size as the standard font words. The signs were erected with a lateral offset of 12 ft from the center of the observation vehicle (or 6 ft) outside of the right edge line, and were raised to a height of 6 ft above the ground. Study results indicated that during the day, the Series E(M) fonts and both of the experimental fonts produced approximately equal reading distances. At night, using low-beam headlights and bright signing materials, the Clear 112 font (occupying as much sign space as the standard font) produced significantly longer legibility distances (22 percent longer) and recognition distances (16 percent increase) than the Series E(M) font. With highway-size signs on 55-mph roadways, this increased legibility could add up to two full seconds, or an additional 160 ft to the interval in which drivers must read and respond to a sign.

Hawkins,et al. (1999) conducted a study of the legibility of three sign alphabets with lowercase letters: the standard U.S.DOT/FHWA Series E(M); Transport Medium (the alphabet used in Great Britain for overhead guide signs with positive contrast); and Clearview®. The British Transport letters were designed in the 1950's to eliminate irradiation when viewed at nighttime using headlights (Hawkins et al., 1999), and consequently a narrower stroke width is used for positive contrast signs (white legends on a blue or green background) than is used for negative contrast signs (black legends on white, yellow, or orange backgrounds). Also, the letters are designed to fit on tiles, which are placed side-by-side to create words, eliminating the need to measure distances between words as is done in the U.S. Hawkins et al. indicate that the Clearview® font retains the visual proportions of the standard FHWA alphabets, but it also incorporates desirable attributes from foreign and domestic typefaces, particularly British Transport Medium. However, the Clearview® letter is typically wider than the same letter in Transport Medium.

Hawkins et al. (1999) employed 54 individuals to participate in the controlled field study as follows: 7 "young" drivers, age 35 or younger; 18 "young-old" drivers, ages 55 to 64; and 29 "old-old" drivers age 65 and older. Word legibility and word recognition data were recorded as an experimenter drove three subjects at a time toward the test signs, during daytime and nighttime. Each test sign was created using three, six-letter words arranged vertically on the sign, all in the same font, using high intensity white letters on green high intensity sheeting. Signs measured 12 by 9 ft and were either ground mounted or mounted overhead. The ground-mounted signs were erected at a height of 7 ft from the ground to the bottom of the sign, and were placed 30 ft from the right edge of the travel lane. The overhead signs were erected 20 ft above the traveled lane. Each word used a 16-in initial uppercase letter, followed by 5 lowercase letters. The lowercase letter size varied somewhat according to the alphabet type, but was generally 75 percent of the uppercase letter size (12 in).

Results indicated that the Clearview® font was more legible at both the mean and 85th percentile levels than the Series E(M) font for signs placed overhead, both under daytime and nighttime conditions. The 85th percentile daytime legibility index for the young-old drivers was 40, and for the old-old drivers it was 30 ft/in for the Series E(M) font. The extent of the improvement was in the range of two percent, however, some driver groups experienced improvements in legibility distance for the Clearview® font that were over nine percent greater than those experienced with the Series E(M) font. Hawkins et al. state that the improvement was greatest for drivers with poor vision (worse than 20/40). For the ground-mounted signs, Clearview® was less legible under daytime conditions than Series E(M), and only slightly (less than 2 percent) more legible at night. The Transport Medium font did not show improvements in legibility distance over the Series E(M) font.

In terms of recognition distance, for the overhead signs, the Clearview® font produced larger recognition distances than the Series E(M) font, in both daytime and nighttime conditions, except for the drivers with minimum (20/40) vision at night. The extent of the improvement in recognition distance was up to 8.7 percent—considerably higher than the improvements found in legibility distance, and translates to an increase in recognition distance of up to 50 ft. For ground-mounted signs, Clearview® produced a small improvement at night among worst-case drivers, but showed no improvement under daytime conditions. The 85th percentile recognition distance for drivers age 65 and older for ground-mounted signs at night with Clearview® font was 8.6 percent greater than that obtained with the Series E(M) font. Under a few conditions (85th percentile daytime distance for ground-mounted signs for all subjects, and for those age 65+), the Transport Medium font produced recognition distances that were, on average 3 percent greater than those obtained with the E(M) font. At nighttime, the 85th percentile recognition distance for drivers age 65 and older was 12.2 percent higher for Transport Medium font on the ground-mounted signs than for the Series E(M)font. The authors note that the recognition data showed significant variability from one condition to the next, and caution readers to take care in applying the results.

Overall, Hawkins et al. (1999), state that the results of their study indicate that the Clearview® font was more effective than the Series E(M) font in the overhead position, in both daytime and at night, with the greatest improvement achieved for the worst-case drivers. They further indicate that while the Clearview® font may be more appropriate than the E(M) font for overhead signs, ground-mounted signs should continue to use only the Series E(M) alphabet. Hawkins et al. suggest using different design parameters for overhead and ground-mounted signs to account for the differences in performance characteristics of each. They also note that the Clearview® font is an evolving font, and that there are differences in the font used in the Garvey et al. (1997) study and in the current research.

In Knoblauch, Nitzburg, and Seifert's (1997) focus group discussions with aging drivers, participants indicated that they prefer overhead signs to those mounted on the side of the road, stating a need for redundant (overhead) signs to provide advance notice of upcoming exits, including the distances to each, and indicating whether the exit is on the right or left side of the highway. This report, coupled with findings that the Clearview® font provides greater recognition and legibility distance over the standard Series E(M) font when used on overhead signs under both daytime and nighttime conditions, identifies highway destination signs (D1-D3) placed over the highway and fabricated using the Clearview® font as the preferred practice to accommodate aging drivers.

A more recent project was conducted to compare the nighttime legibility distance of the Clearview® font (Clearview® Regular Express) to that of the standard series E(Modified) font on overhead and right shoulder-mounted freeway guide signs, fabricated with either the standard ASTM Type III sheeting or with microprismatic sheeting (Carlson, 2001; Carlson and Brinkmeyer, 2002; and Carlson and Hawkins, 2003). Two types of microprismatic sheeting were evaluated: ASTM Type VIII and ASTM Type IX. Participants in this closed-course field study consisted of 20 young drivers (ages 18-34), 20 middle-aged drivers (ages 35-54), and 20 older drivers (age 55+), with 10 males and 10 females in each group. Each had a valid driver's license, and their acuity ranged from 20/10 to 20/50. Test vehicles included a 2001 Chevy Suburban with tungsten-halogen replacement bulb headlights and a 1989 Ford Crown Victoria, LTD with sealed-beam headlamps. Signs were made using 16-in uppercase letters with 12-in lowercase letter heights. All words were presented on a sign background 12-ft wide by 9-ft tall. Sign legends and backgrounds were made with the same type of retroreflective sheeting. The bottom of each overhead sign was 18 ft above the road surface. The bottom of each shoulder-mounted sign was 9 ft above the road surface with an offset of 24 ft from the edge of the right travel lane to the left of the sign background. Study was conducted on a closed-course facility in a dark rural area with no ambient lighting. Test subjects drove each vehicle type on a runway at night under dry conditions, beginning at a distance where the signs were not legible. They accelerated to 35 mph, set the cruise control, and concentrated on reading the test word on a sign. When the subject read the word correctly, a researcher in the vehicle recorded the distance. Each subject read 56 randomly selected test words equally distributed between the Clearview® Series and the Series E(M) alphabets. Of the 56 words, 40 were located in the shoulder-mounted position and 16 were in the overhead distance. Study findings overall indicated that the combined benefit of microprismatic sheeting and Clearview® font resulted in an increased legibility distance of approximately 75 ft, and were greatest for drivers age 55 and older. Detailed results by sign location are provided below.

For shoulder-mounted signs, the overall mean legibility distance associated with Clearview® was 32 ft greater (a 5.2% improvement) than for Series E(M). Improvements in mean legibility distances ranged from 18 to 58 ft, with the largest differences occurring with the sealed beam headlamps and the Type IX sheeting. Assuming a 70 mph roadway, the improvements would result in added time to read a sign between 0.2 and 0.6 sec; for a 55 mph roadway, improvements would range from 0.2 to 0.7 sec. The increased legibility distances associated with the Clearview® alphabet were statistically significant. The largest difference between the Clearview® and the Series E(M) alphabets were associated with aging drivers, where legibility differences were 6.0 percent longer with the Clearview® than the Series E(M). This difference equates to an additional 0.45 sec of reading time for aging drivers. Legibility differences were 5.8 percent and 4.6 percent greater for the Clearview® than the Series E(M) font, for young and middle-aged drivers respectively. The effect of age was significant, as were the main effects of alphabet and sheeting. The interaction between age and alphabet was not significant, however.

For overhead guide signs, overall mean legibility distances were 53 ft greater for the Type IX sheeting than for the Type III sheeting (a 9.5% improvement). Type VIII sheeting was not tested on overhead signs, but would be expected to provide longer legibility distances than Type IX sheeting. The effect of sheeting type was significantly significant, with legibility distances significantly greater with Type IX sheeting than for Type III sheeting. Luminance values and legibility distances were significantly greater for the sealed beam headlights than for the tungsten-halogen bulbs. For Type IX sheeting, the overall mean legibility distance for the Clearview® alphabet was 40 ft greater than for the Series E(M) alphabet (a 6.7% improvement). The main effect of age was significant, as was the interaction between age and alphabet. As age increased, the benefits of Clearview® were more pronounced. For the aging drivers, Clearview® provided an increase in legibility distance of 33 feet, or 6.8% (compared to increases of 2.3% and 3.5% for young and middle-aged drivers). The increased legibility distance results in an additional 0.33 seconds of reading time, assuming a 70 mph) highway.

A legibility analysis using the data collected in the field within the ERGO program showed the sequential and overall benefits in legibility distance expected by switching from Type III sheeting to microprismatic sheeting and by switching from Series E(M) alphabet to Clearview® alphabet. For overhead signs, switching from Type III sheeting with Series E(M) to microprismatic sheeting with E(M) increases mean legibility distance by 44 ft. Switching from microprismatic sheeting with E(M) to microprismatic sheeting with Clearview® adds another 30 ft. Together, switching from Type III with Series E(M) to microprismatic with Clearview® would increase legibility distance by 70 ft, an 11.9 percent improvement. Assuming a 70 mph highway, the overall legibility improvement provides drivers with an extra 0.68 s to read an overhead guide sign (and for 55 mph it is an extra 0.86 s). Assuming a last look distance equal to 3 s before passing the sign, these time improvements equate to a 24.4 percent increase in time to read an overall guide sign at 70 mph and an increase in 21.2 percent on a 55 mph highway. For shoulder-mounted guide signs, switching from Type III sheeting with Series E(M) to microprismatic sheeting with E(M) increases mean legibility distance by 41 ft. Switching from microprismatic sheeting with E(M) to microprismatic sheeting with Clearview® adds another 33 ft. Together, switching from Type III with Series E(M) to microprismatic with Clearview® would increase legibility distance by 74 ft, a 12 percent improvement. Assuming a 70-mph highway, the overall legibility improvement provides drivers with an extra 0.72 s to read an overhead guide sign (and for 55 mph it is an extra 0.92 s). Assuming a last look distance equal to 3 s before passing the sign, these time improvements equate to a 24.1 percent increase in time to read an overall guide sign at 70 mph) and an increase in 19.8 percent on a 55 mph highway.

FHWA issued an Interim Approval for the optional use of the Clearview® font for positive contrast legends on guide signs on September 2, 2004. The conditions of Interim Approval are specified at http://mutcd.fhwa.dot.gov/res-ia_clearview_font.htm.

Carlson and Holick (2005) conducted a controlled field study to determine how the legibility of full-scale unlit guide signs could be maximized with combinations of font and retroreflective sheeting. A total of 30 subjects participated, distributed equally across three age groups (ages 18 to 34; 35 to 54; and 55+), with equal numbers of males and females in each age group. Two fonts were studied: Series E (Modified) and Clearview® 5WR, where "R" stands for "reduced," designed to produce the same word lengths on a sign as Series E (Modified). Clearview® 5WR has letter spacings reduced by 6.4 percent from the standard Clearview® 5W. Five combinations of retroreflective sheeting were studied:

- Type III legends on Type III backgrounds, where Type III was 3M high-intensity encapsulated-lens glass-bead material.
- Type VIII legends on Type III backgrounds, where Type VIII was Avery Dennison T-7500 sheeting, a super-high-intensity microprismatic material.
- Type IX legends on Type III backgrounds, where Type IX was 3M Visual Impact Performance sheeting, a very high-intensity microprismatic material.
- Type VIII legends on Type IX backgrounds
- Type IX legends on Type IX backgrounds.

Two luminance levels were studied: low-beam headlamps at full power and lowbeam headlamps at 27 percent power, to simulate the possible ranges in sign luminance that could result from different conditions such as sign position (over-head or shoulder mounted), signs viewed from heavy trucks, and vehicles with poorly maintained or misaimed headlights. These levels corresponded to 13.0 and 3.6 cd/m$^2$ for the white Type III materials at 640 ft, based on research showing a 50th percentile minimum required luminance of 3.4 cd/m$^2$ for a legibility index of 12.2 m per 40 ft/in of letter height.

All guide signs used in the Carlson and Holick (2005) study had white 16-in uppercase letters on a green background. The lowercase letters were the appropriate size, depending on the font used. Half of the signs were constructed with Series E(Modified) font and half with Clearview® 5WR font. The signs were posted to follow current signing practices as closely as possible (9 ft above the road surface and 30 ft from the edge of the travel lane). The study was conducted on a closed-course facility in a dark rural area with no ambient lighting. Subjects drove a 2000 Ford Taurus sedan, with an experimenter in the front passenger seat who (unaware to the subjects) controlled the headlamp illumination level (to produce two levels of sign luminance throughout the study). Subjects were told to read the word on the guide sign as soon as they could correctly identify it, and that there was no penalty for being wrong.

The effect of font on legibility distance was significant, with the average legibility distance for Clearview® 5WR 593 ft compared to 570 ft for Series E(Modified). In a smaller and independent study conducted within this study, Clearview® 5W was compared to Clearview® 5WR, and the two fonts produced statistically equivalent results, with the legibility of Clearview® 5W equal to 593 ft and the legibility of Clearview® 5WR equal to 590 ft compared with Series E(Modified), which produced an average legibility distance of 539 ft.

For each age group studied by Carlson and Holick (2005), all combinations of sheeting produced higher legibility distances compared to Type III on Type III. Sign brightness was statistically significant and was most evident for the aging subjects. The mean decrease in sign legibility from the full headlight to the reduced headlight condition was 8.5 percent for the young group, 3.3 percent for the middle group, and 16.7 percent for the older group.

All signs with microprismatic legends performed significantly better than signs with Type III legends. There were no significant differences in legibility distance between signs made with microprismatic legends. Signs made with microprismatic backgrounds performed statistically similarly to signs made with high-intensity backgrounds.

The longest legibility distances were achieved with a microprismatic legend on a microprismatic background, but the legibility distances were not statistically different from those achieved with microprismatic legends on Type III backgrounds. The study authors state that this is important because of the cost of the microprismatic materials ($3.00 to $4.00 per sq/ft) compared to the cost of Type III materials ($1.00 to $1.50 per sq/ft.)

Collapsing data across subject age and luminance level, and using only Clearview® font (based on its significantly longer legibility distances), the legibility distances are shown in Table 41 for the retroreflective sheeting types. Combinations within the two groupings (* or x) had statistically similar legibility means.

**Table 41.** Legibility distance on the basis of legend and background sheeting type

| Legend Sheeting Type | Background Sheeting Type | Legibility Distance | Significance Grouping (legibility means with the same symbol are not significantly different from each other) |
|---|---|---|---|
| VIII | IX | 626.4 ft | * |
| IX | III | 602.4 ft | * |
| IX | IX | 595.4 ft | * X |
| VIII | III | 591.5 ft | * X |
| III | III | 549.9 ft | X |

Caution must be taken with the finding by Carlson and Holick (2005) that legibility distance was not affected by background sign material, considering the small sample size within each group. Although the study authors recommend the use of Type II backgrounds over microprismatic backgrounds as a cost-saving measure, earlier findings by Carlson and Hawkins (2003) provide a rationale to first recommend the use of microprismatic materials for both the legend and the background, and then allow for the use of Type III materials for the background if cost is an issue. Carlson and Hawkins (2003) recommended that microprismatic sheeting be used on overhead signs in place of encapsulated sheeting, as a countermeasure for the increasing number of SUVs on the road with reduced headlight illumination on signs. In that study, the legibility distances were smaller for drivers in the Subaru (with larger observation angles, tungsten-halogen bulbs, and reduced light directed toward the sign) than the LTD (a passenger car with smaller observation angles, sealed-beam headlamps, and increased light directed toward the sign).

Moving from a consideration of legibility issues to the broader question of how well a motorist can actually use highway sign information, reading time and ease of recall for sign messages deserve attention. Reading time is the time it actually takes a driver to read a sign message, contrasted with exposure time or available viewing time, which is the length of time a driver is within the legibility distance of the message. As drivers travel, they must look away from the highway to read signs posted overhead or at the side of the road, and then back to the roadway. During each glance, the maximum amount of text that can be read is three to four familiar words or abbreviations. A motorist's rapid understanding and integration of message components in memory will greatly assist his/her recall of the message while deciding upon a response. Two errors in message presentation must be avoided: (1) providing too much information in too short a time and (2) providing ambiguous information that leaves either the intent of the message or the desired driver response uncertain.

Mace, Hostetter, and Seguin (1967) conducted laboratory, controlled field, and observational field studies to evaluate how information presentation time (the amount of time that a sign is readable to a driver) and information lead distance (the distance from an exit that the advance sign is placed) affect exiting behavior at freeway interchanges. They found that 0.25 mi is inadequate for information lead distance and, because there were few differences in driver exiting behavior with information lead distances of 0.5 mi and 1.0 mi, that 0.5 mi is optimal. In addition, a viewing time of 5 s was adequate for signs containing one to four pieces of information. Lunenfeld (1993) noted that a driver's short-term memory span is between 0.5 and 2 min, and that drivers may forget advance interchange information messages if the time span between the advance notification and the exit ramp exceeds the memory limit. He advocates the use of repetition for interchange information treatments (multiple/successive signs), which will also aid in situations where a sign is blocked by foliage or trucks.

The effect of diagrammatic signing on driver performance at freeway interchanges was studied by numerous researchers in the early 1970's. Bergen (1970) found that graphic guide signs permitted significantly better route guidance performance than conventional signs on certain interchanges, such as collector-distributor with lane drop and multiple split ramps. In pilot studies conducted in New Jersey, Roberts (1972) found that diagrammatic signs that included lane lines were more effective (resulted in a significant reduction in erratic maneuvers) than conventional signs at the interchange of I-287 and U.S. 22, a complex interchange with both left- and right-side exits. Flener (1972) commented on the difficulty in evaluating the effectiveness of traffic control devices in reducing erratic maneuvers at exit gore areas using before and after designs, due to the "novelty effect." Although Roberts (1972) noted that the change could be attributed to the greater attention-getting value of novel signs, it was demonstrated that diagrammatic guide signs provide advance information that is readable at a farther distance than that provided by conventional sign text, as well as information about the number of lanes available for any one movement.

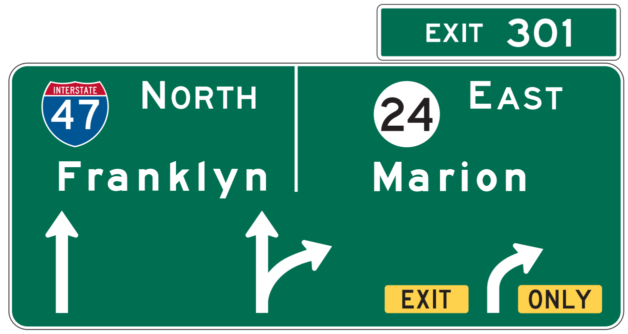
Roberts, Reilly, and Jagannath (1974) studied the effectiveness of diagrammatic versus conventional guide signs in a field study at 10 sites. The results were mixed. Several sites showed a reduction in stopping, backing, or weaving erratic maneuvers after installation of the diagrammatic signs. Some sites showed a reduction in stopping and backing maneuvers but an increase in weaving maneuvers (or vice versa). Still other sites showed no change as a function of sign type. Stopping and backing erratic maneuvers were reduced, however, at 9 of the 10 sites.

Taylor and McGee (1973) noted that the main advantage of diagrammatic signing lies in the ability to provide information regarding the interchange layout prior to the exit area. Sign format, however, remains an issue. Conflicting evidence on the effectiveness of diagrammatic signs was reported by Gordon (1972), who found that conventional signs produced fewer lane-placement errors and errors on exit lanes and were more quickly responded to than experimental diagrammatic signs tested at six interchanges in a laboratory study. At the same time, an analysis of particular diagrammatic designs showed that when a diagrammatic sign provided a single arrow or a forked arrow, reaction time was faster and there were fewer errors compared with the conventional sign. Zajkowski and Nees (1976) studied subject response time and correctness of lane choice as a function of sign type, in the laboratory. They found that response times were consistently longer for diagrammatic signs than for conventional signs; however, the difference may have been attributable to an increase in information on diagrammatic signs. There were more correct lane-choice responses for conventional signs, and subjects reported more confidence in their lane-choice decisions and a preference for conventional signs. Mast, Chernisky, and Hooper (1972) found that some drivers may require more time to read and interpret information on diagrammatic signs in comparison with conventional signs, and driver information interpretation time may increase as the graphic component of the sign becomes more complex.

Aging drivers participating in focus group discussions have indicated that they prefer large, lighted overhead signs with arrows that indicate the lanes for specific destinations, especially if they are approaching a fork in the road (Knoblauch, Nitzburg, and Seifert, 1997). These aging drivers stated that the arrows on the overhead signs do not always point to the correct lane, causing drivers to change lanes needlessly; they also stated a desire to see signs that indicate when two travel lanes bear to the same destination.

Brackett, et al. (1992) conducted a survey of 662 drivers in three age groups (younger than age 25, ages 25-54, and 55 and older) comparing alternative methods of providing lane assignment information on freeway guide signs. The findings of several comparisons in the research are reported, although no analyses using age as an independent variable were performed. First, when two common routes were displayed side by side on an exit guide sign, approximately one-half of the drivers believed that the destinations referred to different routes to be accessed by different lanes (i.e., drivers spatially cluster information with each arrow, assuming that information located on the left side of a sign is associated with an arrow also on the left side, and information on the right side is associated with EXIT ONLY or EXIT ONLY with an arrow). When destinations were arrayed one below another, 85 percent of the drivers understood that they were a common route. Second, white downward arrows used in a side-by-side format with an EXIT ONLY (E11-1) panel to indicate that two lanes could exit, were misunderstood by 80 percent of the subjects. Third, 56 percent of drivers misinterpreted the phrase NEXT RIGHT on conventional signs as an indication of a mandatory exit, and 30 percent misinterpreted the phrase NEXT LEFT in the same manner, when these signs were placed over the right and left lanes, respectively. Fourth, when conventional *MUTCD* diagrammatic signs were compared with modified diagrammatic signs that provided separate arrows for each lane, the modified diagrammatic signs resulted in a 13 to 17 percent greater understanding of when a lane must exit and when an adjacent lane may exit or continue through (two-lane exit with optional lane). When the number of arrow shafts exceeded the number


a




b

**Figure 92.** Example of *MUTCD* diagrammatic sign (a) and modified diagrammatic sign (b) used in comprehension evaluation (Brackett, Huchingson, Trout, and Womack (1992))

of lanes (for example, when there is an auxiliary exit lane downstream of the overhead sign), less than 30 percent of the respondents understood that there would be an added exit lane downstream on the right. With one arrow per lane, comprehension increased by 28 percent over when there were more arrows than lanes (optional use or added lanes). Figure 92 display an example of a conventional diagrammatic sign (from Section 2E.20 of the 2003 *MUTCD*) and a modified diagrammatic sign for this exit situation. The sign in Figure 92b resembles the recommended sign shown in Figure 2E-3 of the 2009 *MUTCD*; Figure 92a is similar to the sign shown in Figure 2E-7 of the 2009 *MUTCD*.

The benefit of using one (upward-pointing) arrow per lane to show the number and direction of lanes for a given highway geometry on freeway guide signs was demonstrated by Golembiewski and Katz (2008). Twenty-four younger (mean age = 33) and 24 older (mean age = 79) drivers viewed five alternative diagrammatic sign designs at the Highway Sign Design and Research Facility at the FHWA Turner-Fairbank Highway Research Center. As the signs were presented to participants, they indicated by a button press when they were sure of which lane(s) could be used to get to their destination. The distance to each sign when the choice was made (decision sight distance) and the correctness of each decision were recorded.

The five designs evaluated in this study included 1) Standard, which followed the 2003 *MUTCD* guidance for freeway guides signs at lane splits; 2) Modified, which followed the same guidance but included Exit Only placards where appropriate; 3) Enhanced, which followed the *MUTCD* guidance but had wider dashed lines and wider arrowheads; 4) Enhanced Modified, which was similar to Enhanced, but included Exit Only placards when appropriate; and 5) Arrow Per Lane, which used upward pointing arrows centered over each lane to indicate movements appropriate for that lane. All study participants viewed all sign designs in a repeated-measures design, counterbalancing the order of presentation across subjects.

Signs using the Arrow Per Lane design yielded significantly better performance for aging drivers than the other types. While the performance of younger participants was significantly better than that of the older participants they, too, benefited from this design. These findings indicate that the Arrow Per Lane sign type is appropriate for all drivers and is especially beneficial for aging drivers. Golembiewski and Katz (2008) conclude that, because signs in this experiment were presented without the surrounding roadway context, the present study may even underestimate the benefit of this design relative to the others evaluated.

# 26 Freeway Entrance Traffic Control Devices

Violations of driver expectancy, use of alcohol, and reductions in the ability to integrate information from multiple sources to make navigation decisions while concurrently controlling the vehicle may all result in driver confusion at critical decision points, resulting in wrong-way maneuvers. Tamburri and Theobald (1965) found that many aging drivers and drinking drivers did not know where their wrong-way movement began (i.e., they could identify neither where the decision point was nor the location of the wrong-way maneuver). The information provided for this design element focuses on positive signing and ramp design for freeway entrances, as well as the use of advanced diagrammatic guide signs on urban multilane arterials leading to freeways, while design element 30 focuses on wrong-way signing and pavement markings at interchanges.

Age-related diminished capabilities contributing to wrong-way movements include the cognitive capabilities of selective attention and divided attention, and the sensory/perceptual capabilities of visual acuity and contrast sensitivity. Selective attention refers to the ability to identify and allocate attention to the most relevant targets in the driving scenario on an instant-to-instant basis, while divided attention refers to the ability to perform multiple tasks simultaneously. Individuals less capable of switching attention, or who switch too slowly, may increase their chances of choosing the wrong response or choosing the correct response too slowly. Treat, et al. (1977) reported that 41 percent of crashes in which aging adults were involved were caused by a failure to recognize hazards and problems, and that 18 to 23 percent of their crashes were due to problems with visual search. The selective attention literature generally suggests that for adults of all ages, but particularly for aging drivers, the most relevant information must be signaled in a dramatic manner to ensure that it receives a high priority for processing in situations where there is a great deal of complexity at the level of information to be processed.

In their study of highway information systems, Woods, Rowan, and Johnson (1970) found that motorists frequently experience difficulty in locating entrance ramps to freeways, and drivers were often confused when there were several side roadways intersecting in close proximity to the interchange area. These researchers suggested that more efficient use could be made of "positive" signing techniques in guiding motorists to the freeway entrance ramps and discouraging drivers from possible wrong-way maneuvers.

**Table 42.** Cross-references of related entries for freeway entrance traffic control devices.

| Applications in Standard Reference Manuals | | | |
|---|---|---|---|
| *MUTCD* (2009) | AASHTO *Green Book* (2011) | NCHRP 500 – Volume 9 (2004) | Traffic Engineering Handbook (2009) |
| Sects. 2A.23, 2B.37, & 2B.38<br>Tables 2B-1 & 2C-1<br>Sects 2D.45, 2E.52, 2B.41, 2E.53, 3B.20, 3D.01<br>Figs. 3B-24, 2B-18, 2B-19,<br>Figs. 2D-11 through 2D-16 | Pgs. 10-83 through 10-87, Sect. on Wrong-Way Entry | Pg. 23, Paras. 1-2 | Pgs. 372-373, Sect. on *Sign Sizes*<br>Pg. 391-392, Sect. on *Older Drivers and Pedestrians* |

Woods et al. (1970) indicated that positive signing which indicates the correct path or turning maneuver to the motorist rather than a restriction may help most to minimize driver confusion at freeway interchanges. Examples include route markers, trailblazers, and a FREEWAY ENTRANCE sign that positively designates an entrance to the freeway. The California Standard specifies that large FREEWAY ENTRANCE signs (48 in x 30 in) be placed on on-ramps, but the location of the sign package (FREEWAY ENTRANCE sign, plus route shield, cardinal direction sign, and down diagonal arrows) should not be controlled by the use of the larger signs; smaller signs (36 in x 21 in) may be used for proper placement, if necessary.


**Figure 93.** Ground-Mounted Diagrammatic Guide Sign for Urban Multilane Arterial, Used by Zwahlen et al. (2003)

Advance guide signs on multilane highway approaches to an interchange provide drivers with information about which lane they should use to enter the freeway in the desired direction of travel. Interchanges may require right turns from the multilane arterial for both available directions of travel on the freeway (cloverleaf interchanges), a left turn to travel left and a right turn to travel right (diamond interchange), or other combinations of right and left turns. This lack of consistency coupled with late recognition of the required entrance ramp lane may result in last-second lane-change maneuvers that increase the potential for crashes. Advance information is important for preventing erratic, risky lane change maneuvers during the approach to the interchange. Although it is desirable to present this information on overhead guide signs, it is costly and not always feasible. Zwahlen, et al. (2003) evaluated the effectiveness of ground-mounted diagrammatic guide signs on urban multilane arterials leading to freeways as a lower-cost alternative to overhead span-type sign bridges. In this field study conducted in actual traffic, 40 drivers (20 males and 20 females) who were unfamiliar with the test city area (Columbus, OH) drove an instrumented vehicle and were accompanied by an experimenter who provided instructions. The average age of the participants was 20 years old, and acuity was described by the researchers as "good." Ground-mounted diagrammatic signs were placed 0.5 mi and 0.25 mi along urban multilane arterials in advance of 6 highway interchanges before the last point of the gore (see Figure 93). The letter height for the destination letters was 6 in for uppercase letters and 4.5 in for lowercase letters. The letter height for the cardinal directions was 6 in (152 mm). The FHWA standard alphabet was used. The arrows were 8 in wide by 90 to 104 in long. All signs were fabricated with microprismatic Stimsonite 6200 traffic signing material (meeting ASTMD 4956 Type III and IV. These signs supplemented existing trailblazer assemblies on entrance ramps.

Subjects in the Zwahlen et al. study began in a parking lot and were asked to start driving and to merge with traffic on a multilane arterial approximately 3 mi in advance of the test interchange. The experimenter told subjects to find their way to a specific freeway entrance ramp (i.e., I-270 Northbound); subjects were always started out in the wrong lane for accessing the freeway in the direction given by the experimenter. The measure of effectiveness was the distance from the point at which the subject realized he or she was in the wrong lane and a lane change was required, to the interchange gore. The study was performed at night to avoid the daytime delays associated with the freeway interchanges. Twenty-one subjects participated before the advanced diagrammatic signs were installed, and 19 drivers participated after installation of the signs. Subjects who participated in the "before" condition did not participate in the "after" condition. Overall, the "after" condition (diagrammatic guide signs present) was associated with a substantial, statistically and operationally highly significant improvement in lane change distance. Combining all six sites, the 50th percentile lane change distance in the "before" condition was 1,237 ft and in the "after" condition 2,686 ft. The 85th percentile lane change distance in the "before" condition was 666 ft and in the "after" condition 1,971 ft. These distances represent an increase in lane change distance by a factor of 2.2 and 3.0 between the before and after conditions. With ground-mounted diagrammatic guide signs, the test subjects (who were unfamiliar to the area) were able to initiate a lane change from the incorrect lane much earlier (4 to 5 times earlier at some interchanges) than in the period before the signs were installed. Although aging drivers were not represented in the sample, it is logical that they would benefit from upstream, redundant signing using positive guidance principles.

Aside from difficulties in the use of signs, problems for aging drivers at interchanges most likely to result from (age-related) deficits in spatial vision relate to the timely detection and recognition of pavement markings and delineation. Data from a study by Blackwell and Blackwell (1971) show that between age 20 and age 70, aging directly reduces contrast sensitivity by a factor of about 3.0. Mace (1988) stated that age differences in glare sensitivity and restricted peripheral vision coupled with the process of selective attention may cause higher conspicuity thresholds for aging drivers. Overall, these deficits point to the need for more effective and more conspicuous signing and delineation.

Vaswani (1974) identified specific sources of wrong-way movements where alcohol was believed not to be a factor. In this study, exit ramps on partial interchanges generated wrong-way maneuvers because, unlike the ramps on full interchanges that converge with right-hand traffic, the ramps meet the crossroad at about 90 degrees to accommodate both left and right turns. Therefore the wrong-way entries consist of left turns off of the exit ramp into wrong-way traffic on a two-way divided highway, right turns from the divided highway into traffic exiting the ramp, and left turns from the crossroad into the exit ramp. At intersections with four-lane divided highways (divided arterial and primary highways), 45 percent of the wrong-way entries were at their intersections with exit ramps or secondary roads. The wrong-way entries were due to left-turning vehicles making an early left turn rather than turning around the nose of the median. Almost all these crashes involved sober drivers.

Some ramp designs are more problematic than others. In Tamburri and Theobald's 1965 analysis of 400 wrong-way incidents where entry was made to the freeway via an off-ramp, the trumpet interchange category had the highest wrong-way entry rate, with 14.19 incidents per 100 ramp-years, and the full cloverleaf interchanges had the lowest wrong-way entry rate, with 2.00 incidents per 100 ramp-years. Parsonson and Marks (1979) also determined that several ramp types were particularly susceptible to wrong-way movements, as follows: half-diamond (3.9 per month), partial cloverleaf ("parclo") loop ramp (11.0 per month) and parclo AB loop ramp (6.7 per month). The parclo loop ramp and the parclo AB loop ramp share the same problem, which is an entrance and exit ramp in close proximity. The half-diamond is susceptible because it is an incomplete interchange, and drivers may make intentional wrong-way entries. A "problem" ramp has been defined as one that experiences more than five wrong-way movements per month; a corrected ramp has less than two per month (Rinde, 1978).

Vaswani (1974) found that on almost all the interchanges on which wrong-way entries had been made into the exit ramp or from the exit ramp onto the crossroad, the corner of the exit ramp flared into the right pavement edge of the crossroad. He suggested that such a flare provides for a very easy but incorrect right-hand turn, and may help to induce a driver to make a wrong-way entry from the crossroad into the exit lane. A countermeasure consisting of a sharp right-hand junction would require a driver to reduce speed and almost come to a stop before maneuvering into the left lane, and would also reduce the chances that a driver exiting the ramp would turn left into wrong-way traffic on the crossroad. Site inspections showed that where the flare was not provided and the left lane of the exit ramp and the passage through the median were channelized, no wrong-way entry to or egress from the exit ramps was reported. Additionally, Vaswani (1974) reported that generous widths of an exit ramp with its junction with the crossroad make wrong-way entry or egress from the exit ramp easy. Narrow pavement widths will discourage such entries. A serious impediment to turning maneuvers by heavy vehicles could also result from this strategy, however.

Vaswani (1974) also indicated that too large a set-back of the median noses from the exit ramp increases the width of the crossover and makes the intersection harder to “read.” Vaswani suggests that if the width cannot be reduced, then pavement nose markings in the form of a striped median should be applied, for improved visibility of this design element. See also the discussion on page 122 of this *Handbook* for design element 5, about extending delineation treatments from a set-back median nose to the intersecting roadway.

## 27 Delineation

The following discussion of exit ramp gore delineation focuses on studies conducted to determine which treatments are necessary to ensure rapid and accurate detection of the gore location and ramp heading, particularly under nighttime or reduced visibility conditions.

Taylor and McGee (1973) reported that the location of the gore is usually perceived easily during daylight hours, because a driver can rely on a direct view of the geometry, as well as signing and delineation. However, this task becomes considerably more difficult during darkness, because the driver can no longer rely on a direct view of the geometry, and exit gore signing may be misleading because of the inconsistency in the distance

**Table 43.** Cross-references of related entries for delineation.

| Applications in Standard Reference Manuals | |
|---|---|
| *MUTCD* (2009) | AASHTO *Green Book* (2011) |
| Sects. 2C.09 & 3F.03 | Pg. 8-17, Paras. 1-2<br>Pgs. 10-89 through 10-101, Sect. on General Ramp Design Considerations |

at which it is placed from the nose of the gore area from location to location. At night, delineation is probably the most beneficial information source to the exiting motorist, because it outlines and therefore pinpoints the location of the gore.

Taylor and McGee (1973) measured the effects of the presence of gore area delineation on driver performance at night, to determine which of various delineation devices (pavement markings, post delineators, raised pavement markers (RPMs), and a combination of treatments) were most effective. Measures of effectiveness included the point of entry into the deceleration lane, the exiting speed, and any erratic maneuvers. Two right-hand exits, one with a parallel-lane type of deceleration lane and one with a direct-taper type, were selected as test sites. Specifically, the treatment conditions were: (1) post delineator treatment—yellow post delineators placed along the ramp edge of the gore area, plus white delineators positioned along the through side; (2) RPM treatment—yellow RPM's placed on the ramp side of the gore (paint) markings, plus white RPM's on the through side; and (3) combination treatment—the post delineator treatment and the RPM treatment installed in combination.

The baseline condition for this study was moderately worn painted diagonal gore markings and edge lines, with no other delineation devices. All three delineation treatments produced earlier points of entry into the deceleration lane than under the baseline condition. The RPMs were more effective than the post delineators and produced earlier exiting points. The earliest exiting points were found with the combination of RPM's and post delineators. Gore area delineation reduced the frequency of erratic maneuvers at night at both sites. The RPM technique and combination treatment produced significantly lower exiting speeds than did the use of post delineators at one site, and all three treatments produced lower exiting speeds compared with the baseline condition.

The work by Taylor and McGee (1973) also included a comprehensive review of several case studies. As a result of their state-of-the-art summary, coupled with the results of their field observations in the study outlined above, a set of recommendations was developed for pavement marking delineation, post delineators, and RPMs; these recommendations, which have since been widely implemented, are described below.

For pavement marking delineation:

- 8- to 12-in wide white lines should be used to outline the exit gore, and where additional emphasis is necessary, diagonal or chevron markings are recommended.
- An 8-in wide line with a 5-ft mark and 15-ft gap should be used as an extension of the mainline right edge line (or median edge line for left exits) and should replace the lane line for at least 1,000 ft upstream from the gore nose at an exit lane drop.

For post delineators:

- Post delineators should be placed in the gore area to enhance nighttime visibility. White delineators are recommended for the through roadway side, and yellow delineators should be used on the exit side. A spacing of 10 to 20 ft, depending on ramp divergence angle, is recommended.

- Yellow delineators should be placed along the right edge of the deceleration lane at a spacing of 100 ft. Beyond the beginning of the gore, the spacing is dependent on the degree of curvature.
- White delineators should be placed on the inside shoulder of the through roadway, at a spacing of 100 ft, to help strengthen the through-way delineation in the exit area.

For RPM's:

- Raised pavement markers are recommended as a supplement to standard gore pavement markings and should be placed inside the "V" formed by the pavement marking lines.
- Raised pavement markers should be supplemented with post delineators where the view of the roadway is limited, such as at vertical sections.

Other researchers have also evaluated the effects of RPM's at exit gore locations. RPM's have been shown to reduce erratic maneuvers through (painted) gores at exits and bifurcations.

Hostetter, et al. (1989) conducted a controlled field study using 15 subjects ages 18 to 60+, to determine the effect of lighting, weather, and improved delineation on driver performance. Data were obtained on two exits in dry and wet weather under full lighting with baseline delineation (see diagram in Recommendation 20 (A1)). The baseline system is similar to the delineation used at many of the partially lighted interchanges cataloged by the study authors during site selection, and in the opinion of an expert panel convened during the research, constituted a minimum system for partially lighted interchanges. Data were then obtained under partial lighting, with baseline and three improved delineation systems.

Upgrade 1 investigated by Hostetter et al. (1989) differed from the baseline in the use of RPM's along the left ramp stripe, and the substitution of fully retroreflective posts (46-in strip of 3-in wide sheeting) for partially retroreflective posts (18-in strip of 3-in wide sheeting) in the physical gore. Upgrade 2 differed from the baseline in the deployment of additional posts along the left ramp shoulder to create a spacing of 50 ft rather than 100 ft and in the installation of wide RPM's ("traffic diverters") on the gore strips to replace the 4-in RPM's placed adjacent to the gore stripes in the baseline system. Upgrade 3 replaced all baseline system partially retroreflective posts with fully retroreflective posts except in the gore, used RPM's along the left ramp stripe, and used beaded profiled tape containing a raised-diamond pattern for gore striping. The tape was used because it would project above a film of water during rain. The test sites were a half-diamond interchange and a full diamond, which contained very little ramp curvature. The exit ramps were 14 ft wide, with a single lane widening to two lanes near the intersection with the crossing roadways. Measures of effectiveness included ramp and spot/trap vehicle speeds, overall travel time, deceleration estimates, and lane placement, as well as selected types of erratic maneuvers and brake and high-beam headlight activations.

Analysis of delineation effects on ramp and spot speeds, and on speed distributions showed few differences under dry conditions. Under rainy conditions, effects were stronger but were neither large enough nor consistent enough to recommend improved delineation over the baseline system. Although Upgrade 3 produced fewer edge line encroachments under both dry and wet conditions, from the standpoint of operations, safety benefit, or cost-effectiveness, the upgrade did not demonstrate enough advantage to merit a recommendation for use on diamond interchanges with little ramp curvature.

Lerner, et al. (1997) conducted a series of laboratory and field studies to identify conspicuity and comprehensibility problems with current object markers across various hazardous situations, for young-middle/aged drivers (ages 20 to 40); young-old drivers (ages 65 to 69) and old-old drivers (age 70 and older). In addition, novel object markers and pavement markings were evaluated to determine whether they improved conspicuity or understanding over the current Types 1, 2, and 3 object markers. With regard to object markers used at gore areas, the MUTCD (Section 2C.65) states that in some cases "there might not be a physical object involved [that needs to be marked], but other roadside conditions exist, such as narrow shoulders, drop-offs, gores, small islands, and abrupt changes in the roadway alignment, that might make it undesirable for a road user to leave the roadway, and therefore would create a need for a marker."

In the laboratory experiment conducted by Lerner et al., 64 subjects viewed color photographic illustrations of an object marker situated within a roadway scene. Six stimuli were used to mark gore areas: (1) a Type-1 object marker; (2) a Type-3 object marker; (3) yellow cones; (4) green cones; (5) modified French gore signs (signs used in France, consisting of two, white isosceles triangles pointing left and right on a green background, were modified to show black triangles with a cut-out base pointing left and right on a yellow background); and (6) a novel treatment displaying double modified chevron arrows (directional arrows pointing left and right, derived from the chevron alignment sign, consisting of black arrows on a yellow background). The dependent measure was the correctness of response (e.g., the subject correctly identified the hazard or described the correct driving action). Percent-correct ratings for each marker presented in a gore situation across age were as follows: Type-1 (80%); Type-3 (75%); yellow cones (46.7%); green cones (73.3%); French gore markers (56.3%); and double modified chevrons (87.5%). For drivers over age 70, the percent correct ratings were as follows: Type-1 (83.3%), Type-3 (76.8), and double modified chevron (100%). One finding of interest that should be highlighted here, is the lack of understanding of directional information presented by a solitary Type-3 object marker. In a study conducted during the problem identification stage of this research, participants were correct 39 percent of the time about the direction the marker conveyed (i.e., drive in the direction of the downward pointing stripes).

Next, the object markers were viewed on a test track by different groups of subjects in the same three age ranges to determine daytime and nighttime detection distances. Each trial began at 1,000 ft. An experimenter drove along a test track toward the object marker, with the subject seated in the passenger seat. When a subject was just able to discriminate some feature of the marking, the experimenter was told to stop, and this detection distance was recorded. The experimenter then continued to drive toward the marking, stopping every 50 ft, at which point the subject described the salient features of the marking. In addition to the markers described above, the following pavement markings were also evaluated: a double edge line pavement marking, and diagonal hash mark pavement markings. The first finding of interest was that the threshold distances were significantly greater for the post-mounted marker types than for the pavement marking types. There were no main effects of age group or marker type for the pavement markings and no interactions between these variables. The mean nighttime detection distance for the hash marks was 224 ft and for the double edge line 226 ft. By comparison, all of the subjects detected all of the other post-mounted markers at 1,000 ft at night under low-beam headlight illumination. This finding underscores the importance of including post-mounted markings at gore areas, to supplement pavement markings applied in these areas. There was no age group effect or interaction between age group and post-mounted marker type for detection distance.

In terms of nighttime symbol recognition distance, the Type-1 and Type-3 object markers had the highest mean recognition distances 790 ft and 910 ft, respectively). While Type 3 was the single best performer, both had significantly higher mean symbol shape recognition distances than all other markers. Next in terms of nighttime symbol recognition distance were the Type-2 object marker, the double modified chevrons, and the French gore signs, which were not significantly different from each other. Significant main effects of age group and marker type were found but there was no significant interaction between the two.

The only marker that resulted in a significant change in daytime detection distance was the small Type-2 marker, for which detection distance was significantly reduced for the age 70 and older group versus the young/middle-aged subjects. The mean detection distance of the Type-2 object marker was 919 ft by the young-old drivers and 803 ft by the old-old drivers, compared to 1,000 ft for the young/middle-aged drivers. In fact, all of the subjects in the age 65 to 69 age group saw all other post-mounted markers at 1,000 ft, and the drivers over age 70 saw all other post-mounted markers at distances ranging from 973 to 1,000 ft. The Type-2 marker also resulted in significantly shorter daytime color recognition distances than any other post-mounted marker type.

Finally, a limited validation study conducted by Lerner et al. on actual roads in Calvert County, Maryland, compared the Type-1 object marker and the double modified chevron post mounted markers at a gore situation. The Type-1 object marker produced a correct response rate of 50 percent, compared to 82.4 percent for the two modified chevron design, across driver age groups. However, the double modified chevron marker was better understood than the Type-1 marker at a gore location, only during the daytime.

Thus, based on the findings of the laboratory and controlled field studies conducted by Lerner et al. (1996), undelineated gores (i.e., without any object marker) were identified only 1.5 percent of the time by drivers age 75 and older, highlighting the importance of using object markers at such locations. Another finding of importance is that the Type-2 object marker is a poor choice for marking gore areas, particularly for aging drivers. The novel double modified chevron marker may be the best candidate for marking gore locations; however, more research would be required to enable a recommendation to be made for its use, based on its poorer nighttime performance compared to the Type-1 marker. Currently, the MUTCD only allows for the use of a Type-2 or a Type-3 marker for objects adjacent to the roadway (such as a gore). Based on the poor performance demonstrated by the Type-2 marker in the Lerner et al. research, a recommendation to use the Type-3 marker at freeway gore locations is made in this Handbook. It is also noted that, based on the comprehension data, a Type-1 marker may be a better candidate—for use as an experimental device—when other treatments have not proven successful.

To meet the needs of aging drivers, the point of controlling curvature on an exit ramp, as well as the curve speed advisory, must be highly conspicuous to create an appropriate expectancy of the required vehicle control actions. With this expectancy, aging drivers should be able to negotiate deceleration lane geometries meeting AASHTO or NCHRP guidelines competently. Raised curve delineation treatments are recommended in this regard; post-mounted delineators or chevrons are particularly effective at improving driver performance on sharp horizontal curves, as noted by Johnston, 1983; Jennings, 1984; Good and Baxter, 1986; Zador, Stein, Wright, and Hall, 1986, and Pietrucha, Hostetter, Staplin, and Obermeyer, 1996.

# 28 Acceleration/Deceleration Lane Design

Studies dating back to the 1960's have addressed the effects of ramp design on driving performance; however, Koepke (1993) reported that the basic design criteria, and therefore design standards, used by governmental agencies to design exit and entrance ramp terminals have not changed in more than 30 years. Recommendations for selected design features for interchange ramps may be justified by both the changing characteristics of the driving population and the operating characteristics of the highway system. Age-related functional decreases in visual acuity, motion judgment, and information-processing capabilities cause increased difficulty for aging drivers entering and exiting highways. At the same time, traffic density has increased dramatically, resulting in more complex decision-making and divided-attention requirements at these

**Table 44.** Cross-references of related entries for acceleration/deceleration lane design.

| Applications in Standard Reference Manuals | | |
|---|---|---|
| ***MUTCD*** **(2009)** | **AASHTO** *Green Book* **(2011)** | **Traffic Engineering Handbook (2009)** |
| Sect 3B.05<br>Fig 3B-8 through 10 | Pgs. 3-6 through 3-8, Sect. 3.2.3 *Decision Sight Distance*<br>Pg. 8-17, Paras. 1-2<br>Pgs. 10-76 through 10-79, Sect. on *Auxiliary Lanes*<br>Pg. 10-92, Para. 4<br>Pgs. 10-103 through 10-105, Sects. on *Left-side entrances and exits & Traffic Control*<br>Pgs. 10-107 through 10-127, Sects. on *Speed-change lanes, Single-Lane Free-Flow Terminals, Entrances, and Single-Lane Free-Flow Terminals, Exits* | Pgs. 251-252, Sect. on *Ramp Design*<br>Pgs. 225-226, Sect. on *Decision Sight Distance (DSD)*<br>Pgs. 65-70, Sect. on *Vehicle Performance* |

sites. In a survey of 664 drivers age 65 and older, one-half of those surveyed (49 percent) reported that the length of freeway entry lanes was a highway feature that was more important to them now compared with 10 years ago (Benekohal, et al., 1992).

The difficulties aging drivers are likely to experience on freeway ramps, particularly acceleration lanes, are a function of changes in gap judgment ability resulting from a diminished capability to accurately and reliably integrate speed and perceived distance information for moving targets; reduced neck/trunk flexibility; and age-related deficits in attention-sharing capabilities. First, the requirement to yield to approaching traffic on the mainline requires a merging driver to assess the adequacy of gaps in traffic by turning his/her head to look over the shoulder and/or by using the sideview mirrors. In a survey of 297 adults ranging in age from 22 to 92, which was conducted to gain a greater understanding of the visual difficulties they encounter while driving, the aging participants reported greater difficulty judging both the speed of their vehicle and the speed of other vehicles, and expressed a concern over other vehicles "moving too quickly" (Kline,et al., 1992).

It has been shown that aging persons require up to twice the rate of movement to perceive that an object is approaching, and require significantly longer to perceive that a vehicle is moving closer at a constant speed, compared with younger individuals (Hills, 1975). Darzentas, McDowell, and Cooper (1980) used Hills' data in a simulation model to estimate conflict involvement for each class of subject as a function of main-road flow and speed. In the model, a conflict occurs when a poor gap acceptance decision is made by a driver, causing an oncoming vehicle to decelerate to avoid collision. The model indicated that aging drivers were involved in more conflicts than younger drivers of the same gender, and male drivers were involved in more conflicts than females in the same age class at all flows.

Other findings describing age differences in driver behavior on acceleration ramps are reported in a National Highway Traffic Safety Administration (NHTSA) study of driver age and mirror use. In this study, which measured the time required to make a "safe/unsafe" maneuver decision in a freeway lane-change situation, old-old drivers (age 75 and older) consistently required longer response times to make a lane-change decision than a group of drivers ages 65–74, who in turn demonstrated exaggerated response times compared with a younger control group (Staplin, et al., 1996). This was a simulator study, using large screens showing dynamic videos of overtaking vehicles, in correct perspective, as the test stimuli; also, all drivers were forced to rely on their mirror information alone to make the maneuver decision in this research. The mean response time for a lane-change decision for the oldest (75 and older) driver group in this study, across a large number of trials in which the relative speed of the overtaking vehicle was varied between 10 and 25 mph (i.e., faster than the subject's own vehicle was traveling when the video was shot), changed with changes in the target distance (separation of overtaking vehicle from driver). At close separation distances (100 to 200 ft), where virtually all aging drivers quickly decided that a lane-change maneuver was unsafe, decision latency averaged approximately 2.1 s. At a 200-ft separation distance, some drivers were more willing to merge, and required longer to reach a maneuver decision, producing a mean latency of 2.5 s. At a 300-ft separation distance and above (between the overtaking vehicle and the driver wishing to change lanes), maneuver decision latency reached an asymptote at 2.95 s, as increasing percentages of subjects accepted the available gap ahead of the overtaking vehicle.

Findings from reviews of crash rates and ramp characteristics are also relevant. Lundy (1967) found that off-ramp crash rates were consistently higher than on-ramp crash rates. However, Oppenlander and Dawson (1970) reported that at urban interchanges, 68 percent of the interchange ramp crashes occurred at entrance ramps, while 32 percent occurred at exit ramps; for rural interchanges, these percentages were reversed. Similarly, Mullins and Keese (1961) reported that in urban areas, 82 percent of the interchange crashes occurred at on-ramps and 18 percent at exit ramps. Further, Lundy's (1967) study of 722 freeway ramps in California found that the crash rate was reduced for off-ramps when deceleration ramps were at least 900 ft (274 m) long (not including the length of the taper), for on-ramps when acceleration lanes were at least 800 ft) long, and for weaving sections that were at least 800 ft long. Oppenlander and Dawson (1970) also concluded that safety was improved for on-ramps, off-ramps, and weaving areas 800 ft in length or greater. Cirillo (1970) found that increasing the length of weaving areas reduced crash rates, and increasing the length of acceleration lanes reduced crash rates if merging vehicles constituted more than 6 percent of the mainline volume. Reduced crash rates from lengthening of deceleration lanes also appears to be related to the percentage of diverging traffic, with significant safety benefits beginning when 6 percent of the mainline traffic diverges (Cirillo, 1970).

The most comprehensive work to develop guidelines for freeway speed-change lanes (SCLs) was conducted in NCHRP project 3-35 by Reilly, et al. (1989), who collected data on the entry and exit processes by videotaping 35 sites in three States. An entrance model was developed, based on gap acceptance and acceleration characteristics of drivers as determined by the controlling geometry. An exit model was developed, based on the driver's behavioral response to design geometrics. The purpose of the research was to develop new criteria that would offer greater flexibility than the (then) current AASHTO (1984) guidelines, which "do not provide the designer with the ability to reflect important geometric and traffic conditions" (Reilly et al., 1989). In this research, it was reported that the AASHTO (1984) SCL design criteria were based on the acceleration and deceleration characteristics of early-model vehicles, with little regard to traffic flow characteristics or driver behavior. The design values produced by the NCHRP project entry model for SCL length were slightly lower at low freeway speeds and significantly higher at moderate to high freeway speeds when compared with the 1984 AASHTO values. The exit model values for length were significantly higher than 1984 AASHTO values for all freeway and ramp speeds. The findings of the study suggest that for certain traffic conditions, the current SCL design criteria do not provide sufficient length for proper execution of the merge or diverge process. This is of particular importance with regard to the age-related diminished capabilities documented above.

Potts, Harwood, and Pietrucha (2001) compared the design values produced by NCHRP Project 3-35 and the AASHTO values for acceleration lane length during the conduct of NCHRP Project 20-7. They concluded that there were only limited cases where NCHRP 3-35 values exceed the AASHTO values, and voiced concern with determining acceleration lane lengths based on NCHRP Project 3-35 because the design criteria are volume dependent. For these reasons, they recommended against changing *Green Book* policy on acceleration lane lengths, stating, "traditionally, AASHTO has been reluctant to adopt volume-dependent design criteria because a project designed in anticipation of one volume level might not meet the criteria for the volume level that actually occurs at some future time." Bared, Giering, and Warren (1999) also compared the acceleration lane length values from NCHRP Project 3-35 to AASHTO's values, presenting models to predict the safety performance of different acceleration lengths and a procedure to determine economic benefits of lengthening acceleration lanes. Bared et al. (1999) concluded that from a safety and economic perspective, minimum lengths of acceleration lanes are comparable to the minimum lengths recommended by AASHTO rather than the longer lengths recommended by NCHRP 3-35. They also concluded that higher benefit-cost ratios are possible by extending deceleration lanes compared to acceleration lanes, due to the higher crash occurrence on deceleration lanes, and that regardless of the original speed-change lane length, the benefit-cost ratio reaches a maximum for additions of 500 ft.

Another issue addressed by NCHRP 3-35 was acceleration lane geometry. Koepke (1993) reported that 34 of the 45 States responding to a survey conducted as a part of NCHRP 3-35 on SCL's use a parallel design for entrance ramps. Thirty of the agencies interviewed use a taper design for exit ramps and a parallel design for entrance ramps. The parallel design requires a reverse-curve maneuver when merging or diverging, but provides the driver with the ability to obtain a full view of following traffic using the side and rearview mirrors (Koepke, 1993). Although the taper design reduces the amount of driver steering control and fits the direct path preferred by most drivers on exit ramps, the taper design used on entrance ramps requires multitask performance, as the driver shifts between accelerating, searching for an acceptable gap, and steering along the lane. Reilly et al. (1989) pointed out that the taper design for entrance lanes poses an inherent difficulty for the driver and is associated with more frequent forced merges than the parallel design. Forced merges were defined as any merge that resulted in the braking of lagging vehicles in Lane 1, or relatively quick lane changes by lagging vehicles from Lane 1 to a lane to the left. The parallel design would thus appear to offer strong advantages in the accommodation of aging driver diminished capabilities. Indeed, aging drivers participating in focus groups voiced support for dedicated acceleration lanes (parallel entrance ramps) in place of tapered entrance ramps, and an analysis of on-ramp crashes involving aging drivers showed a decline of 1 percent in the period following replacement of tapered acceleration lanes with dedicated acceleration lanes with ramp meters (Kihl, 2005; Kihl, et al., 2004). Because the treatment in the "after" period included two countermeasures (ramp geometry plus ramp meters), it was not possible to determine singular effects of geometry and operations on crash rate reduction.

Finally, Keller (1993) provided a review of interchange design principles in need of reconsideration to accommodate aging drivers with diminished capabilities. According to this review, the factors that influence ramp alignment and superelevation design include design consistency and simplicity, the roadway user, design speed, and (stopping and decision) sight distance. Because driver reaction time is slowed when elements of ramp geometry are different than expected, design should provide for long sight distances, careful coordination between horizontal and vertical alignment, generous curve radii, and smooth coordinated transitions, particularly when complex interchange designs are unavoidable. Increasing the sight distance and simplifying interchange layout can reduce some of the effects of decreasing visual acuity, short-term memory decline, reduced decision making ability, reduced ability to judge vehicle speed, decreased muscle flexibility and pain associated with arthritis, and early fatigue and slower reaction times associated with increasing driver age. With regard to design speed, Keller (1993) stated that the ramp proper should be viewed as a transition area with a design speed equal to the speed of the higher speed terminal wherever feasible, and that few diagonal or loop ramps are long enough to accommodate more than two design speeds. Thus, the terminals and the ramp proper should be evaluated to determine the appropriate speed for design.

In terms of stopping sight distance (SSD) requirements, Keller (1993) noted that designers can reduce drivers' stress at interchanges by providing sight distances greater than the minimum SSD's. Although a brake reaction time of 2.5 s is representative of 90 percent of the drivers used in a 1971 study by Johansson and Rumar, and was used in the AASHTO SSD formula, it has been suggested that a 3.5-s perception and braking time should be used to accommodate the elderly with diminished visual, cognitive, and psychomotor capabilities (Gordon, McGee, and Hooper, 1984). Another assumption in the 1984 AASHTO calculations for SSD is a driver eye height of 3.5 ft; the eye height of aging drivers is often less. Finally, alignment affects braking distance, such that curves impose greater demands on tire friction than tangents, resulting in increased braking distance when the friction requirements of curves and braking are combined (Glennon, Neuman, and Leisch, 1985).

Keller (1993) noted that locations where SSD values do not provide the time necessary to process information and react properly highlight the importance of the use of decision sight distance (DSD). Examples of locations at interchange ramps where DSD is desirable include ramp terminals at the main road, especially at an exit terminal beyond the grade separation and at left exits; ramp terminals at the cross road; lane drops; and abrupt or unusual alignment changes. AASHTO guidelines (2004) note that sight distance along a ramp should be at least as great as the safe stopping distance. The sight distance on a freeway preceding the approach nose of an exit ramp should exceed the minimum stopping distance for the through traffic speed, desirably by 25 percent or more, although the desirable goal remains DSD.

DSD values—which include detection, recognition, decision, and response initiation and maneuver times—are provided in AASHTO (2011) Table 3-3 by design speed and type of avoidance maneuver required. Lerner, et al. (1995) measured DSD for three driver age groups (ages 20–40, ages 65–69, and age 70 and older) at six freeway lane drop locations. While perception-reaction time values measured by Lerner et al. (1995) were actually somewhat lower than the values assumed by AASHTO, they nevertheless found that the 85th percentile total time required by each age group for detection, decision and maneuvering exceeded the recommended AASHTO value of 14.5 s. The freeway total times averaged 16.5 s, 17.6 s, and 18.8 s, for the three groups (from youngest to oldest), respectively. The researchers explained that the original AASHTO work assumed free-flow traffic conditions, in which drivers were not required to wait for a gap in traffic to change lanes. The Lerner et al. (1995) study, by comparison, was conducted on heavily traveled urban freeways, and subjects often had to wait for gaps in traffic before maneuvering. This led to significantly higher maneuver times than were assumed by

AASHTO. No modifications to the existing DSD standards were deemed necessary. Keller (1993), reporting on the results of a 1991 survey about distances used when locating ramp exits beyond a crest vertical curve, indicated that 15 (38 percent) of State design agencies use the safe SSD, 9 (23 percent) use the safe SSD plus 25 percent, and 12 (31 percent) use DSD.

# 29 Interchange Lighting

Research has documented that: (1) freeway interchanges experience a higher crash rate than the mainline (Cirillo, 1968); and (2) urban freeway lighting has beneficial safety effects (Box, 1972). Cirillo (1968) also found a reduction in the number of interchange crashes as lighting intensity increased. Gramza, Hall, and Sampson (1980) evaluated the interchanges in the Interstate Accident Research (ISAR-2) database at which lighting had been introduced during the 10-year study period. During the daytime, there were 83 crashes before lighting and 80 crashes after lighting. At nighttime, by comparison, there were 76 crashes before lighting and 43 crashes after lighting. Taylor and McGee (1973) found a reduction in erratic maneuvers at exit lane drop sites in a before after study, when the exit area was illuminated during the "after" period of data collection.

Although nighttime driving is associated with a higher crash risk for drivers of all ages, the effects of aging on the visual system are further compounded by the effects of darkness. The aging process causes gradual declines in a variety of visual functions, including acuity, contrast sensitivity, glare recovery, and peripheral vision, making night driving especially difficult for aging drivers. Of particular difficulty is the ability to notice and recognize objects at night and in low-light conditions such as dawn and dusk, rain, fog, haze, and snow. Between age 20 and age 70, aging directly reduces contrast

**Table 45.** Cross-references of related entries for interchange lighting.

| Applications in Standard Reference Manuals | | | |
|---|---|---|---|
| ***MUTCD*** **(2009)** | **AASHTO** *Green Book* **(2011)** | **NCHRP 500 – Volume 9 (2004)** | **Roadway Lighting Handbook (1978)** |
| Sect. 1A.13, *Sign Illumination*<br>Sects. 2E.06 & 3I.04<br>Sect. 4B.04, Item I<br>Sect. 6G.14 | Pg. 3-172, Para. 4 | Pgs. V-21-V-22 Sect. on *Strategy 3.1 B7: Improve Lighting at Intersections, Horizontal Curves, and Railroad Grade Crossings (T)* | Pgs.14-15, Sects. on *Complete Interchange Lighting & Partial Interchange Lighting*<br>Pgs. 16-26, Sects. on *Analytical Approach to Illumination Warrants & Informational Needs Approach to Warrants*<br>Pgs. 42-45, Sect. on *Summary of Light Sources*<br>Pg. 71, 4th bullet<br>Pgs. 84-89, Sect. on *Interchange Lighting*<br>Pgs. 120-129, Sect. on *Illumination Design Procedure* |

sensitivity by a factor of about 3.0 (Blackwell and Blackwell, 1971); aging drivers are thus at a greater relative disadvantage at lower luminance levels than younger drivers.

The impact for the aging driver of lost sensitivity under nighttime conditions should be assessed against the nature of the night driving task. Even at night, most visual information is processed by the cone or daylight system in the foveal region of the retina where fine detail is resolved. Artificial lighting raises the illumination level of the roadway environment to the photopic range so that reading and tracking functions can occur. The peripheral rod system participates primarily by alerting the driver to a weaker signal away from the foveal line of sight, which may then be oriented to by the driver with a foveal fixation. The implication of a loss in rod sensitivity is that a much brighter peripheral signal will be needed to elicit proper visual attention from the driver, and that signals now falling below threshold will be ignored. In fact, the signal may need to be 10 to as much as 100 times brighter, depending on age and object color (Staplin, Lococo, and Sim, 1990). Since both rod and cone thresholds increase with age, it is also true that more light will be needed to bring important tasks such as reading and tracking (path maintenance) above the cone limit. In a survey of 1,392 drivers ages 50 to 97, 70 percent indicated that more highway lighting is needed on freeways. These respondents identified the following areas where more lighting is needed: interchanges, construction zones, and toll plazas (Knoblauch, Nitzburg, and Seifert, 1997).

There are a number of other aspects of vision and visual attention that relate to driving. In particular, saccadic fixation, useful field of view, detection of motion in depth, and detection of angular movement have been shown to be correlated with driving performance (see Bailey and Sheedy, 1988, for a review). While these visual functions do not appear to have strong implications for highway lighting practice, it could be advantageous to provide wider angle lighting coverage to increase the total field of view of aging drivers. High-mast lighting systems can increase the field of view from 30 degrees (provided by conventional fixtures) to about 105 degrees (Hans, 1993). Such wide angles of coverage provided by high-mast lighting might have advantages for aging drivers in terms of peripheral object detection, thus easing the task of identifying ramp geometry, traffic control devices, and traffic patterns. However, while effective high-mast systems have been demonstrated (Ketvirtis and Moonah, 1995), such installations also tend to sacrifice target contrast for the increased field of view they provide.

Hans (1993) defines “high mast” as any lighting structure that rises at least 60 ft above road level. Some designs extend up to 150 ft (46 m) and higher above the ground. One pole, anchored 50 to 70 ft from the edge of the roadway, may be used to support a cluster of 3 to 12 luminaires. As a comparison, conventional cobra-head poles mounted on the shoulder support 1 or 2 luminaires, at a height of 26 to 50 ft above the road. For example, the New Jersey Roadway Design Manual defines their high-mast lighting system as one that utilizes a mounting height of 100 ft with a cluster of a maximum of eight, 400-watt, high-pressure sodium luminaires, and their conventional lighting system as one that utilizes mounting heights of 26 ft with 150-watt, high-pressure sodium luminaires for ramp application. The NJ Manual states that tower lighting (high mast) shall be considered first (over conventional lighting) for full interchange lighting, preferably using 400-watt cutoff-type luminaires; however, non-cutoff luminaires may be employed if the designer can justify their use.

The following paragraphs summarize studies that: (1) evaluated the effects of lighting on crash experience at interchanges; and (2) evaluated specific aspects of driver performance as a function of number and type of luminaires at an interchange.

Gramza et al. (1980) conducted a crash analysis of 400 nighttime crashes that occurred at 116 interchanges during the period of 1971–1976, in five States (Maine, Maryland, Minnesota, Texas, and Utah). In an analysis of the presence of high-mast lighting at interchanges, versus no lighting or other kinds of interchange lighting, the presence of high-mast lighting was found to significantly reduce total crash rates, total crashes involving fatalities and injuries, and crashes involving fatalities and injuries other than the vehicle-to-vehicle and vehicle-to-fixed-object categories (e.g., crashes caused by striking pedestrians). Table 46, taken from Gramza et al. (1980), shows the predicted effect of high-mast lighting on annual number of crashes.

**Table 46.** Relative annual effect of lighting type on total nighttime crashes (n=400) at urban and nonurban interchanges (Gramza, Hall, and Sampson, 1980).

| Night Traffic Volume | Urban | | | Nonurban | | |
|---|---|---|---|---|---|---|
| | Non-High-Mast | High-Mast | % Decrease | Non-High-Mast | High-Mast | % Decrease |
| 5,000 | 2.0 | 0.0 | 100 | 3.6 | 0.4 | 89 |
| 7,500 | 3.8 | 0.6 | 84 | 5.4 | 2.2 | 59 |
| 10,000 | 5.7 | 2.5 | 56 | 7.3 | 4.1 | 44 |

Gramza et al. (1980) also found that although the number of lights at an interchange and the level of illumination had no significant effect on the total number of nighttime crashes, significant decreases in a variety of distinct crash types were found with increases in illumination. Increases in the illumination level—measured in lux or horizontal foot-candles (hfc)—at interchanges were associated with significant reductions in two types of crashes: vehicle-to-fixed-object crashes involving property damage, and vehicle-to-vehicle crashes involving fatalities and injuries. In addition, increases in the number of lights active at an interchange were found to significantly influence (reduce) the following two crash types: vehicle-to-fixed-object crashes involving fatalities and other injuries, and other property damage crashes. The number of lights at an interchange ranged from 0 to 114, with an average of 16 active lights and a median of 10. Thirty-two percent of the interchanges were unlit. As lighting levels increased, crash rates decreased. Illumination ranged from 0.0 lux to 10.76 lux (0.0 hfc to 1.0 hfc), with an average of 5.49 lux (0.51 hfc) for the lighted sections. These four crash types accounted for 61 percent of the crashes observed in the sample.

Since there were relatively few crashes per interchange per year, Gramza et al. (1980) employed a model to predict the number of each crash type per year, assuming three levels of traffic volume (average nighttime traffic of 5,000, 7,500, and 10,000 vehicles) at partial cloverleaf and other types of interchanges, and allowing varying levels of illumination or varying numbers of lights. The predicted relationships between traffic volume, lighting, and crash frequency showed that reductions in number of lights and in level of illumination (hfc) resulted in higher frequencies of vehicle-to-fixed-object and other property damage crashes, for all traffic volumes. Vehicle-to-vehicle crashes were also shown to increase in frequency as illumination was reduced, for all interchange types.

In addition, the findings at the level of one interchange were translated to estimate, as an overall annual impact for the five-State sample, the relative influence of the lighting variables on numbers of crashes at interchanges through three levels of night traffic volume. A level of 7.53 lux (0.7 hfc) was used to represent the allowable base of average maintained illumination. Overall, the model predicted that reductions in levels of illumination appear to cause greater increases in the number of crashes than do reductions in numbers of lights (Gramza et al., 1980).

Although the work of Gramza et al. (1980) is noteworthy in its attempt to quantify the complex relationships between interchange lighting and safety, it is critical to remember that their model was applied to data derived to fit 1975 conditions—including, by implication, both the then-current number of aging drivers and their exposure to this highway feature during nighttime operations. By contrast, present and anticipated future driving patterns of aging drivers—whose actual numbers, as well as their percentage of all drivers, will increase dramatically—show much higher use rates for freeways (Lerner and Ratté, 1991). This trend should sharply accentuate the safety impacts cited by Gramza et al.

Janoff, Freedman, and Decina (1982) conducted a study to determine the effectiveness of partial lighting of interchanges, where partial interchange lighting (PIL) was defined as lighting that consists of a few luminaires located in the general areas where entrance and exit ramps connect with the through traffic lanes of the freeway (between the gore and the end of the acceleration ramp/beginning of the deceleration ramp). A complete interchange lighting (CIL) system includes lighting on both the acceleration and deceleration areas plus the ramps through the terminus. In their survey of approximately 50 agencies which supplied information on over 14,000 interchanges and over 7,500 interchange lighting systems, it was found that 37 percent of the interchange lighting was CIL and 63 percent was PIL. An observational field study was conducted to determine the effects of lighting level (various levels of PIL, CIL, no lighting, and daylight), geometry of the interchange (straight versus curved ramps), and presence of weaving area versus no weaving area on driver behavior and traffic operations. PIL was stratified by the number of lights at each ramp, and included three levels: PIL 1 (one light), PIL 2 (two lights), and PIL 4 (four lights). CIL test sites included a full cloverleaf in suburban Baltimore, Maryland, and a three-leg interchange in suburban Philadelphia, Pennsylvania, with luminaire mounting heights of 40 and 31 ft, respectively. The dependent measures included speed and acceleration of individual vehicles traversing the interchanges; merge and diverge points of individual vehicles entering the main road or leaving it; and erratic maneuvers such as brake activations, use of high beams, and gore or shoulder encroachments.

Both field studies indicated that CIL provided a better traffic operating environment than did PIL and that any interchange lighting performed better than no lighting (although the differences were not always as great as between CIL and PIL). In particular, to the extent that traffic flow and safety are important issues, the Janoff et al. study concluded that existing CIL systems should not be reduced to PIL systems. When installing new lighting and economics are not an overriding issue, a CIL system is preferred over a PIL system. However, a PIL system with one or two luminaires per ramp will normally perform better than no lighting at far lower cost than a CIL system. PIL systems with fewer luminaires (one or two) frequently performed better than PIL systems with greater numbers of luminaires (four). This was explained by the fact that drivers may experience transitional visibility problems under the PIL conditions when they are forced to drive from dark to light to dark areas and at the same time perform complex maneuvers such as diverging, merging, and tracking a 90-degree curve.

Hostetter, Crowley, Dauber, and Seguin (1989) noted that when luminaires are not placed downstream of the physical gore of a partially lighted exit ramp, a driver proceeds from a lighted area to a nonlighted area. Citing evidence from various researchers (Boynton and Miller, 1963; Boynton, 1967; Boynton, Rinalducci, and Sternheim, 1969; Boynton, Corwin, and Sternheim, 1970; Rinalducci and Beare, 1974; and Fredericksen and Rotne, 1978), they reported that the effect of going from higher to lower levels of luminance results in a reduction in visual sensitivity, which would help explain the findings of Janoff et al. (1982) that performance under partial lighting was better with fewer luminaires.

On a final note, Bjørnskau and Fosser (1996) conducted a before-after study on a section of roadway in Norway to record driver behavior as a function of roadway lighting. One interesting finding was that the percentage of aging drivers and female drivers increased after the introduction of roadway lighting. Thus, a secondary benefit of roadway lighting (beyond its capability to reduce crashes) is increased mobility and access to goods and services for aging drivers.

## 30 Restricted or Prohibited Movements

It has been reported that out of 100 wrong-way crashes, 62.7 result in an injury or fatality, versus 44.2 out of 100 for all freeway or expressway crashes (Tamburri and Theobald, 1965). These data highlight the fact that wrong-way crashes are more severe than most other types. The most frequent origin of wrong-way incidents, as reported by these authors, was entering the freeway via an off-ramp.

Results of investigations of the wrong-way problem in California indicate that fatal wrong-way crashes as a percentage of all fatal crashes on freeways have decreased

**Table 47.** Cross-references of related entries for traffic control devices for restricted or prohibited movements.

| Applications in Standard Reference Manuals | | | |
|---|---|---|---|
| ***MUTCD*** **(2009)** | **AASHTO** *Green Book* **(2011)** | **NCHRP 500 – Volume 9 (2004)** | **Roadway Lighting Handbook (1978)** |
| Sects. 2A.23, 2B.37 through 2B.41<br>Tables 2B-1 & 2C-1<br>Sects. 2E.53, 3B.20, 3D.01<br>Figs. 3B-24, 2B-18, 2B-19 | Pgs. 10-83 through 10-87, Sect. on *Wrong-Way Entry* | Pg. 23, Paras. 1-2 | Pgs. 373-374, Sect. on *Mounting Height and Lateral Clearance* |

substantially in the last 20 years (Copelan, 1989). The actual number of wrong-way fatal crashes was the same in 1987 as it was in 1963 (about 35 per year), despite the fact that freeway travel has increased fivefold; the reduction appears to be related to the countermeasures employed by California Department of Transportation over the intervening years, including the implementation of guide and wrong-way signs and pavement markings providing better visual cues. Copelan (1989), while noting that half of the wrong-way driving on freeways was from deliberate, illegal U-turns, reported that additional improvements could still significantly reduce wrong-way crashes.

Early studies found that the rate of wrong-way driving based on vehicle-miles of travel increased with driver age (Tamburri and Theobald, 1965). In their analysis of 1,214 wrong-way driving incidents which occurred over two 9-month periods on California highways, they found a moderate increase in incidents for drivers ages 30–39 and those ages 40–49. Over age 60, the incidents rose rapidly; and over age 70, incidents occurred at rates approximately 10 times higher than for drivers ages 16–29. Lew (1971) reported on an analysis of 168 wrong-way crashes by civilians on California freeways in which the age of the wrong-way driver was recorded. While certain age groups (i.e., 30–39, 50–59, and 60–69) were represented to an extent corresponding closely to their proportion of the driving population, other groups such as those ages 16–19, 40–49, and 70–79 deviated markedly from expectation. Drivers ages 16–19 experienced approximately one-half of the wrong-way crashes expected for their age group; drivers ages 40–49 experienced three-quarters of the rate expected; and drivers ages 70–79 experienced over twice the number of freeway wrong-way crashes than would be expected.

Aging drivers' use of signs designed to control wrong-way movements is affected by their visual performance capabilities. Letter acuity declines during adulthood (Pitts, 1982) and aging adults' loss in acuity is accentuated under conditions of low contrast, low luminance, and high visual complexity. A field investigation of the effect of driver's age on nighttime legibility of highway signs indicated that aging subjects perform substantially worse than younger subjects on a nighttime legibility task using a wide range of sign materials (Sivak, Olson, and Pastalan, 1981).

Preventative measures for reducing the frequency and severity of wrong-way maneuvers include modifications in ramp and roadway geometry, and signing and pavement markings, and the use of warning and detection devices and vehicle arresting systems. Traffic prohibition signing and marking are discussed in this section, while positive guidance signing for freeway entrances and ramp geometry and delineation were discussed under Design Element 26.

Campbell and Middlebrooks (1988), following the recommendation of Parsonson and Marks (1979) to widely separate the on- and off-ramps at partial cloverleaf interchanges, experimented with a design in which close exit and entrance ramps would be combined into one paved surface separated only by a double yellow line. Ten ramps in the Atlanta, Georgia, area were redesigned and evaluated using actual counts of wrong-way movements. Two of the ramps were monitored before and after they were converted to combined ramps. At the first location, the wrong-way rate per month before construction was 86.7; after combining the ramps, the rate fell to 0.3 per month. At the second location, the wrong-way rate was 88.6 per month. After the installation of four countermeasures (trailblazers, lowered DO NOT ENTER and WRONG WAY signs, 18-in stop bar, and 8-in yellow ceramic buttons in the centerline of the crossroad), the rate dropped to 2.0 per month. Once the ramps were combined at this second location, the wrong-way rate jumped to 30.0 per month, even when ceramic buttons, permanent signing, and pavement markings and a dotted channelizing line (i.e., pavement markings that lead turning vehicles onto the ramp) were employed.

The mixed results of the Campbell and Middlebrooks study (1988) led to the evaluation of 15 additional combined ramps in the same research project, 12 of which were partial cloverleaf, with the balance consisting of median entrance/exit ramps (designed for future access by high-occupancy vehicles to the median lanes, but during the study period were open to all traffic). The study periods ranged from 30 to 102 days. The results clearly indicated that the concept of combined exit and entrance ramps can work when signing and markings conform to MUTCD specifications. It was recommended that 8-in yellow ceramic buttons be installed along the cross street centerline if all other countermeasures do not work.

With regard to signing, Friebele, Messer, and Dudek (1971) noted that the use of oversized signs and reflectorization may be needed in locations where motorists are apt to disregard wrong-way warnings, and Copelan (1989) suggested that the larger, highly retroreflective signs may be helpful for confused or elderly drivers.

Parsonson and Marks (1979) found that lowering the DO NOT ENTER and WRONG WAY signs to 18 in above the pavement to place them in the path of the headlight beams at night and placing trailblazer signs on the on-ramp were effective, inexpensive countermeasures. Individually, these two countermeasures reduced the wrong-way incidence to about one-third to one-half of its original rate. This is consistent with California's Standard Sign Package, which specifies that the DO NOT ENTER and FREEWAY ENTRANCE packages be mounted with the bottom of the lower sign 24 in above the edge of the pavement. It also specifies that ONE WAY arrows be mounted 18 in above the pavement. The Virginia Department of Highways and Transportation (1981b) noted concern regarding the 18 in mounting height of the ONE WAY signs, however, stating that the signs may become obscured by vegetation and by guardrails (when the sign is mounted behind a guardrail). Thus, mounting height was revised for this State to 36 in, to alleviate these concerns. An additional concern with lowering the mounting height of these signs is the increased potential to impact a passenger vehicle windshield if struck by a motorist entering or exiting the freeway who strays off of the ramp and crashes into the sign support. However, wrong-way entries onto high-speed facilities can cause very serious head-on collisions in locations where there is a high incidence of wrong-way entry or a high likelihood of wrong-way entry due to geometrics. Since windshield penetration is less likely to occur at a location near the ramp terminus than at other locations because of lower travel speeds of drivers traveling in the correct direction along the ramp (who are slowing down for a stop or a signalized turn) and drivers making the wrong-way movement (who are accelerating from a turn), the anticipated benefit of increased sign conspicuity and prevention of wrong-way freeway entries is judged to significantly outweigh the risk of sign penetration.

California uses the DO NOT ENTER and WRONG WAY signs together on a single signpost, with the WRONG WAY sign mounted directly beneath the DO NOT ENTER sign (the Do Not Enter Package). This sign package is placed on both sides of the ramp. For off-ramp signing, the Standard specifies the use of at least one Do Not Enter package (DO NOT ENTER and WRONG WAY signs), to be placed to fall within the area covered by the car's headlights and visible to the driver from the decision point on each likely approach; three or four packages may be required if the off-ramp is split by a traffic island. In addition, ONE WAY arrows should be placed as close to the crossing street as possible. As they are retrofitted and newly installed, the Do Not Enter sign packages in California have high intensity sheeting (Copelan, 1989).

Increases in conspicuity distance have been reported in the literature on fluorescent signing. As stated earlier in Chapter I for Design Element 12, Burns and Pavelka (1995) found that signs with fluorescent red sheeting were detected by 90 percent of the participants in a field study conducted at dusk. Only 23 percent of the subjects were able to detect the standard red signs, under the same lighting conditions. To improve the daytime conspicuity of DO NOT ENTER and WRONG WAY signs, as well as conspicuity of these signs under low luminance conditions (dawn and dusk), fluorescent red sheeting is recommended. In addition, use of retroreflective sheeting that provides for high brightness at the wide observation angles typical of the sign placements and distances at which these signs are viewed (e.g., 1.0+ degrees), as well as lowering the sign heights for these signs will enhance their nighttime conspicuity under low-beam headlight illumination.

Turning to a consideration of pavement markings, Tamburri (1969) found that a white pavement arrow placed at all off-ramps pointing in the direction of the right-way movement can be effective in reducing the number of wrong-way maneuvers. However, Parsonson and Marks (1979) found that at a parclo AB loop off-ramp that has its crossroad terminal adjacent to the on-ramp, standard pavement arrows, lowered DO NOT ENTER and WRONG WAY signs, trailblazer signs, and a 24-in (600-mm) wide stop bar were not sufficient, as the ramp still showed 22.3 wrong-way movements per month. Large pavement arrows (24-ft long) and yellow ceramic buttons (with a diameter of 8 in) to form a median divider on the crossroad were required, in addition. It was specified that the ceramic buttons should touch each other to form a continuous, unbroken barrier, and should extend far enough toward the interchange structure (the freeway) to prevent a wrong-way driver from avoiding the buttons by turning early. The length required is typically 100 ft. The addition of the ceramic buttons reduced wrong-way maneuvers from a rate of 88.6 per month to a rate of 2.0 per month. Campbell and Middlebrooks (1988) also found that installing yellow ceramic buttons to the extension of the centerline of the crossroad to aid in channelizing left-turning traffic entering the freeway, in combination with countermeasures employed by the Georgia Department of Transportation as standard practice—trailblazer sign, 18-in wide stop line at the end of the off-ramp, 18-ft long arrow pavement marking, and lowered WRONG WAY and DO NOT ENTER signs—reduced wrong-way maneuvers. It was also recommended in the Parsonson and Marks (1979) study that the two-piece, 24-ft long arrow pavement marking (part of the California standard) be adopted. This use of the wrong-way arrow is described in *MUTCD* section 3B.20 and shown in *MUTCD* Figure 3B-24.

Cooner, Cothron, and Ranft (2004) provided guidance for the application of wrong-way countermeasures and treatments for freeway exit ramps. In their survey of State DOTs, they found that some agencies use red retroreflective raised pavement markers as a supplement to wrong-way pavement arrows on freeway exit ramps. TxDOT's standard wrong-way pavement arrow is comprised of raised pavement markers, arranged in a design that is slightly longer and wider than the national standard. Cooner et al. (2004) indicate that although these provide good visibility at night, they can be a maintenance concern because they are often run over, particularly on high-volume exit ramps in urban areas. This results in missing markers in wrong-way pavement arrows, or arrows that are worn in appearance. In addition to recommending the use of wrong-way pavement arrows on freeway exit ramps (comprised of retroreflective raised pavement markers in a revised design according to TxDOT's standard), Cooner et al. (2004) recommend that deficient wrong-way pavement arrows be repaired and their maintenance be made a priority. No studies demonstrating safety or driver performance benefits for this treatment were described by Cooner et al. (2004).

# PROMISING PRACTICES

## 31 Advance Pavement (Route Shield) Markings at Major Freeway Junctions

**Description of Practice**: Route shield markings on the pavement in advance of major freeway junctions are used to supplement diagrammatic or other guide signs, to provide additional confirmation to drivers that the lane leads to the desired destination. Such route shield markings are currently in use in many locations in the country including Orlando, Florida and Columbus, Ohio. Route shield markings are permitted as an option in Section 3B.20 of the 2009 MUTCD.

**Anticipated Benefits to Aging Road Users**: Guidance information acquired from signs by drivers who are approaching a freeway junction at high speed must be remembered as they divide attention between concurrent demands—e.g., maintaining safe separation from other traffic while negotiating lane changes and/or anticipating and reacting to other drivers changing lanes. A driver may have been exposed to route guidance information on upstream signing, but cannot recall it with confidence moments later when he/she is engaged in other tasks; and, safe operation of his/her own vehicle may preclude visual search. Under such conditions, drivers who experience age-related decline in divided attention ability and working memory should realize a disproportionate benefit with advance pavement markings that confirm which lanes lead to which destination routes, provided, as always, that these markings are applied and maintained at contrast levels sufficient to ensure legibility to an "aging design driver."

## 32 Wrong-Way Driving Countermeasures

**Description of Practice**: According to FHWA Office of Safety (2013), numerous studies of the contributing causes and issues surrounding wrong-way driving (WWD) crashes, conducted primarily by state departments of transportation since the 1960s, indicate that WWD crashes are much more likely to result in fatalities or severe injuries than other highway crash types and highlight several factors that must be acknowledged by any WWD-related road safety audit (RSA). The NTSB's FARS analysis determined that drivers over the age of 70 are over-represented in fatal wrong-way crashes (NTSB, 2013). Categorically, there are significant human factors and environmental conditions generally associated with WWD crashes. Various research efforts have found the following correlations:

- A substantial percentage of wrong way drivers are impaired by alcohol.
- Over-representation of certain driver age groups, such as older drivers (particularly those over the age of 70) and younger drivers (under the age of 25).
- The majority of WWD crashes that result in a fatality occur at night, when visibility of roadway attributes and signs are diminished, and a disproportionate number occur on the weekend, which potentially coincides with elevated levels of alcohol consumption amongst the driving population.

Based on this information, RSA teams should carefully consider the conditions under which to conduct an RSA that includes review of WWD crashes. The RSA should consider the potential for various human factors, such as impaired driving, older drivers with diminished eyesight, and inexperienced drivers prone to driving mistakes, to affect WWD crash potential. In addition, ATSSA (2012) has published a document containing descriptions of selected WWD treatments and case studies on their installation; that document should also be consulted when considering the implementation of WWD countermeasures.

**Anticipated Benefits to Aging Road Users**: Treatments such as improved lighting help drivers to better recognize the configuration of intersections and interchanges. Channelization helps to physically prohibit movements that lead to wrong-way driving where exit ramps intersect with surface streets. Signing and marking, particularly in advance of the intersection, provide the driver with important information on movements that are appropriate and reduce the likelihood of wrong-way driving.

## CHAPTER 9

# Roadway Segments

The following discussion presents the rationale and supporting evidence for Handbook treatments pertaining to these ten proven and promising practices.

### Proven Practices

33. Horizontal Curves
34. Vertical Curves
35. Passing Zones
36. Lane Control Devices

### Promising Practices

37. Lane Drop Markings
38. Contrast Markings on Concrete Pavement
39. Utilize Highly Retroreflective Marking Material
40. Curve Warning Markings
41. Road Diets
42. High Friction Surface Treatments

## PROVEN PRACTICES

# 33 Horizontal Curves

Pavement markings and delineation devices serve important path guidance functions on horizontal curves, particularly under adverse visibility conditions, at twilight, and at nighttime. They provide a preview of roadway features ahead and give the driver information about the vehicle's lateral position on the roadway. Delineation must provide information that results in recognition of the boundaries of the traveled way both at "long" preview distances (5 to 8 s of travel time) and at more immediate proximities (within 1 s of travel time) where attention is directed toward instant-to-instant vehicle control responses.

Surface pavement markings in current practice may vary along four dimensions: (1) brightness, (2) width, (3) thickness, and (4) the addition of structure to "thick" applications. Stripes of increased thickness have an advantage in wet weather because the material is more likely to protrude above the level of surface water and to provide a degree of retroreflectivity greater than that provided by thinner applications of paint. Also, the commercially available structured stripes (tapes) are brighter than other marking treatments, even under dry conditions. This is due to the ability of the raised element of the structure to reflect more light back to the driver than a horizontal surface. Even greater benefits are provided by raised retroreflectorized treatments, including raised

**Table 48.** Cross-references of related entries for horizontal curves.

| Applications in Standard Reference Manuals | | | |
|---|---|---|---|
| ***MUTCD*** **(2009)** | **AASHTO** *Green Book* **(2011)** | **NCHRP 500 – Volume 9 (2004)** | **Traffic Engineering Handbook (2009)** |
| Sect. 1A.13, *center line markings, delineator, edge line markings, object marker, raised pavement marker, & retroreflectivity*<br><br>Sects. 3A.05 & 3A.06<br><br>Sect. 3B.01, Items A & B<br><br>Figs. 3B-4<br><br>Table 3B-1<br><br>Sect. 3B.04<br><br>Sect. 3B.06<br><br>Sect. 3B.11<br><br>Table 3D-1<br><br>Sects. 2C-63 & 2C-65<br><br>Fig. 3F-1<br><br>Sects. 3F.01 through 3F.04<br><br>Table 3F-1<br><br>Sect. 6F.77 | Pg. 3-176, Paras. 1 & 3<br><br>Pg. 5-32, Sect. on *Signing and Marking*<br><br>Pg. 7-43, Para. 5<br><br>Pgs. 3-91 through 3-97, Sect. 3.3.10 *Traveled Way Widening on Horizontal Curves* | Pgs. V-22-V-23, Sect. on *Strategy 3.1 B8: Improve Roadway Delineation (T)* | Pgs. 358-359, Sect. on *Warning Signs*<br><br>Pgs. 364-368, Sect. on *Horizontal Alignment Warning Signs*<br><br>Pgs. 382-385, Sect. on *Centerline and Edge Line Markings*<br><br>Pgs. 226-231, Sect. on *Horizontal Alignment* |

pavement markers (RPM's), post-mounted delineators (PMD's), and chevron signs, which may be used to improve the nighttime visibility of delineation and to indicate roadway alignment.

A number of driver visual functions that have an impact on the use of pavement markings and delineation show significant age-related decrements: dynamic acuity, contrast sensitivity, dark adaptation, and glare recovery. Dynamic visual acuity (DVA) includes the ability to resolve the details of a high-contrast target that is moving relative to an observer. Activities that rely on dynamic acuity include making lateral lane changes and locating road boundaries when negotiating a turn. In these situations, greater speeds are associated with poorer DVA. Contrast sensitivity influences the response to both sharply defined, bright-versus-dark visual targets, and those with grayer, less distinct edges. In general, aging adults tend to have decreased contrast sensitivity (Owsley, Sekuler, and Siemsen, 1983). This loss is more pronounced at lower light levels (Sloane, Owsley, and Alvarez, 1988; Sloane, Owsley, and Jackson, 1988) and is associated with a heightened sensitivity to glare (Wolf, 1960; Fisher and Christie, 1965; Pulling, et al, 1980). The findings of Blackwell and Blackwell (1971) indicate that a 60-year-old observer needs approximately 2.5 times the contrast as a 23-year-old observer for the same level of visibility.

Highway research studies that have varied one or more of the four dimensions of pavement markings are discussed below, along with studies on the effectiveness of RPM's, PMD's, chevron signs, and combinations of delineation treatments. Age differences are reported wherever data are available.

An early study of surface pavement markings, carried out with an interactive driving simulator plus field evaluations, concluded that driver performance—measured by the probability of exceeding lane limits—was optimized when the luminance (brightness) contrast between pavement markings and the roadway was 2.0 (Blackwell and Taylor, 1969). A study by Allen, O'Hanlon, and McRuer (1977) also concluded that delineation contrast should be maintained above a value of 2.0 for adequate steering performance under clear night driving conditions. In other words, these studies have asserted that markings must appear to be at least three times as bright as the road surface, because contrast is defined as the difference between target and background luminance, divided by the background luminance alone. A difficulty with these studies, however, is that their data were not derived from—and thus are not representative of—normatively aged drivers. The ideal viewing conditions assumed by Allen et al. (1977) also disregard the effects of glare as well as adverse visibility, and both factors have a disproportionate impact on the performance of aging drivers. In Blackwell and Taylor's work, a minimum preview time of 3 to 4 s was recommended for accurate maneuvering under adverse conditions. However, more conservative estimates of preview time to accommodate aging drivers (e.g., 5 s) have frequently appeared in the literature.

Freedman, et al. (1988) showed significant performance decrements for 65-year-old drivers, as compared with 35-year-old drivers, in the visibility distance of 4-in pavement stripes on a simulated wet roadway. Staplin, Lococo, and Sim (1990) confirmed the need for higher levels of line brightness for aging drivers in a simulator study, where the contrast for a 4-in white edge line was continuously varied within a 40-step range in a method of limits. Under simulated opposing headlamp glare conditions, subjects ages 65–80 required an increase in contrast of 20 to 30 percent over a younger sample to correctly discern downstream curve direction at criterion viewing distances. To accommodate less capable older drivers, this study's results indicated that a 300-percent increase in stripe brightness versus that required by younger drivers may be warranted.

To describe the magnitude of the effects of age and visual ability on delineation detection/recognition distance and retroreflective requirements for threshold detection of pavement markings, a series of analyses using the Ford Motor Company PC DETECT computer model (cf. Matle and Bhise, 1984) yielded the stripe contrast requirements shown earlier in this *Handbook* in Table 18 for Design Element 6 (Delineation of Edge Lines and Curbs) in the Rationale and Supporting Evidence section for Intersections. PC DETECT is a headlamp seeing-distance model that uses the Blackwell and Blackwell (1971, 1980) human contrast sensitivity formulations to calculate the distance at which various types of targets illuminated by headlamps first become visible to approaching drivers, with and without glare from opposing headlights. The top 5 percent (most capable) of 25-year-olds and bottom 5 percent (least capable) of 75-year-olds were compared in this analysis.

The more realistic operating conditions modeled as described above, together with the widely cited multiplier for aging observers advocated in the seminal work by Blackwell and Blackwell (1971), support the recommendation that an in-service pavement edge striping contrast value on horizontal curves maintained at or above 5.0 is appropriate to accommodate the needs of the large majority of aging drivers on highways and arterials without median separation between opposing directions of traffic. Where a median barrier (e.g., concrete safety shaped barrier) high enough to shield drivers from direct view of oncoming headlights is present, or where median width exceeds 49 ft, a horizontal curve edge line contrast value of 3.75 or higher is recommended. It is important to note that these recommendations are not limited to standard striping width (4 in). Where wider pavement markings are implemented, either as general or spot treatments, the same contrast values apply.

This leads logically to discussion of stripe width. This is one characteristic that has been advanced as a countermeasure to accommodate aging drivers, at least on roadways 22 ft or more in width. The use of wider stripes has been advocated both as a general treatment and as a spot treatment on curves. A survey of State highway agencies by Wright (1983) found that engineers believe that treatments such as chevrons, delineators, and warning signs are more effective than surface markings for spot improvements at curves. Deacon (1988), who has concluded that 8-in edge lines should be used instead of standard 4-in edge lines on two-lane rural highways, states that "... while this finding is not based on benefits to older drivers, older drivers will share—probably proportionally more—the safety benefits with others who travel these highways during periods of impaired visibility."

Relevant work in this area includes a report by Good and Baxter (1986) that 6-in edge lines result in more favorable driver control than 3-in edge lines for "short range delineation," which was defined as that which is useful to the driver for tracking the roadway at night under poor visibility conditions. In addition to the assumption that a wider stripe will provide greater visibility distances and be more conspicuous to aging drivers, there is evidence from a study by Hughes, et al. (1989) that 8-in edge lines offer the potential for cost-effective application. This conclusion is based on the finding that for 8-in edge lines to be a cost-effective replacement for 4-in edge lines, crashes need to be reduced by only 0.7 percent when the daily traffic exceeds 1,000 vehicles.

However, while the use of a wide edge line is conceptually attractive for improving aging driver performance, the complete operational and safety benefits are not at all clear. For example, Hall (1987) reported that wide edge lines do not reduce the incidence of run-off-the-road (ROR) crashes, nor do they reduce the incidence of such crashes at night or on curves. A study by Cottrell (1988) also showed that the use of wide edge lines does not reduce the risk of crashes on curves or at night; still, he agrees that the use of wide edge lines only in the vicinity of curves, while retaining conventional edge lines on tangents, could be an effective spot improvement. Lum and Hughes (1990) have expressed concern over both the Cottrell and the Hall studies because the number of miles sampled was small. And finally, in a simulator study conducted to determine the most effective horizontal curve delineation treatments to accommodate aging drivers, Pietrucha, et al. (1996) found that although the recognition distance for a 8-in wide white edge line at in-service brightness level (ISBL) in combination with a standard yellow centerline produced longer recognition distance among the aging driver sample (mean recognition distance: 217.5 ft compared to a 4-in wide white edge line at ISBL in combination with a standard yellow centerline (mean recognition distance: 179.4 ft), the difference was not significant.

Thus, wider edge lines deserve consideration wherever practical, particularly as spot treatments on horizontal curves, to accommodate the difficulties aging drivers have with visibility at nighttime. And it may be inferred from these various studies of stripe width that markings that are maintained at or above the recommended contrast levels and are wider than the conventional 4-in (100-mm) treatment will provide the greatest benefit to aging drivers. What is important to remember is that contrast remains the preeminent factor in stripe visibility, and increased width alone does not substitute for lower-than-recommended contrast levels.

A current area of investigation which potentially could lead to the development of standards directly impacting stripe visibility is the measurement of the retroreflectivity of pavements and pavement markings. There is currently no pavement marking retroreflectivity requirement specified in design manuals, although the Roadway Delineation Practices Handbook (Migletz, Fish, and Graham, 1994) states that several separate studies have concluded that the value of approximately 100 millicandelas per lux per square meter (mcd/lux/$m^2$) is the minimum value for the coefficient of reflected luminance (RL) for pavement markings. More common is the expression of delineation (pavement marking) retroreflectivity in millicandelas per square meter per lux, or the amount of reflected light per unit area of striping material, as a function of the incident illumination level. For present purposes, what is important is that, for a given amount of incident illumination (i.e., from a vehicle's headlight beam distribution) the ratio of mcd/$m^2$/lux returned from the pavement marking to the mcd/$m^2$/lux returned from the adjacent pavement surface generally describes the brightness of the treatment as viewed by an approaching motorist.

Graham, Harrold, and King (1996) conducted a field study at nighttime on public roadways to determine the minimum pavement marking retroreflectivity requirements to accommodate aging drivers. Thirty-six drivers ages 60 to 80, with a mean age of 71.3 years, and 29 drivers ages 20 to 59 rated the adequacy of 60-m long white and yellow stripes on tangent highway sections on clear, dry nights, under low-beam headlight illumination only. Using a 1980 model four-door sedan as the test vehicle, the retroreflectance values of the markings ranged from 28 to 301 mcd/m$^2$/lux. In 12 of the 14 locations where the pavement markings measured 100 mcd/m$^2$/lux or higher, they were rated as adequate or above by at least 85 percent of the subjects age 60 and older. Markings with retroreflectivity levels of 142 mcd/m$^2$/lux or higher were rated as adequate or above by 95 percent or more of drivers age 60 and older. There was no significant effect of marking color, a result replicated by Schnell and Zwahlen (1996).

Graham, Harrold, and King (1996) also documented the effects of a dirty windshield and headlights on pavement marking visibility. They made measurements on a sample of in-service vehicles and found that for the 85th percentile vehicle, the light transmitted through a clean windshield was increased by 8 percent compared to an unclean windshield, and that cleaning the headlamps increases target luminance by 12 percent. Further, they note that vehicles in use from the mid-1990's have headlamp systems that may provide less reflected light from pavement markings than the headlight system on the 1980 test vehicle.

Next, Garvey, Gates, and Pietrucha (1997) addressed delineation as an area where engineering improvements could accommodate the needs of aging drivers. Their report indicates that the very best aging drivers will require 130 mcd/m$^2$/lux, whereas the majority of the aging driver population will require 300 mcd/m$^2$/lux. Jacobs, Hedblom, Bradshaw, Hodson, and Austin (1995) performed a field study of the visibility of a 4-in-wide by 10-ft-long isolated centerline located 12 ft from the right edge of the road, with approximately one-third of their subject sample between the ages of 50 and 60. Results were interpreted in relation to the visibility distance needed for a 5-s preview of road heading at varying speeds. It was found that a pavement marking retroreflectivity level of 100 mcd/m$^2$/lux was able to provide the required visibility distance only at a speed of 15 mph. To achieve a 5-s preview distance (403.5 ft at 55 mph by the 50th percentile driver in this study—who was under 60 years old—required a stripe retroreflectance of 1,000 mcd/m$^2$/lux. The vehicle used in the study was a 1993 model 4-door sedan.

The development of retroreflectivity requirements for pavement markings is complicated by the geometric relationships that must be taken into account—including entrance and observation angle specifications which are sensitive to driver eye height, headlight type and height, the longitudinal separation from the target marking and the driver/headlight lateral position in the travel lane—as well as the lack of data regarding the retroreflectivity of different types of pavement surfaces under wet and dry conditions and different degrees of wear. Perhaps the most rigorous work in this area to date has been reported by Zwahlen and Schnell (1998), who conducted studies to define the performance levels of markings required to provide a 62-year-old design driver with a preview time of 3.65 s. Finding no reliable data on the reflective properties of road surfaces under an automobile headlamp geometry (i.e., with observation angles less than 1 degree), the researchers conducted luminance and illuminance measurements for two bituminous/asphalt (worn and relatively new) and two concrete (worn and relatively new) roadway surfaces in the field. The results of the measurements indicated that the new asphalt road surface (RL=20 mcd/m$^2$/lux) was substantially less reflective than the weathered, worn asphalt surface (RL=40 mcd/m$^2$/lux). In comparison, the worn concrete road surface (RL=28 mcd/m$^2$/lux) was considerably darker than the new concrete road surface

(RL=55 mcd/m$^2$/lux). Their matrix of readings for each pavement type as a function of entrance angle and observation angle were included in a subsystem of the CARVE (Computer Aided Road Marking Visibility Evaluator) model that was a key product of their research. Zwahlen and Schnell (1998) subsequently selected old asphalt as the road surface for a controlled field study of pavement marking visibility. They also selected an entrance angle of 88.7 degrees and an observation angle of 1.05 degrees to represent the vehicle/observer geometry of an "average large car driven by an average size adult."

The Zwahlen and Schnell (1998) controlled field study used younger and older drivers with near normal visual performance to quantify the visibility distance of pavement markings on fully marked two lane rural roads (white edge lines, dashed yellow centerline), to calibrate the CARVE computer model. The older driver group contained 5 males and 5 females with an average age of 68.3 years, and the younger driver group contained 5 males and 5 females with an average age of 23.2 years. The authors note that their use of only subjects with healthy vision suggests that the visibility distances obtained in the study are likely to be longer than what would be obtained with a larger sample that represented the U.S. driver population, including individuals with diminished visual capabilities. The study measured detection distances for 4-in- (100-mm-) wide pavement markings under low- and high-beam headlight illumination.

Based on the results of Zwahlen and Schnell (1998), the CARVE model was exercised to yield recommended retroreflectivity levels for white and yellow pavement markings under dry conditions, assuming a typical H6054 type vehicle headlamp. The 3.65-s preview time noted earlier was retained for roads with no raised treatments; when RPM's are used in addition to pavement markings, the authors revised the preview time downward to 2.0 s. The (white) edge line minimum required retroreflectivity (RL) values emerging from this effort are shown in Table 49.

The specification of RL values for pavement markings is likely to remain a difficult problem for some time, as indicated in the preceding discussion. It may also prove to be largely an academic issue. It is the effective contrast of a marking against the surrounding pavement area that a driver's visual system responds to, and which determines both (detection) performance and subjective comfort with the information provided by such treatments. While this index can be arrived at through complicated calculations based on the retroreflectivity levels of pavements and markings, it can also be done through a

**Table 49.** Minimum required RL (mcd/m$^2$/lux) recommended by Zwahlen and Schnell (1998) for roads consisting of two white edge lines and a dashed yellow or white centerline.

| Vehicle Speed (km/h) | Vehicle Speed (mph) | Minimum Required RL (mcd/m$^2$/lux) for White Edge line | |
|---|---|---|---|
| | | Without RPM's<br>Preview Time = 3.65 s | With RPM's<br>Preview time = 2.0 s |
| 0-40 | 0-25 | 30 | 30 |
| 41-56 | 26-35 | 50 | 30 |
| 57-72 | 36-45 | 85 | 30 |
| 73-88 | 46-55 | 170 | 35 |
| 89-104 | 56-65 | 340 | 50 |
| 105-120 | 66-75 | 620 | 70 |

simple, direct measurement of stripe and pavement luminance under the observation conditions of interest (e.g., nighttime, low beam headlights, dry pavement) at any site where the need for restriping must be determined. Based on luminance meter readings of stripe luminance and pavement luminance, obtained at any practical distance, the dimensionless number denoting contrast level for the pavement marking can be calculated as described in Appendix B of this *Handbook*.

What deserves emphasis—aside from the fact that when one measures contrast, one is measuring what drivers actually see—is just how straightforward it is to obtain this information. An engineer or technician, with a single hand-held piece of equipment (luminance meter) can quickly obtain the measures needed for the contrast calculation, under any operating condition of interest (see Appendix B).

This discussion now turns to raised and reflectorized treatments. Raised pavement markers have received widespread use because they provide better long-range delineation than conventional pavement markings, particularly under wet conditions. When used on a road edge, they also provide brighter peripheral cues, which could be advantageous to the aging driver for path guidance. Over time, however, RPM's also are subject to loss of their initial retroreflectivity; in colder climates, RPM's may be damaged by plowing operations.

Deacon (1988), in his review of research on delineation and marking treatments that he believed would be of particular benefit to the aging driver, found that highways with RPM-enhanced centerlines had lower crash rates than those with painted centerlines only. The average reduction in crash rates was approximately 0.5 crash per million vehicle-miles. Zador, et al. (1986) observed that after-modification vehicle paths were shifted away from the centerline on right and left curves with RPM's mounted on both sides of the double yellow centerlines, and that placement changes were largest with RPM's compared with PMD's and chevrons. It has also been observed that RPM's placed in the centerlines and edge lines at pavement width reductions at narrow bridges produce significant reductions in 85th percentile speeds and centerline encroachments (Niessner, 1984). On two-lane rural curves, RPM's in conjunction with the double yellow centerline have been recommended.

An RPM spacing study was conducted by Blaauw (1985), who tested several RPM patterns on 656-ft radii and 3,281-ft radii horizontal curves using a visual occlusion technique. White RPM's were used for the tests, at spacing distances of approximately 40 ft, 80 ft, and 120 ft. On 656-ft radius curves, the 80-ft and 120-ft spacing led to speed reductions and lane errors. Based on these results, it was recommended that on curves of this severity, the spacing of RPM's be restricted to 40-ft spacing. In general, no differences between treatments were observed for the more gentle, 3,281-ft radius curves. Accordingly, this *Handbook* includes a recommendation for RPM installation, at standard (40-ft) spacing, on all horizontal curves with radii below 3,281 ft.

Roadside delineators and treatment combinations are also important to this discussion. Because of its increasing use throughout the United States, and because it accommodates different types of sheeting in varying amounts and different designs, the primary roadside delineation device of current interest is the flat, flexible post. The general crash data have shown that the installation of PMD's is associated with lower crash rates for highway sections with or without edge lines (Bali, et al., 1978; Schwab and Capelle, 1979). Deacon (1988) confirmed that installation of PMD's lowered crash rates, for sections with or without edge lines. The reduction in crash rates resulting from the installation of these delineators averaged 1.0 crash per million vehicle-miles. Thus, especially for lower functional classification roadways where the use of enhanced (e.g., wider) edge lines may be limited (due to pavement width restrictions), existing data suggest that PMD's can be an effective countermeasure.

In a driver performance study evaluating the effects of chevron signs, PMD's, and RPM's, both Johnston (1983) and Jennings (1984) found that driver performance on sharp curves was the most favorable when chevrons were used. With chevrons, drivers followed a better path around the curve (defined in terms of the ratio of the vehicle's instantaneous radius to the actual curve radius). These studies also revealed that drivers use a corner-cutting strategy, and that chevron signs and PMD's facilitated this strategy. On right curves with chevrons, drivers had an average midcurve placement closest to the centerline. On left curves with chevrons, vehicle placement was not significantly different. In the Good and Baxter (1986) study, chevron signs had a detrimental effect on control behavior, but were rated favorably by drivers in reducing task difficulty. Zador et al. (1986) found that chevrons (as well as RPM's) tend to shift vehicles away from the centerline on right and left curves, while PMD's shift vehicles away from the centerline on right curves. A particular advantage for chevrons with high intensity retroreflective sheeting was demonstrated for drivers age 65 and older in a study by Pietrucha, et al. (1996), when used in combination with other treatments.

The Pietrucha et al. (1996) study was specifically directed to the difficulties aging drivers have with horizontal curve delineation elements, and the possible benefits of brighter materials, larger target sizes, redundant and/or multidimensional cues using combinations of elements, and novel designs or configurations of elements. Twenty-five distinct delineation/pavement marking treatments (a baseline treatment and 24 enhancements) were initially presented to subjects in 3 driver age groups (18–45, 65–74, and 75 and older). The baseline treatment was a 4-in (100-mm) yellow centerline at in-service brightness level (ISBL). The 24 treatments varied according to the presence/absence of an edge line, edge line width, whether the edge line was enhanced with RPM's, whether the centerline was enhanced with RPM's, and the presence/absence of off-road elements and their characteristics (material, color, brightness, and/or spacing). Measures of effectiveness were downstream roadway feature recognition (subjects were required to report the direction in which the roadway curved) and recognition distance in a 35-mm simulation of nighttime driving. Treatments that included the addition of RPM's to both the centerline and edge line, and all treatments that included delineating the roadway edge with high intensity chevrons or high intensity PMD's, resulted in significantly longer mean recognition distances when compared with the baseline treatment, across all age groups. For the subjects age 65 and older, only a subset of the treatments with delineated roadway edges resulted in significantly longer mean recognition distances, due to the increased variance among older subjects' data. Next, field evaluations were conducted with a subset of the most promising treatments. The treatment with the longest recognition distance for both age groups consisted of a 4-in wide yellow centerline at ISBL with yellow RPM's at ISBL and standard spacing, a 4-in wide white edge line, and fully reflectorized T-post delineators with standard spacing. For the 500-ft radius of curvature used in this study, spacing for the PMD's was 65 ft. This treatment included PMD's that were fully retroreflectorized (i.e., retroreflective material extended from the top of the post to the ground and provided more retroreflective area than the standard posts most frequently used).

Blaauw (1985) tested combinations of PMD's and RPM's, resulting in the following recommendations: (1) RPM's exclusively at the center are favorable for lateral vehicle control inside the lane (short-range delineation) but are less adequate for preview information on the lane to be followed (long-range delineation); therefore, it is necessary to delineate both lane boundaries; (2) effective centerline delineation can be realized with RPM's; (3) delineation at the outside of the traffic lane can be realized with RPM's at the location of the lane boundary or with PMD's spaced laterally at 5 ft—both configurations are equally efficient, but PMD's at an approximate 12-ft spacing are less efficient; and (4) RPM's at the location of the center and/or lane boundaries must be applied with a maximum spacing distance of 40 ft on a curve with 656-ft radius or less.

In a laboratory study of drivers' responses to videotapes of four rural horizontal curves, six levels of delineation were studied by Nemeth, Rockwell, and Smith (1985). Seventy-eight drivers ages 18 to 63 participated. The levels of delineation included: no delineation; centerline only; centerline plus edge line; centerline plus edge line plus PMD's; centerline plus edge line plus RPM's; and centerline plus edge line plus PMD's plus RPM's. Subjects were required to identify precisely the instant that they could detect the presence of a curve (left or right) and then express their level of confidence with their response. The largest increase in detection distance was associated with the addition of RPM's and PMD's to the centerline and edge line treatments, respectively. While the treatment condition that included all delineators (PMD's and RPM's, in addition to the centerline and edge line) produced the greatest detection distance (an increase in 148 percent over centerline and edge line delineation only), the most significant change occurred with the addition of the RPM's to a road that initially had only the centerline and edge line (a 112 percent increase in detection distance over centerline and edge line only). The addition of PMD's to the centerline and edge line only condition resulted in an increase in detection distance of 58 percent.

While no specific roadside treatment on horizontal curves is advocated in this *Handbook*, a recommendation for roadside delineation devices at minimum spacing keyed to curve radius appears justified by the findings reported above. Using current practice as a guide, a spacing of 40 ft represents the median value in Table 3F-1 of the *MUTCD*, Approximate Spacing for Delineators on Horizontal Curves, for curves with radii from 50 to 500 ft. This value is also consistent with the 40-ft spacing requirement for RPM's on curves with radii 656 ft noted above.

Finally, as noted by Puvanachandran (1995), vehicle speed upon curve entry is a function of vehicle speed at the approach to the curve, and is not necessarily related to the sharpness of the curve. This underscores the importance of efforts to reduce traffic speeds on the tangent sections preceding the points of curvature. In an IIHS-sponsored study, Retting and Farmer (1998) evaluated the effectiveness of an experimental pavement marking message in reducing excessive traffic speeds at rural and suburban two-lane roadway locations with sharp horizontal curvatures. The experimental text/symbol message employed in this study consisted of the word "SLOW" in 8-ft high white retroreflective letters, a 8-ft long white retroreflective left curve arrow, and a 18-in wide white retroreflective line perpendicular to the centerline of the road at both the beginning and end of the message. This message was placed 220 ft in advance of a 90-degree curve. Traffic speeds were measured at this site on the tangent section at two points: 650 ft and 90 ft prior to the point of curvature, both before and after application of the markings. Speeds were also measured at a control site located on the same roadway in the opposite direction of travel that contained a 45-degree left curve. Data were collected on Saturdays beginning at 10:30 a.m., and ending Sundays at 3:00 a.m., allowing for analysis of daytime (10:30 a.m. to 5:00 p.m.), evening (5:00 p.m. to midnight), and late night (midnight to 3:00 a.m.) traffic speeds. All measurement periods were free from precipitation. Data were analyzed for approximately 800 passenger cars at each location; driver age was not a variable in this study.

The experimental message was associated with a significant decrease in mean speed under daytime, evening, and late-night conditions, and a significant decrease in the percentage of drivers exceeding 40 mph under the daytime and late-night conditions, compared to the upstream and control sites. During the daytime, the mean speeds at the experimental site dropped from 34.3 to 33.2 mph, while the speeds at the upstream site increased from 40.2 to 41.7 mph, and the speeds at the control site increased from 39.6 mph to 41.1 mph. The percentage of drivers exceeding 64 decreased from 9.1 percent to 3.5 percent at the experimental site, but increased from 54 to 66 percent at the upstream site, and from 47 to 62 percent at the control site. During the late-night period, the mean traffic speed decreased from 35.1 to 31.7 mph at the experimental site, and the percentage of drivers exceeding 40 mph decreased from 18.5 to 1.6 percent. This 10 percent decrease in speed was significantly different from the 3 percent decrease in speed measured at the upstream site. Retting and Farmer (1998) state that these average traffic speed reductions, and the reductions in the proportion of high traffic speeds associated with the experimental markings are highly significant; given the exponential relationship between fatality risk and change in velocity during collisions, even seemingly small reductions in mean traffic speeds are likely to result in significant safety benefits. The benefits of this experimental treatment to enhance the safety of aging drivers are unknown at this time, and therefore, no treatment has been included in this Handbook. However, based on the factors that contribute to run-of-the-road, head-on, and rollover collisions on curves (e.g., driver impairment, fatigue, attention, visual deficits, and excessive vehicle speed), it may be expected that such advance information would disproportionately benefit aging drivers with age-related diminished visual and attentional capabilities.

Roadway alignment is a key factor in unsafe vehicular operation: i.e., increasing degrees of curvature cause more crashes (Haywood, 1980). The widening of lanes through horizontal curves, minimizing the use of controlling or maximum curvature for a given design speed, and the use of special transition curves for higher speed and sharper curve designs have all been suggested as countermeasures. Whereas in the past lane widening has been advocated to accommodate the tracking of large trucks through curves, the present focus is on the accommodation of aging drivers, whose diminished physical and perceptual abilities make curve negotiation more difficult. Lane widths on horizontal curves range from 9 ft to 13 ft, but are usually 11-ft or 12-ft wide. Neuman (1992) recommended that when less than 12-ft wide lanes are used, consideration should be given to widening the lane to this dimension through horizontal curves; and a further increase in width of 1–2 ft may be advised to provide for an additional margin of safety through the curve for heavy vehicles. This margin of safety could also be justified in terms of its benefit to aging drivers with diminished physical abilities.

Aging drivers, as a result of age-related declines in motor ability, have been found to be deficient in coordinating the control movements involved in lanekeeping, maintaining speed, and handling curves (Brainin, Bloom, Breedlove, and Edwards, 1977). McKnight and Stewart (1990) also reported that aging drivers have difficulty in lanekeeping, which results in frequently exceeding lane boundaries, particularly on curves. Drivers who lack the required strength, including aging drivers and physically limited drivers, often swing too wide in order to lengthen the turning radius and minimize rotation of the steering wheel.

Joint flexibility is an essential component of driving skill. Osteoarthritis, the most common musculoskeletal disability among aging individuals, affects more than 50 percent of the population age 65 and older (Roberts and Roberts, 1993). If upper extremity range of movement is impaired in the aging driver, mobility and coordination are seriously weakened. Aging drivers with some upper extremity dysfunction may not be able to steer effectively with both hands gripping the steering wheel rim. In a study of 83 people with arthritis, 7 percent used only the right hand to steer and 10 percent used only the left hand (Cornwell, 1987).

The general relationship between pavement width and safe driving operations has been well documented. Choueiri and Lamm (1987) reported the results of several early studies that found an association between decreasing crash frequency and increasing pavement widths. Krebs and Kloeckner (1977) reported that for every 3.3-ft increase in pavement width, a decrease of 0.25 crash per million vehicle-kilometers could be expected. Hall, et al. (1976) examined the nature of single-vehicle crashes involving fixed objects along the roadside of non-freeway facilities. They found that the majority of these types of crashes were reported as non-intersection-related, and occurred most frequently on weekends, at night, under adverse pavement and weather conditions, and on horizontal curves (especially outside of curve). These crash types have high injury severity to drivers and passengers. Wright and Robertson (1979) reported that 40 and 31 percent of all fatal crashes in Pennsylvania and Maryland, respectively, resulted in a vehicle hitting a fixed object such as a tree, utility pole, or bridge abutment. In a study focused on 600 crash sites (and 600 comparison sites) involving fixed objects, crash locations were best discriminated from comparison locations by a combination of curvature greater than 9 degrees (radius: 637 ft) and downhill gradient steeper than 3 percent; and, for the fatal fixed-object crash population, the crash locations were best discriminated from comparison locations by a combination of curvature greater than 6 degrees (radius: 955 ft) and downhill gradient steeper than 2 percent.

Glennon and Weaver (1971) evaluated the adequacy of geometric design standards for highway curves by filming vehicles entering unspiraled highway curves with curvature ranging from 2 to 7 degrees (radius: 2,865 to 819 ft). While driver age was not analyzed, results of the study indicated that most vehicle paths, regardless of speed, exceed the degree of highway curve at some point on the curve. Glennon, Neuman, and Leisch (1985) measured vehicle speed and lateral placement on horizontal curves and found that drivers tend to overshoot the curve radius, producing minimum vehicle path radii sharper than the highway curve, and that the tendency to overshoot is independent of speed. They observed that the tangent alignment immediately in advance of the curve is the critical region of operations, because at about 200 ft before the beginning points of the curve (or approximately 3 s driving time), drivers begin to adjust both their speed and path. Such adjustments are particularly large on sharper curves. Thus, the margin of safety in current AASHTO design policy is much lower than anticipated.

Zegeer, Stewart, Reinfurt, Council, Neuman, Hamilton, Miller, and Hunter (1990) conducted a study to determine the horizontal curve features that affect crash experience on two-lane rural roads and to evaluate geometric improvements for safety upgrading. An analysis of 104 fatal and 104 nonfatal crashes on rural curves in North Carolina showed that in more of the fatal crashes, the first maneuver was toward the outside of the curve (77 percent of the fatal crashes versus 64 percent of the nonfatal crashes). For approximately 28 percent of the fatal crashes (versus 8.8 percent of the nonfatal crashes), the vehicle ran off the road to the right and then returned to be involved in a crash. Further, an analysis on 10,900 horizontal curves in the State of Washington with corresponding crash, geometric, traffic, and roadway data variables showed that the percentages of severe nonfatal injuries and fatalities were greater on curves than on tangents with the same width, where total road width (lanes plus shoulders) was 30 ft.

Zegeer et al. (1990) concluded that widening lanes or shoulders on curves can reduce curve crashes by as much as 33 percent. Specifically, Table 50 shows the predicted percent reduction in crashes that would be expected on horizontal curves by widening the lanes and by widening paved and unpaved shoulders (Zegeer et al., 1990).

The evidence cited above from the engineering studies describing curve negotiation, pavement width, and crash reduction, together with the documented difficulties in lane keeping and diminished motor abilities of aging drivers, support the recommendation

**Table 50.** Percent reduction in crashes on horizontal curves with 8 ft beginning lane width as a result of lane widening, paved shoulder widening, and unpaved shoulder widening. Source: Zegeer et al., 1990.

| Total Amount of Lane or Shoulder Widening (ft) | | Percent Crash Reduction | | |
|---|---|---|---|---|
| Total | Per Side | Lane Widening* | Paved Shoulder Widening | Unpaved Shoulder Widening |
| 2 | 1 | 5 | 4 | 3 |
| 4 | 2 | 12 | 8 | 7 |
| 6 | 3 | 17 | 12 | 10 |
| 8 | 4 | 21 | 15 | 13 |
| 10 | 5 | * | 19 | 16 |
| 12 | 6 | * | 21 | 18 |
| 14 | 7 | * | 25 | 21 |
| 16 | 8 | * | 28 | 24 |
| 18 | 9 | * | 31 | 26 |
| 20 | 10 | * | 33 | 29 |

* *Values of lane widening correspond to a maximum widening of 8 ft to 12 ft for a total of 4 ft per lane, or a total of 8 ft of widening.*

for a minimum pavement width (including shoulder) of 18 ft on arterial horizontal curves over 3 degrees of curvature (radius: 1,910 ft), (cf. Cirillo and Council, 1986). It is understood that limited-access highways already exceed this recommended lane-plus-shoulder width. However, aging drivers often report a preference to travel on two-lane arterials, and these facilities may be deficient in this regard, especially in rural settings.

# 34 Vertical Curves

From a human factors perspective, the accommodation of aging driver needs should be a high priority at sight-restricted locations because of the potential for violation of expectancy, even though the actual percentage of crashes occurring under conditions of limited (vertical) sight distance is quite small (Pline, 1996). Aging drivers, as a result of their length of experience, develop strong expectations about where and when they will encounter roadway hazards and "high-demand" situations with increased potential for conflict. At the same time, aging driver reaction time is slower in response to unexpected information, and aging drivers are slower to override an initial incorrect response with the correct response. Further, aging is associated with physical changes that may interfere with rapid vehicle control when an emergency maneuver is required.

Of greatest importance during the approach to sight-restricted locations are the cognitive components of driving, most notably selective attention and response speed (complex reaction time). Selective attention refers to the ability to identify and allocate attention appropriately to the most relevant targets at any given time (Plude and Hoyer, 1985). One

**Table 51.** Cross-references of related entries for vertical curves.

| Applications in Standard Reference Manuals | | | |
|---|---|---|---|
| ***MUTCD*** **(2009)** | **AASHTO** *Green Book* **(2011)** | **NCHRP 500 – Volume 9 (2004)** | **Traffic Engineering Handbook (2009)** |
| Tables 2C-1 through 2C-5<br>Sects. 2B.28, 2C.05, 2C.36, 2C.45, & 2C.55<br>Sect. 5C.04 | Pg. 2-40, Paras. 1 & 2<br>Pgs. 3-1 through 3-8, Sects. 3.2.1 through 3.2.3 *General Considerations, Stopping Sight Distance, and Decision Sight Distance*<br>Pg. 3-15, Sects. on *Stopping Sight Distance Object & Passing Sight Distance Object*<br>Pgs. 3-149 through 3-164, Sect. 3.4.6 *Vertical Curves*<br>Pg. 3-175, Final Paragraph<br>Pgs. 421-423, Sect. on *Sight Distance*<br>Pg. 445, Sects. on *Sight Distance & Alignment*<br>Pg. 458, Para. 3<br>Pg. 678, Sect. on *Vertical Control* | Pgs. V-8-V-11, Sect. on *Strategy 3.1 B1: Provide Advance Warning Sings (T)* | Pgs. 231-235, Sect. on *Vertical Alignment* |

important finding in the selective attention literature, as noted above, is that aging adults respond much more slowly to stimuli that are unexpected (Hoyer and Familant, 1987), suggesting that aging adults might be particularly disadvantaged when an unexpected hazard appears in the road ahead. In fact, Stansifer and Castellan (1977) suggested that hazard recognition errors can be interpreted more as attention failures than as sensory deficiencies. The selective attention literature suggests that for adults of all ages, but particularly for aging people, the most relevant information should be signaled in a dramatic manner to ensure that it receives a high priority for processing.

Next, appropriate vehicle control behaviors when unexpected hazards are encountered depend upon "speeded responding," or how quickly an individual is able to respond to a relevant target, once identified. A timely braking response when one recognizes that the car ahead is stopped or that a red signal or STOP sign is present can determine whether or not there is a crash. Thus, reaction time or the ability to respond quickly to a stimulus is a critical aspect of successful driving. Mihal and Barrett (1976) measured simple, choice, and complex reaction time and reported that simple and choice reaction time were not correlated with crashes, but complex reaction time was. Moreover, when only aging adults were examined, the correlation with crash involvement increased from 0.27 for complex reaction for the total sample to 0.52, suggesting the relationship to be particularly marked for aging adults. There is nearly uniform agreement among researchers that reaction time increases with age. In particular, studies have demonstrated a significant and disproportionate slowing of response for aging adults versus young and middle-aged adults as uncertainty level increased for response preparation tasks. Preparatory intervals and length of precue viewing times appear to be crucial determinants of age-related differences in movement preparation and planning (Eisdorfer, 1975; Stelmach, Goggin, and Garcia-Colera, 1987; Goggin, Stelmach, and Amrhein, 1989).

In summary, the age-related deficits in reaction time and various aspects of attention are not independent of one another, and more than one of these mechanisms is likely to reduce driving efficiency in the aging adult. Because of these deficits, sight-restricted locations pose a particular risk to aging drivers, presenting a need for treatments addressing both geometry and signing that can be reconciled with available highway research findings in this area.

Unfortunately, there is a lack of conclusive data on this subject. Kostyniuk and Cleveland (1986) analyzed the crash histories of 10 matched pairs of sites on 2-lane rural roadways. The 10 limited sight distance (vertical curve) locations were defined as those below the minimum stopping sight distance (SSD) recommended by AASHTO in 1965, and ranged from 118 ft to 308 ft. The control site locations were defined as those that more than met the standard (SSD greater than 700 ft). Seven of the limited sight distance sites had more crashes than the matched control sites, two were approximately equal, and one had fewer crashes (Pline, 1996). Overall, the set of sites with less than minimum SSD had over 50 percent more crashes in the study period than the control sites.

Farber (1982) performed sensitivity analyses of the effects of change in eye height, object height, friction, and speed on SSD on crest vertical curves. He found that SSD was relatively insensitive to a reasonable range of changes in driver eye height, but was very sensitive to speed, friction, and reaction time. Thus, stopping distance on vertical curves that are of inadequate length or are substandard according to other design criteria, and where major redesign, repaving, or excavation is not feasible, could most efficiently be made safer by modifying a driver's approach speed and/or reaction time. For 55 mph traffic, stopping distance increases 81 ft for every 1-s increase in reaction time. Similarly, stopping distance decreases about 26 ft for each 1 mph reduction in speed. A need for more effective traffic control countermeasures is thus highlighted.

A reevaluation of crest vertical curve length requirements was performed by Khasnabis and Tad (1983). These researchers reviewed the historical changes in parameters that affect the computation of SSD and evaluated the effect of these changes on the length requirements of crest vertical curves. Principal conclusions were that further tests on reaction time are needed to more accurately reflect the changing age distribution and composition of the driving population. In addition, the validity of the assumption of a speed differential for wet pavement conditions between design speed and top driving speed is questionable, since there is very little evidence to substantiate the assumption that all motorists are likely to reduce their speed on wet pavements. Of particular interest, Khasnabis and Tad (1983) noted that the object height of 6 in appears to be somewhat arbitrary, and stated that reducing the object height to 3 in would improve the safety elements of crest curves.

In contrast, there are strong proponents of the position that the obstacle height criterion for design of vertical curves should be raised to 18 in, or the approximate height of a passenger vehicle's rear taillights (see Neuman, 1989). Fambro, Fitzpatrick, and Koppa (1997) evaluated the 1994 AASHTO stopping sight distance model during the conduct of NCHRP project 4-42, and recommended that the object height be raised to 24 in (600 mm) in future revisions to the *Green Book*. This treatment was adopted and reflects the height in the current *Green Book* (2011). The rationale provided by Fambro et al. (1997) includes the following points:

- Crashes involving small objects are extremely rare events and almost never result in injuries to vehicle occupants.
- Small objects are beyond most drivers' visual capabilities at the stopping sight distances required for most rural highways, and especially at night.
- Large animals (e.g., cattle, deer) and other vehicles are more realistic and more frequent hazards to drivers, and from a potential hazard standpoint, the critical object for stopping sight distance should be the smallest visible object during the day and at night that represents a hazard to the driver.
- Approximately 95 percent of the taillight heights and 90 percent of the headlight heights exceed 600 mm, and therefore, 600 mm is recommended as the appropriate object height for determining required stopping sight distances except in those locations where the probability of rocks or other debris in the roadway is high. In these locations, a shorter object is appropriate.

While McGee (1995) has reported that available data are insufficient to definitively establish the relationship between (limitations in) vertical alignment and highway safety, and on the surface it sounds reasonable to use a height criterion corresponding to the most commonly encountered obstacle on the road (i.e., another vehicle), this approach disproportionately penalizes aging drivers in those rare circumstances when a hazard (of any type) appears unexpectedly due to sight-restricting geometry. Also, the simple argument that a conclusive relationship cannot be demonstrated as justification for changing current practice is somewhat disingenuous—a significant relationship between visual acuity and crash involvement has proven elusive, over decades of study, yet there is widespread acknowledgment that good vision is necessary for safe driving.

In consideration of potential countermeasures, since stopping distance is sensitive to decreases in speed and reaction time any traffic control device that lowers either parameter is beneficial. In one study, a LIMITED SIGHT DISTANCE sign (W14-4 in the 1988 *MUTCD*) with a speed advisory was found to be understood by only 17 percent of the 631 respondents who passed through the study sight (Christian, Barnack, and Karoly, 1981). Part of the problem may be that unlike the hazards cited by other warning signs, the phrase "limited sight distance" has no tangible manifestation, and even when drivers have topped the crest of a vertical curve, they may not be aware of the extent to which their sight distance was reduced. Freedman, Staplin, Decina, and Farber (1984) developed and tested the effectiveness of both word and symbol alternative warning devices for use on crest vertical curves using drivers ages 16 to 75. The existing LIMITED SIGHT DISTANCE sign, with or without a supplementary speed advisory panel, did not produce desirable driver responses (braking or slowing) as frequently, nor was it recalled, comprehended, recognized, or preferred as often as the alternatively worded SLOW HILL BLOCKS VIEW sign, or an alternative symbol sign that depicted two vehicles approaching from opposite sides of a hill.

The MUTCD 2009 states that the HILL sign (W7-1 or W7-1a) is intended for use in advance of a downgrade where the length, percent of grade, horizontal curvature, or other physical features require special precautions on the part of road users. While the LIMITED SIGHT DISTANCE sign is not included in the 2009 MUTCD, practitioners are aware of the need to alert drivers of sight restrictions due to vertical curvature, and continue to use the LIMITED SIGHT DISTANCE sign in many jurisdictions. Since the SLOW HILL BLOCKS VIEW sign is explicit in telling drivers what they should do and why they should do it, its use is recommended over both the LIMITED SIGHT DISTANCE sign and the HILL sign. The HILL BLOCKS VIEW sign (W7-6) is included in the 2009 MUTCD, and the guidance associated with its use states that it should be supplemented by an Advisory Speed (W13-1P) plaque indicating the recommended speed for traveling over the hillcrest based on available stopping sight distance

Next, several studies have shown that the use of active sign elements, such as flashing warning lights for SLOW WHEN FLASHING and MAX SPEED ___ MPH messages supplementing various standard warning signs, increases the conspicuity of the signs and results in greater speed reductions (Zegeer, 1975; Hanscom, 1976; Lanman, Lum, and Lyles, 1979; Lyles, 1981) as well as a 60 to 70 percent reduction of crashes at grade crossings compared with the static sign alone conditions (Hopkins and Holmstrom, 1976; Hopkins and White, 1977). According to Pline (1996), several agencies have experienced success with the use of flasher-augmented warning signs with the legend PREPARE TO STOP when there is limited sight distance to a signalized intersection, activated at the time of signal change (red phase).

Lyles (1980) compared the effects of warning signs at horizontal and crest vertical curves with limited sight distance (less than 500 ft). Five warning devices were evaluated:

1. the standard intersection crossroad warning symbol sign;
2. a warning sign with the message VEHICLES ENTERING;
3. a sequence of two warning signs and a regulatory sign (REDUCED SPEED AHEAD, crossroad symbol, and 35 mph speed limit sign);
4. a VEHICLES ENTERING sign with constantly flashing warning lights; and
5. the same as (4) but with a WHEN FLASHING plate, with flashing warning lights activated only in the presence of crossroad traffic.

Overall, the standard crossroads and VEHICLES ENTERING signs had less speed-reducing effect (0.5–2 mph) than the warning-warning-regulatory sequence and the signs with warning lights (4–5 mph). This trend was the same for both horizontal and vertical curves, and there was no significant difference between the warning-warning-regulatory sequence and the signs with warning lights. Motorists were twice as likely to recall the warning-warning-regulatory sequence and signs with warning lights than the standard signs. A van positioned at the crossroad was also reported to have been seen more often with these sign configurations.

If the combination of advance warning messages—in particular, PREPARE TO STOP—and flashers appears to offer the greatest benefit, the activation of the flashers on the red phase only may be problematic. Drivers may associate the absence of flashers to signify an "all clear" condition, when a queue remains from the prior red phase. On the other hand, continuously activated flashers would provide no information about the status of the upcoming signal or traffic conditions (queue) resulting from a red signal, and could therefore breed disregard for the sign, because it carries false information. Therefore, the present treatment is to augment the sign panel with advance warning flashers (AWF) that are activated by the traffic signal controller prior to the onset of the yellow phase, and flash until the signal turns green, long enough for the expected queue to dissipate.

As reviewed above, there is ample reason for concern that at highway approach speeds, a safe response by aging drivers to a revealed obstacle at a crest vertical curve will be problematical. There is evidence of significant age-related decline in the capability to respond to unexpected hazards, specifically in the information processing requirements that precede a brake or steering action (object detection, recognition, and decision to respond). However, while analyses of curve length and sight distance requirements conclude that safety benefits will result from a lower object height criterion, crash data analyses have prompted a move in the opposite direction, toward a more liberal criterion. In fact, current standards (AASHTO, 2011) assume an obstacle height of 2.0 ft, in contrast to the previous value of only 6 in. At the same time, controlled braking rather than locked-wheel braking is assumed, which carries significance because stopping sight distance reflects not only a driver's perception-reaction time (PRT) but also the assumed deceleration rate for a given design speed. With the widely recognized interrelationship between these parameters, and the stance reflected in the AASHTO 2011 design standards, the remaining variable—the driver's PRT—accordingly is the subject of the initial treatment regarding vertical curves: at a minimum, a PRT value of 2.5 s should be used in the design of these roadway features. In addition, conspicuous and comprehensible warning devices should be especially beneficial to aging drivers in sight-restricted situations.

# 35 Passing Zones

The safety and effectiveness of passing zones depend upon the specific geometric characteristics of the highway section, as well as on how drivers receive and process information provided by signs and pavement markings, integrate speed and distance information for opposing vehicles, and control their vehicles (brake and accelerate) during passing maneuvers. As the number of aging drivers in the population increases dramatically over the years 1995–2025, many situations are expected to arise where not only the slower-moving vehicle, but also the passing vehicle, is driven by an aging person.

The capabilities and behavior of aging drivers, in fact, vary with respect to younger drivers in several ways crucial to this discussion. Studies have shown that while driving speed decreases with driver age, the sizes of acceptable headways and gaps tend to increase with age. While motivational factors (e.g., sensation seeking, risk taking) have been shown to play a major role in influencing the higher speeds and shorter headways accepted by young drivers, they seem to play a less important role in aging driver behavior. Instead, the relatively slower speeds and longer headways and gaps accepted by aging drivers have been attributed to their compensating for decrements in cognitive and sensory abilities (Case, Hulbert, and Beers, 1970; Planek and Overend, 1973).

The ability to judge gaps when passing in an oncoming lane is especially important. For some aging drivers, the ability to judge gaps in relation to vehicle speed and distance is diminished (McKnight and Stewart, 1990). Depth perception—i.e., the ability to judge the distance, and changes in distance, of an object—decreases with age (Bell, Wolfe, and Bernholtz, 1972; Henderson and Burg, 1973, 1974; Shinar and Eberhard, 1976).

**Table 52.** Cross-references of related entries for passing zones on two-lane highways.

| Applications in Standard Reference Manuals | | |
|---|---|---|
| ***MUTCD*** **(2009)** | **AASHTO** *Green Book* **(2011)** | **Traffic Engineering Handbook (2009)** |
| Table 2B-1<br>Sects. 2B.28 & 2B.29<br>Tables 2C-1 through 2C-5<br>Sects. 2C.07 & 2C.45<br>Sect. 3B.02 | Pg. 2-38, Para. 1<br>Pgs. 3-8 through 3-14, Sect. 3.2.4 Passing Sight Distance for Two-Lane Highways<br>Pgs. 3-110 through 3-111, Sect. on Passing Sight Distance<br>Pgs. 3-132 through 3-140, Sect. 3.4.4 Methods for Increasing Passing Opportunities on Two-Lane Roads<br>Pgs. 3-156 through 3-157, Sect. on Design controls: passing sight distance<br>Pg. 5-29, Sect. on Passing Sight Distance<br>Pgs. 6-4 through 6-5, Sect. on Sight Distance<br>Pg. 7-3, Sects. on Sight Distance & Alignment<br>Pgs. 7-7 through 7-8, Sect. 7.2.8 Provision for Passing<br>Pgs. 7-16, Sect. on Climbing Lanes on Multilane Arterials | Pgs. 384-385, Sect. on No-Passing-Zone Markings<br>Pgs. 618-619, Sect. on No-Passing Zones<br>Pgs. 224-225, Sect. on Passing Sight Distance (PSD) |

One study found that the angle of stereopsis (seconds of visual arc) required for a group of drivers age 75 and older to discriminate depth using a commercial vision tester was roughly twice as large as that needed for a group of drivers ages 18 to 55 to achieve the same level of performance (Staplin, Lococo, and Sim, 1993). McKnight and Stewart (1990) reported that the inability to judge gaps is not necessarily associated with a high crash rate, to the extent that drivers can compensate for their deficiencies by accepting only inordinately large gaps. This tactic has a negative impact on operations as traffic volumes increase, however, and may not always be a feasible approach.

Judging in-depth motion is made difficult by the fact that when no lateral displacement occurs, the primary depth cue is the expansion or contraction of the image size of the oncoming vehicles (Hills, 1980). Studies of crossing-path crashes, where gap judgments of oncoming vehicle speed and distance are critical as in passing situations, indicate an age-related difficulty in the ability to detect angular movement. In laboratory studies, aging persons required significantly longer to perceive that a vehicle was moving closer (Hills, 1975). Staplin and Lyles (1991) reported research showing that, relative to younger drivers, older ones underestimate the speed of approaching vehicles. Similarly, Scialfa, Guzy, Leibowitz, Garvey, and Tyrrell (1991) showed that older adults tend to overestimate approaching vehicle velocities at lower speeds and underestimate at higher speeds, relative to younger adults. Aging persons also apparently accept a gap to cross in front of an oncoming vehicle that is a more-or-less constant distance, regardless of the vehicle's speed. Analyses of judgments of the "last possible safe moment" to cross in front of an oncoming vehicle showed that older men accepted a gap to cross at an average constant distance, whereas younger men allowed a constant time gap and thus increased distance at higher speeds (Hills and Johnson, 1980). A controlled field study showed that older drivers waiting (stationary) to turn left at an intersection accepted the same size gap regardless of the speed of the oncoming vehicle (30 mph and 60 mph [48 and 96.5 km/h]), while younger drivers accepted a gap that was 25 percent larger for a vehicle traveling at 60 mph (96.5 km/h) than their gap for a vehicle traveling at 30 mph (48 km/h) (Staplin et al., 1993).

The minimum passing sight distances listed in Table 3B-1 of the *MUTCD* (FHWA, 2009) for marking passing zones are shorter than the minimum passing sight distance values for the design of two-lane highways, as listed in Exhibit 3-7 of AASHTO's 2004 *Green Book*; however, AASHTO revised its PSD values in the 2011 *Green Book* (Table 3-4) to match those found in the *MUTCD*. Although the minimum passing sight distances specified by AASHTO are based on observations of successful car-passing-car observations, Hughes et al. (1992) commented that the model does not take into account the abortive passing maneuver, nor does it consider the length of the impeding vehicle. Saito (1984) determined that the values specified by the *MUTCD* for minimum passing distance are inadequate for the abortive maneuver, while Ohene and Ardekani (1988) asserted that the *MUTCD* sight distance requirements are adequate for the driver to abort if the driver decelerates at a rate of 10.5 ft/s$^2$ for a 40-mph passing speed and at a rate of 12.8 ft/s$^2$ for a 50-mph passing speed. In any event, it cannot be assumed that drivers will always use the maximum acceleration and deceleration capabilities of their vehicles, particularly aging drivers.

Consistent with the AASHTO operational model (AASHTO, 2011), passing sight distance is provided only at places where combinations of alignment and profile do not require the use of crest vertical curves. For horizontal curves, the minimum passing sight distance for a two-lane road is about four times as great as the minimum stopping sight distance at the same speed (AASHTO, 2011). By comparison, the *MUTCD* defines passing sight distance for vertical curves as the distance at which an object 3.50 ft above the pavement surface can be seen from a point 3.50 ft above the pavement. For horizontal curves, passing sight distance is defined by the *MUTCD* as the distance measured along the centerline between two points 3.50 ft (1.07 m) above the pavement on a line tangent to the embankment or other obstruction that cuts off the view of the inside curve (*MUTCD*, 2009). The length of passing zones or the minimum distance between successive no-passing zones is specified as 400 ft (120 m) in the *MUTCD*; specifically, where the distance between successive no-passing zones is less than 400 ft, no-passing markings should connect the zones. As Hughes, Joshua, and McGee (1992) pointed out, the *MUTCD* sight distance requirements were based on a "compromise between a delayed and a flying passing maneuver, traceable back to the AASHTO 1940 policy that reflected a compromise distance based on a passing maneuver such that the frequency of maneuvers requiring shorter distances was not great enough to seriously impair the usefulness of the highway."

The basis for the minimum length of a passing zone is unknown, however, because research has indicated that for design speeds above 30 mph the distance required for one vehicle to pass another is much longer than 400 ft (Hughes et al., 1992). Weaver and Glennon (1972) reported that, in limited studies of short passing sections on main rural highways, most drivers do not complete a pass even within an 800-ft section; and use of passing zones remains very low when their length is shorter than 900 ft. Not surprisingly, it has been mentioned in the literature (Hughes et al., 1992) that the current AASHTO and *MUTCD* passing sight distance values are probably too low. Several studies have indicated that both the *MUTCD* and AASHTO passing sight distances are too short to allow passenger cars to pass trucks and for trucks to pass trucks (Donaldson, 1986; Fancher, 1986; Khasnabis, 1986).

Several research studies have been performed that have established and evaluated passing sight distance values for tangent sections of highways. As early as 1934, the National Bureau of Standards measured the time required for passing on level highways during light traffic and found that the time to complete the maneuver always ranged between 5 and 7 s regardless of speed. Passing maneuvers were observed at speeds ranging from 10 to 50 mph. They concluded that 900 ft of sight distance was required for passing at 40 mph (64 km/h). Harwood and Glennon (1976) reported that drivers are reluctant to use passing zones under 880 ft (268 m). They recommended that design and marking standards should be identical and include both minimum passing sight distances and minimum length of passing zones, with minimum passing sight distance values falling between the AASHTO and *MUTCD* values. Kaub (1990) presented a substantial amount of data on passing maneuvers on a recreational two-lane, two-way highway in northern Wisconsin. Under low and high traffic volumes, respectively, he found that 24–35 percent and 24–50 percent of all passes were attempted in the presence of an opposing vehicle; the average time in the opposing lane (60 mph) was 12.2 s under low-traffic conditions and 11.3 s with high-traffic volumes.

Passing lanes, also referred to as overtaking lanes, are auxiliary lanes provided on two-lane highways to enhance overtaking opportunities. Harwood, Hoban, and Warren

(1988) reported that passing lanes provide an effective method for improving traffic operational problems resulting from the lack of passing opportunities, due to limited sight distance and heavy oncoming traffic volumes. In addition, passing lanes can be provided at a lower cost than that required to construct a four-lane highway. Based on Morrall and Hoban (1985), the design of overtaking lanes should include advance notification of the overtaking lane; a KEEP RIGHT UNLESS OVERTAKING sign at the diverge point; advance notification of the merge and signs at the merge; and some identification for traffic in the opposing lane that they are facing an overtaking lane. They reported that there is general agreement that providing short overtaking lanes at regular spacing is more cost-effective than providing a few long passing lanes. This feature becomes increasingly attractive as the diversity of driving styles and driver capability levels grows, with more aggressive motorists accepting greater risks to overtake slower-moving vehicles.

Brewer, et al (2011) studied operational and safety effects of passing lane corridors (also called “Super 2” corridors) in Texas. Previous research (Wooldridge, et al. 2001) demonstrated that periodic passing lanes can improve operations on two-lane highways with average daily traffic (ADT) lower than 5000. Brewer’s research expanded on the Wooldridge research to develop design guidelines for passing lanes on two-lane highways with higher volumes, investigating the effects of volume, terrain, and heavy vehicles on traffic flow and safety. Results indicated that passing lanes provide added benefit at higher traffic volumes, reducing crashes, delay, and percent time spent following. Empirical Bayes analysis of crash data revealed a 35 percent reduction in expected non-intersection injury crashes. Simulation results indicated that most passing activity takes place within the first mile of the passing lane, so providing additional passing lanes can offer greater benefit than providing longer passing lanes. Whether adding new passing lanes or adding length to existing lanes, the incremental benefit diminished as additional length is provided and the highway more closely resembles a four-lane alignment. The simulation study also showed that the effects of ADT on operations were more substantial than the effects of terrain or truck percentage for the study corridor.

Finally, the benefits of fluorescent retroreflective sheeting for increased daytime and nighttime conspicuity are reported by Jenssen, Moen, Brekke, Augdal, and Sjøhaug (1996). They conducted a controlled field study of daytime and nighttime visibility performance of fluorescent and non-fluorescent yellow traffic signs, both fabricated with retroreflective sheeting that provides for high brightness at wide observation angles (ASTM D4956-01,Type IX). The subjects included younger (ages 18-25) and older (ages 55-75) drivers. Under daytime conditions, the fluorescent yellow signs with Type IX sheeting provided a 295 ft increase in sign shape recognition distance over the non-fluorescent yellow signs with Type IX sheeting for the aging driver sample, and a 187 ft increase for the younger driver sample. At a speed of 62 mph, this additional detection distance would translate to 3.2 s of extra reaction time for the older drivers and 2.1 extra seconds of reaction time for the younger drivers. At nighttime, the signs fabricated with Type IX sheeting provided an additional sign shape recognition distance of 945 ft over signs fabricated with engineering grade sheeting (Type I), and an additional 489 ft of shape recognition distance over signs made with high intensity sheeting (Type III) for the older driver sample. The younger driver sample performed similarly, with increased sign shape recognition distances for the signs made with Type IX sheeting (1,010 ft over the signs made with Type I engineering grade sheeting, and 482 ft over the signs fabricated with Type III high intensity sheeting). These increased distances translate to an additional 5 to 10 seconds of reaction time, at a speed of 60 mph (100 km/h).

The age differences in driver capability and behavior noted earlier—i.e., age-related difficulties in judging gaps and in increased perception-reaction time, coupled with slower driving speeds—support a recommendation for use of the more conservative passing sight distance values specified by AASHTO (2004). In addition, a raised treatment to improve drivers' preview of the end of a passing zone—the widely recognized NO PASSING ZONE pennant, either oversized or fabricated with fluorescent yellow retroreflective sheeting that provides for high brightness at wide observation angles (e.g., Type IX) for added daytime and nighttime conspicuity— can reasonably be expected to facilitate aging drivers' decisions and responses in situations where safe operations dictate that they should abort a passing maneuver. Finally, a recommendation to implement passing/overtaking lanes may be justified in terms of overall system safety and efficiency.

# 36 Lane Control Devices

With the increasing need to provide more capacity on freeways and urban arterials, more jurisdictions are moving to the use of reversible lanes to accommodate peak-period traffic flows. The control of wrong-way movements on these facilities may be accomplished through the use of lane control signals (LCS). The MUTCD (section 4M.01) defines lane-use control signals as "special overhead signals that permit or prohibit the use of specific lanes of a street or highway or that indicate the impending prohibition of their use." The meanings of LCS indications (steady downward green arrow, steady yellow X, and steady red X) are defined in MUTCD section 4M.02. LCS's provide real-time information to motorists about which downstream lanes are open (green downward arrow), which are closed (red X) and which lanes are about to be closed (yellow X) either because of an incident downstream or because the lane is a reversible lane. Drivers should vacate lanes over which an LCS displays a yellow X, and they should not enter lanes designated by a red X. Safe and effective responses to these indications by aging drivers hinge upon the same visual target detection and recognition processes which have been documented elsewhere in this Handbook to decline systematically with advancing age.

Ullman, et al. (1996) conducted legibility studies of commercially available lane-use control symbols (LCSs) being used in freeway traffic management systems throughout Texas. Subjects included drivers ages 16-44 and drivers age 65 and older. In the first

**Table 53.** Cross-references of related entries for lane control devices.

| Applications in Standard Reference Manuals | |
|---|---|
| ***MUTCD*** **(2009)** | **AASHTO** *Green Book* **(2011)** |
| Chapter 4M | Pgs. 7-48 through 7-50, Section on Reverse Flow Operation<br>Pgs. 8-28 through 8-31, Section on Reverse-Flow Roadways |

**Table 54.** Median legibility distance (meters) of lane control signals, as a function of driver age, LCS type, and LCS symbol (Ullman, Parma, Peoples, Trout, and Tallamraju, 1996).

| Driver Age | Signal 1 | | | Signal 2 | | | Signal 3 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Red X | Yellow X | Green Down Arrow | Red X | Yellow X | Green Down Arrow | Red X | Yellow X | Green Down Arrow | Yellow Diagonal Arrow | Yellow Down Arrow |
| Young/Middle Aged (16-44) | 366 | 457 | 396 | 335 | 457 | 457 | 427 | 457 | 457 | 427 | 457 |
| Older (65+) | 274 | 274 | 198 | 168 | 350 | 290 | 305 | 274 | 335 | 396 | 427 |

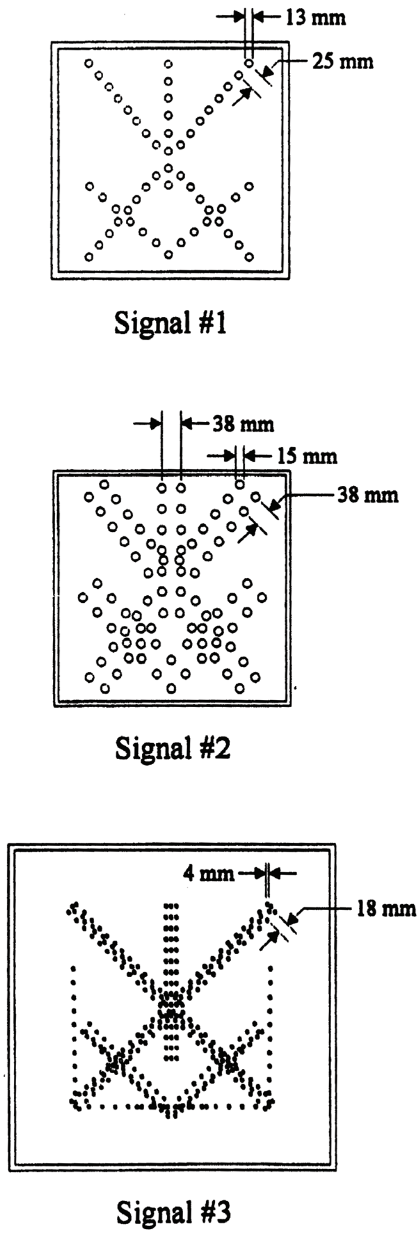



**Figure 94.** Pixel layout of LCD Heads employed in research conducted by Ullman et al. (1996)

study, subjects were seated in the driver's seat of a test vehicle that was positioned 460 m from an overhead sign structure that displayed three fiber optic LCSs mounted side by side. They were shown one symbol presented on one LCS for a 1.5-s duration, and were asked to describe the symbol and the color. If a subject could not correctly identify the color and symbol, he or she moved closer to the LCS, until the color and symbol could be correctly identified. The study was conducted during the day. The symbols on all three LCS heads measured 14 in in height, but the arrangement of the pixels varied for the three sign manufacturers. Signal 1 utilized a single-stroke arrangement of pixels, arranged using 0-5 in lenses spaced 1 in apart. Signal 2 utilized a double-stroke arrangement of pixels, arranged using 0.6-in lenses spaced 1.5 in apart. Signal 3, besides displaying the three standard MUTCD symbols, was also able to display a yellow arrow pointing downward, or pointing to the left or right. Signal 3 utilized a double-stroke arrangement of pixels for the green arrow, the red X, and the yellow X, but utilized a single-stroke arrangement for the downward and diagonal yellow arrows. The lenses measured 0.15 in, and spacing was 0.7 in. Figure 94 presents the pixel layout of the three LCS heads used in this research. The legibility distances by symbol type are presented in Table 54, by signal type and driver age.

Results indicate that median legibility distances for the older drivers viewing the red X, yellow X, and green arrow were 298 to 649 ft shorter than those for the younger drivers. The biggest discrepancies between younger and older drivers were for the red X on Signal 2 and the green down arrow on Signal 1. Signal 3 produced the most uniform legibility distances for all symbols. The authors state that comments from the older drivers indicated that the double-stroke pixel arrangement combined with the larger pixel lenses on Signal 2 caused irradiation effects, resulting in older drivers' inability to identify the shape of the red "glow" until they were 50 percent closer to the signal than younger drivers. The actual cause of the poor legibility of the green down arrow on Signal 1 for older drivers was unknown, but hypothesized by the researchers to be a result of being slightly more "blue" than the green down arrows on the other two signals.

On the other hand, although the yellow downward and diagonal arrows displayed on Signal 3 are not standard MUTCD symbols for LCS's, they showed the highest legibility distance of all symbols for the older drivers, and yielded a legibility distance that was 30 m shorter than younger drivers' legibility distance. These symbols were created with a single line of closely spaced small pixels. The legibility distance was greater than that of the double-stroke yellow X presented on the same display. Results of a preliminary field study conducted in this same project indicated that the yellow X and yellow down/diagonal arrows were interchangeable, resulting in similar proportions of drivers exiting a closed lane.

The authors also studied the effects of age, dirt accumulation, and regular maintenance on LCS legibility. The combined effect of age and dirt accumulation significantly reduced the visibility of the green arrow and red X for both younger and older driver groups. The signal had been installed for 6 years, and had an 18-month accumulation of dirt, since its last cleaning. Subjects viewed the symbols before and after cleaning and replacement of each of the 50-watt halogen light bulbs in the signal face. The legibility distances before maintenance and cleaning ranged from 600 to 1,099 ft for drivers under age 45, and 351 to 899 ft for drivers age 65 and older. After maintenance and cleaning, visibility distances increased significantly for both driver groups. Median visibility distances for the younger drivers ranged from 850 to 1,250 ft, and for the older drivers ranged from 699 to 1,099 ft. There appears to be permanent loss of visibility of the red and green symbols over time; after maintenance, the legibility distances for both driver groups were two-thirds to three-fourths of those shown for the new LCS. The effect of dirt and signal age did not affect legibility distance of the yellow X.

# PROMISING PRACTICES

## 37 Lane Drop Markings

**Description of Practice**: Pavement markings in advance of a lane drop are used to supplement the warning sign messages that indicate the lane is a dropped lane. Section 3B.04 of the 2009 *MUTCD* discusses standards and guidance for dotted white lane line markings and other lane-drop markings. Note that this is a different marking application than lane reduction markings, which are described in Section 3B.09.

**Anticipated Benefits to Aging Road Users**: As the result of normal aging, drivers may be at higher risk of failing to detect advance warning signs posted at the side of the road due to loss of visual sensitivity in the periphery; a narrowing of the attentional (or "useful") field of view; or a reduced ability to engage in a search of the visual periphery when, for example, road or weather conditions increase demands for path guidance information. To the extent that aging drivers experience any of these limitations, they should derive an extra benefit from advance warning messages presented as pavement markings—if these markings are applied and maintained at contrast levels sufficient to ensure legibility to an "aging design driver."

## 38 Contrast Markings on Concrete Pavement

**Description of Practice**: Duplicate black markings applied immediately upstream or downstream from broken line longitudinal markings (staggered markings), or black contrast marking surrounding either side of broken or continuous longitudinal markings, are used to increase the visibility of markings on concrete and other light colored pavements. Routine use of such "contrast markings" occurs in Arkansas, Colorado, Georgia, Idaho, Missouri, North Carolina, Oklahoma, Pennsylvania, Texas, Utah, Virginia, Wisconsin, and the District of Columbia. The use of supplemental contrast markings is included as an option in the 2009 MUTCD.

**Anticipated Benefits to Aging Road Users**: Any treatment that improves the contrast and therefore the detectability of lane, gore, and other longitudinal pavement markings, whether broken or continuous, will have a disproportionate benefit to aging drivers, who as a group experience diminished contrast sensitivity due to normal changes in the lens of the eye and also evidence a higher prevalence of ocular diseases.

# 39 Utilize Highly Retroreflective Marking Material

**Description of Practice**: Oversize glass beads in traditional paint markings, profiled thermoplastic markings, and preformed pavement marking tape designed for rumble strip applications all offer strategies to increase the retroreflectivity and thus the visibility of pavement markings at night and in wet weather conditions. Preformed pavement marking tape is utilized statewide in Iowa and on Detroit-area freeways in Michigan. Virginia utilizes the pavement marking tape on all interstate routes.

**Anticipated Benefits to Aging Road Users:** Any treatment that improves the contrast and therefore the detectability of lane and road edge boundaries will have a disproportionate benefit to aging drivers, who as a group experience diminished contrast sensitivity due to normal changes in the lens of the eye and also evidence a higher prevalence of ocular diseases. The continuous guidance information offered by treatments that enhance the contrast of pavement markings is especially helpful to aging drivers under adverse visibility conditions and when there is only a brief preview of changing roadway geometry downstream.

# 40 Curve Warning Markings

**Description of Practice**: Curve warning markings on the pavement in advance of horizontal curves are used to supplement warning sign messages such as the Curve Ahead sign and other curve delineation devices such as chevron signs. Such advance markings are currently in use in many locations in the country, including Irvine, California and Williamston, Michigan.

**Anticipated Benefits to Aging Road Users**: As the result of normal aging, drivers may be at higher risk of failing to detect advance curve warning signs posted at the side of the road due to loss of visual sensitivity in the periphery; a narrowing of the attentional (or "useful") field of view; or a reduced ability to engage in a search of the visual periphery when, for example, road or weather conditions increase demands for path guidance information. To the extent that aging drivers experience any of these limitations, they should derive an extra benefit from advance warning messages presented as pavement markings—if these markings are applied and maintained at contrast levels sufficient to ensure legibility to an "aging design driver."

# 41 Road Diets

**Description of Practice**: The classic roadway reconfiguration commonly referred to as a "road diet" involves converting an undivided four-lane roadway into three lanes made up of two through lanes and a center two-way left turn lane. The reduction of lanes allows the roadway to be reallocated for other uses such as bike lanes, pedestrian crossing islands, and/or parking. Midblock locations tend to experience higher travel speeds, contributing to increased injury and fatality rates. More than 80 percent of pedestrians hit by vehicles traveling at 40 mph or faster will die, while less than 10 percent will die when hit at 20 mph or less. (FHWA Office of Safety 2012)

Road diets can be low-cost treatments if planned in conjunction with reconstruction or simple overlay projects, since a road diet mostly consists of restriping. Roadways with Average Daily Traffic (ADT) of 20,000 or less may be good candidates for a road diet and should be evaluated for feasibility. It has been shown that roads with 15,000 ADT or less had very good results in the areas of safety, operations, and livability. Driveway density, transit routes, the number and design of intersections along the corridor, as well as operational characteristics are some considerations to be evaluated before deciding to implement a road diet.

It is a good practice to know well in advance when road reconstruction and overlay projects will be initiated so an evaluation can be conducted. It is important to analyze and understand the effects of the proposed change, obtain input from the community stakeholders, and ensure the appropriate elements are included in the project. Improvements to intersection turn lanes, signing, pavement markings, traffic control devices, transit stops, and pedestrian and bicyclist facilities may be needed to support this concept. It should be noted that the classic four-to-three-lane road diet is very compatible with single-lane roundabouts.

**Anticipated Benefits to Aging Road Users**: Road diets have multiple safety and operational benefits for vehicles as well as pedestrians, such as:

- Decreasing vehicle travel lanes for pedestrians to cross, therefore reducing the multiple-threat crash (when one vehicle stops for a pedestrian in a travel lane on a multi-lane road, but the motorist in the next lane does not, resulting in a crash) for pedestrians.
- Providing room for a pedestrian crossing island.
- Improving safety for bicyclists when bike lanes are added (such lanes also create a buffer space between pedestrians and vehicles).
- Providing the opportunity for on-street parking (also a buffer between pedestrians and vehicles).
- Reducing rear-end and side-swipe crashes.
- Improving speed limit compliance and decreasing crash severity when crashes do occur.

When appropriately applied, road diets have generated benefits to users of all modes of transportation, including bicyclists, pedestrians, and motorists. The resulting benefits include reduced vehicle speeds, improved mobility and access, reduced collisions and injuries, and improved livability and quality of life. When modified from four travel lanes to two travel lanes with a two-way left-turn lane, roadways have experienced a 29 percent reduction in all roadway crashes. The benefits to pedestrians include reduced crossing distance and fewer midblock crossing locations, which account for more than 70 percent of pedestrian fatalities. (FHWA Office of Safety 2012) A Michigan study (Taylor 2004) compared before-after crash data for eight corridors treated with road diets and found that the weighted average number of crashes per year declined by 25 percent and injury crashes by 30 percent, but for crashes specifically involving aging drivers, the weighted average number of crashes per year declined by 39 percent and injury crashes by 48 percent.

# 42 High Friction Surface Treatments (HFSTs)

**Description of Practice:** Horizontal curves made up only 5 percent of the country's highway miles in 2008. Yet, more than 25 percent of highway fatalities in the United States occur at or near horizontal curves each year. While some of the factors contributing to these crashes include excessive vehicle speed or distracted driving and driver error, at some locations, the deterioration of pavement surface friction may also be a contributing factor. Variable friction creates the need to consider pavement improvements for surface characteristics, particularly for friction, at certain locations in order to increase safety.

High friction surface treatments (HFSTs) are the site-specific application composed of "tough" polish-resistant, abrasion-resistant aggregates bonded to the pavement surface using a resin that restores and maintains pavement friction where the need for a safer pavement surface is the greatest. Maintaining the appropriate amount of pavement friction is critical for safe driving. Vehicles traversing horizontal curves require a greater side force friction, and vehicles at intersections require greater longitudinal force friction.

HFSTs have been used on horizontal and vertical curves, at intersections, at on and off-ramps, and on bridge decks. HFSTs are known to reduce crashes, have a significant benefit/cost ratio, are relatively low-cost compared to geometric improvements, are durable and long-lasting, produce negligible environmental impacts and have minimal impact to traffic. HFSTs have been tried and proven in over 40 states, and they are a recommended treatment as part of FHWA's Every Day Counts initiative (FHWA, 2012).

HFSTs can be placed manually or mechanically depending on the size of the project. Costs typically run $20 to $40 per square yard, depending on the size of the project. Friction values immediately increase with HFST and retain their values over much longer time periods (7-10 years) than typical pavement mixes. Because HFSTs are placed on the pavement, there is seldom any need for right-of-way or environmental approvals, which lead to a quick solution at a reduced cost compared to geometric improvements. This in turn leads to a reduction in crashes and can be used proactively on other areas with similar geometrics. (ATSSA, 2013)

**Anticipated Benefits to Aging Road Users:** A higher friction surface amplifies braking and expedites the reduction in vehicle speeds, helping drivers retain control. Furthermore, it meets the need underscored by AASHTO's 2011 *Green Book* to provide skid resistant pavements for wet, snow and ice covered surfaces to address side friction needs. While these benefits have been shown for the driving population as a whole, they are expected to be at least as applicable for aging drivers to help offset declining reaction times in steering and braking.

## CHAPTER 10

# Construction/Work Zones

The following discussion presents the rationale and supporting evidence for Handbook treatments pertaining to these seven proven and promising practices.

### Proven Practices

43. Signing and Advance Warning
44. Portable Changeable (Variable) Message Signs
45. Channelization (Path Guidance)
46. Delineation of Crossovers/Alternate Travel Paths
47. Temporary Pavement Markings

### Promising Practices

48. Increased Letter Height for Temporary Work Zone Signs
49. Work Zone Road Safety Audits

# PROVEN PRACTICES

## 43 Signing and Advance Warning

Minimum requirements for safely negotiating a lane closure include an awareness of a decrease in pavement width ahead, and of the direction of the lateral shift in the travel path; a detection of traffic control devices marking the location of the lane drop (beginning of taper); a timely decision about the most appropriate maneuver, taking other nearby traffic into account; and smooth vehicle control through maneuver execution. In the vicinity of a lane closure, the longer the information needs supporting these requirements remain unmet for the least capable drivers within the traffic stream, the less likely is a smooth transition through the work area for all drivers (Goodwin, 1975). The more time that is required for aging drivers to prepare and initiate a merging maneuver, the more dense following traffic (including the adjacent lane) is likely to become; this, in turn, will make gap judgments and maneuver decisions at the point of a lane closure more difficult, and will increase the likelihood of erratic vehicle movements resulting in conflicts between motorists.

Relevant alterations in aging adults' cognitive-motor processes include: failure to use advance preparatory information (Botwinick, 1965); difficulty in processing stimuli that are spatially incompatible (Rabbitt, 1968); initiation deficit in dealing with increased task complexity (Jordan and Rabbitt, 1977); and inability to regulate performance speed (Rabbitt, 1979; Salthouse, 1979; Salthouse and Somberg, 1982). Stelmach, Goggin, and Garcia-Colera (1987) found that older adults showed disproportionate response slowing when compared with younger subjects, when there was low expectancy for a required movement. When subjects obtained full information about an upcoming response, reaction time (RT) was faster in all age groups. Stelmach et al. (1987) concluded that

**Table 55.** Cross-references of related entries for signing and advance warning.

| Applications in Standard Reference Manuals | | |
|---|---|---|
| *MUTCD* (2009) | NCHRP 500 – Volume 9 (2004) | Traffic Engineering Handbook (2009) |
| Sect. 6C.05<br>Sect. 6C.06<br>Sects. 6F.16 & 6F.17<br>Sects. 6F.81 to 6F.83<br>Sect. 6F.61<br>Sect. 6F.63<br>Sect. 6G.04<br>Sect. 6G.10<br>Sects. 6G.12 through 6G.19<br>Tables 6C-1 & 6C-3<br>Figs. 6H-3, 6H-5, 6H-6, 6H-10 through 6H-12, 6H-15, 6H-16, 6H-18, 6H-19, & 6H-21 through 6H-46 plus associated notes with each fig. | Pgs. V-8-V-11, Sect. on *Strategy 3.1 B1: Provide advance Warning Signs (T)*<br>Pgs. V-26-V-27, Sect. on *Strategy 3.1 B11: Improve Traffic Control at Work Zones (T)* | Pgs. 357-376, Sects. IIA through IID<br>Pgs. 391-392, Sect. on *Older Drivers and Pedestrians* |

aging drivers may be particularly disadvantaged when they are required to initiate a movement in which there is no opportunity to prepare a response. Preparatory intervals and length of precue viewing times are determining factors in age-related differences in movement preparation and planning (Goggin, Stelmach, and Amrhein, 1989). When preparatory intervals are manipulated such that aging adults have longer stimulus exposure and longer intervals between stimuli, they profit from the longer inspection times by performing better and exhibiting less slowness of movement (Eisdorfer, 1975; Goggin et al., 1989). Since aging drivers benefit from longer exposure to stimuli, Winter (1985) proposed that signs should be spaced farther apart to allow drivers enough time to view information and decide which action to take. Increased viewing time will reduce response uncertainty and decrease aging drivers' RT.

In focus group discussions consisting of 81 drivers ages 65 to 86, pavement width transitions were identified as sources of difficulty by 50 percent of the participants (Staplin, et al., 1997). The drivers participating in these discussions suggested longer merging areas to give them more opportunity to find a safe gap and the use of multiple warning signs to allow them to plan their maneuver at an earlier point upstream. Use of multiple signs to give advance notice of downstream work zones and of required maneuvers was also offered as a desired change by aging drivers participating in an earlier focus group (Staplin, Lococo, and Sim, 1990).

Lyles (1981) conducted studies on two-lane rural roads to evaluate the effectiveness of alternate signing sequences for providing warning to motorists of construction and maintenance activities that required a lane closure. The signs tested included a standard *MUTCD* warning sequence, the same sequence augmented with continuously flashing warning lights on the signs, and a sequence of symbol signs (WORKER and RIGHT LANE CLOSED). The most effective sign sequence was one that was flasher augmented; this treatment was twice as effective as similar signs with no warning lights in slowing vehicles in the vicinity of the lane closure.

The use of word messages on signs in highway work areas raises sign legibility issues for aging drivers. In research conducted to improve the legibility of the RIGHT/LEFT LANE CLOSED and ROAD CONSTRUCTION series signs using test subjects in three age groups (18–44, 45–64, and 65 and older), Kuemmel (1992) concluded the following for black on orange (negative contrast) signs: (1) signs that increased both letter size and stroke width (SW) while maintaining or increasing the standard alphabet letter series resulted in the best improvement; (2) increasing letter size while decreasing the alphabet series (e.g., from C to B) reduces sign legibility, particularly at night; (3) the use of letter series E, with its 21-percent increase in SW-to-letter height over 8-in series C letters, appears to overcome the problems of irradiation (or overglow phenomenon) with high intensity retroreflective materials, thus increasing night legibility; (4) the legibility distance of the ROAD CONSTRUCTION signs can be increased by changing the word "construction" to "work," and increasing the letter size from 175-mm (7-in) series C to 200-mm (8-in) series C; and (5) for the RIGHT LANE CLOSED series, use of symbol signs will have to supplement word legend signs, and for the CENTER LANE CLOSED series, redundant signs will have to be employed if a 48-in maximum sign size is to be maintained. The author pointed out that the minimum required visibility distance (MRVD) for both signs is 331 ft at 55 mph and 369 ft at 65 mph. The legibility distances obtained in this study for the current standard construction work zone signs ranged from 650 ft for the best observers to 140 ft for the worst observers. In addition, 85th percentile values were closer to the minimum legibility distances than they were to the maximum legibility distances. This finding reinforces the need for redundant signing during the approach to a work zone.

Several studies have centered on the use of fluorescent orange signs for work zone applications, particularly as their increased conspicuity may benefit aging drivers with diminished visual capabilities by providing longer detection distances. Jenssen, et al. (1996) state that fluorescent materials have the potential to increase daytime conspicuity through increased contrast, while the nighttime brightness is sustained through a microprismatic retroreflective system. Burns and Pavelka (1995) explain that the high visibility of fluorescent materials is due to their ability to absorb energy in the near ultraviolet and visible region of the electromagnetic spectrum, and then to re-emit the energy as longer wavelength, visible light. Conventional colorants don't have this property. During the daylight hours from dawn to dusk, there is always sufficient solar energy to elicit light emission from fluorescent materials, irrespective of the cloud cover. Therefore, fluorescent colors maintain a significant daytime visibility advantage over ordinary colors in all types of weather. Improvements in legibility distance have also been found using signs with fluorescent orange microprismatic sheeting (sheeting that provides for high retroreflectance overall, particularly at widest available observation angles).

Chrysler, Carlson, and Hawkins (2002) conducted a controlled field study to determine nighttime sign legibility distance for small ground-mounted signs as a function of retroreflective sheeting type, font, and color. Study methods and results presented here are limited to those describing orange signs. Two font types, both using 6-in black letters were compared, with all signs created using 4-letter words chosen from the *MUTCD*. The baseline font was Highway Series D. D-Modified font, created for Alabama DOT for use on work zone signs with a thicker stroke width than Highway Series D, was also used. Three types of retroreflective sheeting were used:

- ASTM Type III (high-intensity encapsulated lens glass bead material), orange.
- ASTM Type VIII (super-high-intensity microprismatic material), fluorescent orange.
- ASTM Type IX (very-high-intensity microprismatic material), fluorescent orange.

Participants in the Chrysler et al. (2002) study included 12 licensed drivers ages 55 to 64 and 12 licensed drivers ages 65 to 75, with males and females equally represented in both groups. Binocular acuity for 21 participants was 20/25 or better, one subject had acuity of 20/30, one had 20/40 acuity, and one had 20/50 acuity. Subjects drove a passenger sedan around a closed course at 30 mph at night using low-beam headlights (HB4 halogen), while attempting to read ground-mounted signs on the right shoulder. Subjects were accompanied by an experimenter who sat in the front passenger seat. Subjects were told to say the word as soon as they could correctly identify it, but were also told that there was no penalty for being wrong, and that it was OK to guess. All signs were offset 14 ft from the right edge line with a height of 8 ft to the center of the sign.

Chrysler et al. (2002) found no significant differences in legibility distance as a function of font type, with the mean of 160 ft for D-Modified, and a mean of 167 ft for Highway Series D. The difference in performance between the two microprismatic sheetings was not significant (Type VIII mean legibility distance = 175 ft and Type IX mean = 169 ft), but both produced significantly longer distances than Type III (mean = 148 ft). There were no significant effects of age on legibility distance for the orange signs. Based on their findings of superior legibility performance with fluorescent microprismatic sheeting, Chrysler et al. (2002) recommended its use for work zone signs over the use of Type III orange sheeting. They also recommended a more conservative legibility index of 33 ft/in (in place of the standard of 40 ft/in) based on their study findings which averaged 24 to 34 feet of legibility per inch of letter height across the 4 sheeting colors evaluated.

Jenssen et al. (1996) conducted a controlled field study using 35 younger subjects (ages 18 to 25) and 44 older subjects (ages 55 to 75) to compare the detection distance, color recognition distance, and the legibility distance of fluorescent signs to traditional signs, under daytime and nighttime conditions. In this study, subjects sat in an open-ended container on a railway car that moved at a speed of 9 mph along a set of unused railroad tracks. Subjects used a response form and were trained to look for specific signs. They activated a response lever that sent a signal to a distance-measuring computer, and then recorded what they observed in the categories provided on their response forms for sign detection, shape, color, symbol, and text. The signs of interest for this discussion were those with an orange background and black text.

Signs with fluorescent orange Type VII retroreflective sheeting were compared to signs with standard orange Type VII retroreflective sheeting, signs with standard orange Type III high intensity grade retroreflective sheeting, and signs with standard orange Type I engineering grade retroreflective sheeting. In the daytime, only signs with Type VII optics were used. The Norwegian town names "LENSVIK," "LAKSVIK," or "LEKSVIK," appeared in randomized order on the signs. The height, angle, and distance of the signs relative to the track were adjusted according to standards for Norwegian two-lane roadways, to ensure realistic viewing positions. Signs were always placed on the right side of the track. For nighttime trials, original headlights for a Volkswagen Golf type 1 vehicle (placed on the railcar at the standard vehicle headlight orientation) were used.

Detection, shape recognition, color recognition, and content recognition were accomplished at significantly greater distances for fluorescent orange retroreflective signs than for the standard orange retroreflective signs, for both younger and older subjects under daytime conditions. The mean detection distance for all subjects during daytime conditions for the fluorescent orange retroreflective signs was 2,697 ft, compared to 2,569 ft for standard orange retroreflective signs. This difference in detection distance was statistically significant. The difference in mean detection distance was larger for the older subjects than for the younger subjects; however, both age groups demonstrated significantly longer detection distances when viewing the fluorescent orange retroreflective signs. The mean shape recognition distance across all subjects during the daytime was 2,441 ft for the fluorescent orange retroreflective signs and 2,136 ft for the standard orange retroreflective signs. Younger subjects were able to correctly recognize the shape of fluorescent signs at an average distance that was 335 ft longer than for the standard signs, and older subjects demonstrated an average shape recognition distance difference of 194 ft. Fluorescent signs also showed significantly longer correct color recognition distances (1,916 ft across age groups) than standard signs (1,539 ft across age groups). Color recognition distances were 429 ft longer for younger subjects, and 350 ft longer for older subjects when viewing the fluorescent signs during the daytime compared to the standard signs. In terms of legibility distances during daytime, across all subjects, the fluorescent signs significantly outperformed the non-fluorescent signs, with a difference in mean legibility distance of 43 ft.

At nighttime, there were no significant differences in detection, shape recognition, color recognition, or contents recognition distances between fluorescent orange retroreflective signs with Type VII sheeting and standard (non-fluorescent) orange retroreflective signs with Type VII sheeting, for either age group. However, comparisons between the three types of retroreflective sheeting indicated that the signs with Type VII sheeting produced detection distances that were 138 ft longer than the signs with high intensity grade sheeting, and 203 ft longer than the signs with engineering grade sheeting, for the older drivers. For the younger drivers, detection distances for the signs with Type VII sheeting were 62 ft longer than those produced by the signs with high intensity grade sheeting, and 118 ft longer than those produced by the signs with engineering grade sheeting.

The mean sign detection distance, shape recognition distance, color recognition distance, and contents recognition distance are presented in Table 56, as a function of subject age group and lighting condition (day vs. night) for the signs with standard orange Type VII sheeting and for the signs with fluorescent orange Type VII sheeting.

Burns and Pavelka (1995) conducted a field study using 14 drivers ages 19 to 57 (median age: 40 years), to compare the visibility and conspicuity of durable retroreflective

**Table 56.** Subject performance as a function of sheeting type (fluorescent orange Type VII vs. standard orange Type VII), as a function of subject age group and lighting condition (Jenssen, Moen, Brekke, Augdal, and Sjøhaug, 1996).

| Lighting Condition | Age Group | Sign Color (Type VII Sheeting) | Mean Distance (m) | | | |
|---|---|---|---|---|---|---|
| | | | Sign Detection | Shape Recognition | Color Recognition | Contents Recognition |
| Daytime | Young | Standard Orange | 828 | 707 | 518 | 123 |
| | | Fluorescent Orange | 851 | 808 | 648 | 131 |
| | Old | Standard Orange | 726 | 591 | 410 | 92 |
| | | Fluorescent Orange | 776 | 650 | 516 | 108 |
| Nighttime | Young | Standard Orange | 838 | 707 | 592 | 88 |
| | | Fluorescent Orange | 815 | 623 | 548 | 93 |
| | Old | Standard Orange | 771 | 589 | 471 | 92 |
| | | Fluorescent Orange | 758 | 555 | 430 | 66 |

fluorescent sheetings (orange, red, yellow, and yellow-green) to the same color standard highway sheeting (orange, red, yellow, yellow-green, and green), at midday and at dusk. Circular targets with an area measuring 0.01 $ft^2$ were viewed in pairs (one fluorescent and one standard highway color sign) against a 4-ft by 4-ft background. The background consisted of a complex camouflage pattern made up of 23 percent light green, 34 percent green, 25 percent brown, and 18 percent black. The targets were placed 1 ft apart, and were viewed at four distances during the daytime (394 ft, 295 ft, 197 ft, and 98 ft). At dusk (15 min before sunset, and 15 min after sunset), signs were viewed only at 98 ft. Subjects viewed the target pairs while seated in a vehicle that had the headlights turned off. An electronic shutter system provided a viewing duration of 2 s. After each target pair was viewed, subjects provided responses to indicate:

1. number of targets detected (0, 1, or 2);
2. target location (left or right);
3. target color (left color and right color); and
4. attention-getting value (was one target perceived more easily, or did one target attract your attention more than the other?).

During the daytime, the durable fluorescent targets evaluated in the Burns and Pavelka (1995) study were detected with a higher frequency (close to 100 percent) and at greater distances than the standard highway colors. At midday (facing north on an overcast day) from a distance of 396 ft, 93 percent of the subjects were able to detect the fluorescent orange targets; however, only 43 percent of the subjects could detect the standard orange targets at this distance under the same lighting conditions. At 90 m, 100 percent of the subjects detected the fluorescent signs, compared to 92 percent who detected the standard orange signs. At dusk (15 min after sunset) at a distance of 100 ft, the fluorescent orange signs were detected by 96 percent of the subjects and the standard orange signs were detected by 85 percent of the subjects.

The fluorescent signs also showed greater color recognition than the standard highway signs at all distances. During midday (overcast facing north), the fluorescent orange signs were correctly identified by 61 percent of the subjects at 120 m, 58 percent of the subjects at 90 m, 86 percent of the subjects at 60 m, and 82 percent of the subjects at 30 m. By comparison, the standard orange signs were identified correctly by 7 percent, 23 percent, 64 percent, and 93 percent of the subjects at the same distances. At dusk (15 minutes before sunset) at 30 m, the fluorescent orange signs were correctly identified as orange by 74 percent of the subjects, compared to 62 percent of the subjects for the standard orange signs.

The fluorescent orange sign in each pair of viewings was subjectively determined to be more conspicuous (more attention-getting) than the standard orange highway sign, at 30 m, under all lighting conditions (midday, 15 min before sunset, and 15 min after sunset). Luminance measurements were taken of the targets and their backgrounds, so that a contrast ratio could be calculated. The fluorescent signs always produced a higher contrast ratio than the standard signs. The contrast ratios for the fluorescent orange and standard orange signs are shown in Table 57, under the various, natural lighting conditions utilized in the study.

**Table 57.** Luminance contrast ratio ([Lt-Lb]/Lb) under different lighting conditions, for fluorescent orange and standard highway orange signs (Burns and Pavelka, 1995).

| Color | Sign Direction and Lighting Condition | | |
|---|---|---|---|
| | South facing midday—clear | North facing midday—overcast | North facing dusk—overcast |
| Fluorescent Orange | 5.4 | 4.4 | 1.0 |
| Standard Orange | 1.8 | 2.0 | 0.5 |

The authors concluded that fluorescent orange signs are more conspicuous than standard highway orange sign colors during the daytime (as were the other fluorescent colors); are detected with higher frequency; and are recognized with greater accuracy at farther distances. Fluorescent signs provide a greater contrast with the background scene, and therefore should be considered as a countermeasure to address problems that aging drivers have in the detection and recognition of traffic signs when viewed against a cluttered background.

Finally, Hummer and Scheffler (1999) conducted a field study at seven long-term work zones in North Carolina with left lane drops on multilane highways, to determine whether the increase in the conspicuity of fluorescent orange signs leads to positive operational changes in driver behavior. All seven sites were left lane drops on four-lane highways (with standard lane and shoulder widths), with the following sequence of orange signs (in pairs, with one sign on each side of the highway):

- Two fluorescent BEGIN WORK ZONE text message signs located 0.4 to 1.2 mi from the taper.
- Two text message LEFT LANE CLOSED AHEAD signs located 0.25 to 0.68 mi from the taper.
- Two symbol message LEFT LANE CLOSED AHEAD signs located 0.1 to 0.31 mi from the taper.
- Two text message LEFT LANE CLOSED signs at the beginning of the taper.

Six sites had 55 mph speed limits and wide grassy medians, and one site had a 65 mph speed limit. Before the study was conducted, both treatment and control sites existed as work zones with standard orange signs, except for the first sign in the pair, which was fluorescent. In the "before" period, five operational measures were collected on this standard set of signs. In the "after" period, the standard orange signs were replaced with fluorescent signs (same size and message) at the "treatment sites," and the same measures were recorded at these treatment sites, as well as at the "control sites" where the standard signs were left in place. Two weeks elapsed before data were collected in the "after" period, to eliminate novelty effects. The operational measures included:

1. traffic conflicts (one vehicle brakes or swerves to avoid hitting another);
2. percentage of all vehicles in the left lane;
3. percentage of trucks in the left lane;
4. mean speed; and
5. speed variance.

These data were collected at the beginning of the taper, at the BEGIN WORK ZONE sign, and at the midpoint of the approach.

With regard to traffic conflicts, a reduction from 153 to 136 at the treatment sites (with fluorescent signs) was observed in the before and after periods, respectively, while an increase from 160 to 187 was observed at the control sites (with standard signs) in the before and after periods. This reduction in conflict frequency was statistically significant, when sites without potential confounding factors were removed from the analysis. Regarding the number of vehicles in the left lane, there was a significant reduction in the percentage of vehicles at the midpoint of the work zone approach at the sites with fluorescent signs (more than a 5 percent reduction, or 100+ fewer vehicles); similarly, an increase in the percentage of trucks that moved out of the left lane before the midpoint (16 more trucks, or 30 percent more than expected) and at the taper (12 more trucks than expected) was observed at the sites with fluorescent signs, compared to sites with the standard orange signs.

Differences in mean speeds were not statistically significant; speeds increased by approximately 1 mph at the midpoint and taper of treatment sites, and decreased by the same amounts at the control sites. However, speed variance decreased at the midpoint and at the taper of the treatment sites (with fluorescent signs), relative to speeds monitored at the control sites (with standard orange signs).

Hummer and Scheffler (1999) state that the operational changes documented during their study would translate to fewer collisions in work zones that display fluorescent orange signs compared to those that display the standard orange signs. Although the overall reduction in traffic conflicts in this study was small (approximately 7 percent), they recommend that agencies use fluorescent orange sheeting on warning signs in work zones similar to those studied, as well as for work zones where warning drivers is as critical or more critical than it was in the current study. These would include long-term work zones where there is flagging, temporary traffic signals, sharp lane shifts, and changed merging patterns, as well as in many temporary and moving work zones. Hummer and Scheffler (1999) state that fluorescent orange sheeting costs only a few dollars more per sign installation than standard orange sheeting, and even if work zone collision frequencies declined by only one or two percent, the benefit-to-cost relationship would be substantial.

Next, a number of studies have been performed to determine the effectiveness and motorist comprehension of static signs and changeable message signs (CMS's)—also referred to as variable message signs (VMS's)—for lane closures. A general indication of the importance of CMS's to accomplish lane control in advance of work zones is provided by a field study on a four-lane section of I-35 in San Antonio conducted by Dudek, Richards, and Faulkner (1981) to evaluate the effects of CMS messages on lane changes at a work-zone lane closure. The measure of effectiveness used to evaluate the CMS was the percentage of vehicles that remained in the closed (median) lane as traffic progressed toward the cone taper. The results indicated that the CMS did encourage drivers to vacate or avoid the closed lane, compared with driver responses at the same site without use of the CMS. The percent volumes in the closed lane were significantly lower when a lane-closure message was displayed than during periods when the sign was blank. Specifically, there was a 46 percent greater reduction in the lane volume attributable to the CMS.

During the conduct of field studies for NCHRP project 3-21(2), the relative proportions of traffic in the through and closed lanes approaching construction lane closures were observed for a sample of more than 196,500 vehicles (Transportation Research Board, 1981). Data gathered in Georgia, Colorado, and California were used to compare these lane distributions between baseline (no CMS) conditions and various CMS applications. A fourth data set, gathered in South Carolina, was used to determine relative effects between certain CMS message alternatives (i.e., speed and closure, speed and merge, closure and merge advisories), and various placement configurations (i.e., one CMS at 2,000 ft in advance; or one CMS at 3,960-ft advance placement; or two CMS devices, one at each advance location; or one CMS placed at 3,960 ft in advance of the taper and an additional arrow panel at the 2,000-ft location). Findings indicated increased preparatory lane change activity, smoother lane-change profiles, and significantly fewer "late exits" (exit from a closed lane within 100 ft of closure) in locations where a CMS was applied at the 3,960-ft advance location and an arrow panel at the 2,000-ft location.

Additional studies of flashing arrow panels at construction sites have shown that they are effective in shifting approaching traffic out of a closed lane (Bates, 1974; Shah and Ray, 1976; Graham, Migletz, and Glennon, 1978; Bryden, 1979; Faulkner and Dudek, 1981). These studies found that arrow panels were effective because they promote early merging into the open lane and fewer vehicles remained in the closed lane at the start of the lane-closure taper. A basis thus exists to assert that a CMS used to give advance notice of the need to exit a lane, followed by the application of an arrow panel, would be of clear benefit to drivers with diminished capabilities resulting from aging, inattentiveness, or transient impairment (e.g., due to fatigue, alcohol, or drugs). While the specific location of the arrow panel in this approach should be consistent with the signing sequence indicated in the *MUTCD* Part 6H (Figure 6H-33 for divided highways), placement at the beginning of the taper is suggested by the findings reported above.

Mace, Finkle, and Pennak (1996) conducted a static and a dynamic field study to determine the minimum and optimum lamp intensities needed for arrow panel legibility (left arrow or chevron vs. right arrow or chevron presentation) during the day, and minimum and maximum intensity for nighttime operations to minimize glare effects. The authors cite the work of Faulkner and Dudek (1982), who found that sight distances to arrow panels (AP's) influences driver behavior, such that when AP's are used too far in advance of a lane closure, (e.g., 4,000 ft, drivers tend to return to a vacated lane. Also, if sight distance is less than 1,500 ft, an advance supplemental AP is desirable. While no data exist to document problems in the safe use of AP's by aging drivers, the following recommendations (see Table 58) suggested by Mace et al. (1996) for arrow panel lamp intensity provide a useful reference for practitioners. These values ensure visibility for DSD's of 1,500 and 930 ft, for high-speed and low-speed roadways, respectively.

**Table 58.** Recommended minimum on- and off-axis lamp intensities of arrow panels to ensure daytime visibility by aging drivers, and the maximum intensity recommended for nighttime operations to ensure safe levels of discomfort and disability glare for aging drivers, for high-speed (≥45 mph) and low-speed (<45 mph) roadways (Mace, Finkle, and Pennak, 1996).

| Situation | Luminous Intensity Requirements (cd per lamp) | | |
|---|---|---|---|
| | Minimum On-Axis | Minimum Off-Axis | Maximum Hot Spot |
| Low-Speed Day | 300 | 60 | n/a |
| High-Speed Day | 500 | 100 | n/a |
| Low-Speed Night | 90 | 18 | 370 |
| High-Speed Night | 150 | 30 | 370 |

A questionnaire also was completed during the conduct of NCHRP Project 3-21(2), by 489 subjects ranging in age from under 20 to 80 to gather measures of driver detection, recognition, and comprehension of the CMS devices. Twenty percent of the drivers were age 60 and older. Five tested message conditions were:

1. speed and closure advisory (MAX SPEED 45 MPH/RIGHT LANE CLOSED);
2. speed and merge advisory (MAX SPEED 45 MPH/MERGE LEFT);
3. merge and closure advisory (RIGHT LANE CLOSED/MERGE LEFT);
4. speed advisory only (SLOW TO 45 MPH); and
5. closure advisory only (RIGHT LANE CLOSED AHEAD).

Drivers consistently reported that the speed advisory and lane closure message combination was most helpful, was the easiest to read, best met their information needs, and would be most likely to cause them to change lanes early and reduce speed.

A human factors laboratory study was conducted to determine which CMS message alternatives would be most likely to enhance motorists' compliance with lane control messages in work zones (Gish, 1995). The subjects were divided into two age groups consisting of 24 subjects each: the youngest drivers had a mean age of 23.1 years (range: 16–33), and the oldest drivers had a mean age of 70.2 years (range: 65–84). The results of this study indicated that older drivers were more likely to reduce their speed and change lanes than the younger drivers, and that both older and younger drivers' compliance with lane-change messages was strongly influenced by surrounding vehicles and by the visibility of the lane closures themselves, which exerts a strong influence on message credibility. Other factors, such as traffic density, static displays, and merge arrows (arrow panels), influence driver compliance with CMS messages. To optimize lane-change compliance, Gish (1995) recommended that static displays, merge arrows, and other devices be used in addition to CMS messages. A need to study the long-term effectiveness on nonstandard messages was also indicated, and potential improvements in work-zone safety and operations through the use of condition-responsive (real-time) traffic control systems that provide continuously updated information to motorists (for enhanced credibility) were identified.

# 44 Portable Changeable (Variable) Message Signs

The effectiveness of changeable message signs (CMSs), gauged in terms of observable driver behaviors that traffic management procedures are designed to elicit, rests upon a set of reasonably well-understood human factors. A motorist information system must be rational, relevant, and reliable. Driver sensory/perceptual and cognitive capabilities must be thoughtfully considered to ensure that a message will be acquired and then understood, recalled, and applied by the driver within a desired timeframe; the message must seem to clearly apply to the driver and to reflect current conditions to be credible; and it must be accurate in describing what the driver experiences downstream. The credibility of a highway advisory message certainly depends in part upon a presentation strategy that is "rational," but it also must be perceived to be relevant to the individual motorist, and reliable to the point of being virtually error-free. Reliability requirements—being dependent on real-time data on operations as input to the traffic control system—are most difficult to meet, but probably the most important if high rates of compliance in drivers' vehicle control decisions are ever to be realized.

A motorist's ability to use highway information is governed by: (1) information acquisition, or how well the source can be seen or heard; and (2) information processing, or the speed and accuracy with which the message content can be understood, and its ease of recall by the motorist after message presentation is completed.

In the acquisition of CMS information, a visual task, the key factors are: (1) its conspicuity, or "attention-getting value" to the motorist; (2) the size, brightness (contrast), stroke width-to-height ratio, and spacing of individual characters of text, which together determine the legibility of the message; (3) the placement of the CMS device—overhead versus one side versus both sides of the highway—which affects its likelihood of being blocked from a motorist's view by other vehicles, as well as the "eyes away from the road" time required to fixate upon the message; and (4) the exposure time, or available viewing time, of each message phase presented on a CMS.

Conspicuity is generally not a problem for any type of CMS under low-traffic volumes, although under high volumes with a significant mix of heavy vehicles, a motorist may fail to notice a roadside device because of obscuration. Good conspicuity is achieved by overhead devices under all conditions. While the attention value of a CMS display

**Table 59.** Cross-references of related entries for portable changeable (variable) message signs.

| Applications in Standard Reference Manuals | | |
|---|---|---|
| *MUTCD* (2009) | NCHRP 500 – Volume 9 (2004) | Traffic Engineering Handbook (2009) |
| Chapter 2L<br>Sects. 6F.60 & 6F.61<br>Figs. 6H-4, 6H-17, 6H-22, 6H-23, 6H-24, 6H-30 through 6H-35, 6H-37 through 6H-39, 6H-42, & 6H-44 plus associated notes with each fig. | Pgs. V-26-V-27, Sect. on *Strategy 3.1 B11: Improve Traffic Control at Work Zones (T)* | Pg. 368, Para. 7<br>Pg. 371, Sect. on *Changeable Message Signs* |

can be maximized by flashing operations, research by Dudek et al. (2006) indicates this strategy may detract from message comprehension, and is thus discouraged as a standard operating procedure. In rare circumstances, for a unit of information deemed particularly critical by the highway authority, the flashing of a single text element within a message at a slow rate may be justified. Also, if the CMS in question always has some type of message displayed, then slowly flashing (e.g., two cycles per phase) the problem statement line only may be warranted to attract attention. A preferred strategy under such circumstances would be to activate a flashing warning light separate from, though clearly attached to, the CMS.

If it is standard policy to leave the signs blank, then the mere display of a message will capture the driver's attention, without the need to resort to flashing elements. Indeed, driving simulator study findings argue against the use of flashing message elements on CMS's with rare exceptions, as noted above (Dudek, Schrock, Ullman, and Chrysler, 2006). By extension, the use of these devices to display any content except highway safety advisories or traffic control messages should be universally prohibited.

The legibility of a CMS is influenced by the same factors influencing character and message legibility of static signs, including the key factor of driver visual performance capability. Letter acuity declines during adulthood (Pitts, 1982) and aging adults' loss in acuity is accentuated under conditions of low contrast, low luminance, and where there is crowding of visual contours (Sloane, Owsley, Nash, and Helms, 1987; Adams, Wong, Wong, and Gould, 1988). In any event, the legibility for current CMS's is determined primarily by the technology and the device configuration (numbers of rows, characters per row, and number, size, and spacing of pixels per character) as fabricated by a given manufacturer, and for all practical purposes can be treated as a fixed factor—modified by environmental considerations—in considering whether a particular system as implemented in the field will meet motorists' needs.

For any given speed, aging drivers' needs dictate a legibility distance that permits the entire CMS message to be read twice in its entirety. As a general rule, at least 1,000 ft of legibility distance for a motorist with 20/40 visual acuity should be provided on a 55 mph facility. Of the studies that assessed various character matrix forms (number of elements per character cell), most found a 7 x 9 element matrix to be necessary when using lowercase letters, because of the descenders and ascenders, but a 5 x 7 font was generally deemed acceptable with uppercase-only lettering. The *MUTCD* recommends a minimum legibility requirement of 0.5 mi for trailer– or large-truck-mounted Portable Changeable Message Signs, and a minimum letter height of 18 in (Section 6F.60). Given that the most common format for a portable sign is 18-in tall characters arranged in three lines of eight characters, this provides for a legibility distance of 147 ft/in of letter height. The *MUTCD* provides for the use of smaller letter heights (minimum of 10 in) on CMSs mounted on service patrol trucks, provided that the message is legible from at least 650 ft. This provides for a legibility distance of 65 ft/in. Other variables found to significantly affect CMS legibility for aging observers are font, letter width-to-height ratio, contrast orientation, letter height, case, and stroke width (Jenkins, 1991; Mace, Garvey, and Heckard, 1994). The most consistent finding across studies evaluating CMS design elements was that the results found for aging drivers were quantitatively but not qualitatively different from those of their younger counterparts. That is, if a manipulation of a variable resulted in an improved score for younger observers, it almost invariably improved aging observer performance.

Garvey and Mace (1996) conducted several laboratory and controlled field studies to determine optimum legibility requirements of CMS's, particularly for aging drivers. The laboratory studies included 24 "young" subjects ages 16 to 40 (mean age: 26.6); 25 "old" subjects ages 62 to 73 (mean age: 67.9); and 21 "old-old" subjects age 74 and older (mean age: 77.2). The first laboratory study used a CMS simulator that was programmed on a PC, simulating nighttime viewing conditions. Only positive contrast signs (light letters against a dark background) were used. The objectives were: (1) to determine the optimum width-to-height ratio (W:H) and stroke-width-to height ratio (SW:H); (2) to identify the CMS font that produced the smallest size legibility thresholds; and (3) to determine the effect of color on legibility. Six different sizes of each sign were evaluated. The dependent variable in the study was the threshold size at which a character became legible, which was converted into a legibility index (LI) reported in ft/in (m/cm). Seven combinations of CMS matrix size, W:H, and SW:H combinations were evaluated to determine the optimum character legibility, as shown in Table 60.

Results indicated that for all conditions, the younger group performed significantly better (smaller letter size required for legibility) than both older groups, and the "old" group performed better than the "old-old" group. The authors indicated that, generally, what worked well for one age group worked well for all ages. Across all age groups, increasing the width-to-height ratio (W:H) of a character from 0.7 to 1.0 increased the legibility index (LI) by 7 ft/in. This provides an advantage of 38 meters of legibility for the wider letter when using an 18 in letter height, or 1.5 s at 55 mph. A significant stroke-width-to height (SW:H) effect was also found. For the narrow letters (W:H = 0.8), a thinner stroke performed better than a wider stroke by 5 ft/in. This effect was not significant with wider letters. There were no significant differences in legibility index as a function of matrix density. Therefore, for uppercase letters, increasing the number of elements beyond the standard 5 x 7 format did not improve legibility. The authors state that a typical CMS font with a W:H of 1.0 and a SW:H of 0.13 is optimal for the three age groups studied, from the median to the 85th percentile observer. Their data indicate that the 85th percentile old-old observer was capable of reading such a letter at the LI typically expected of CMS's (35 ft/in).

**Table 60.** Variables evaluated by Garvey and Mace (1996) using a CMS simulator to determine the optimum character legibility.

| Matrix Size | Width-to-Height Ratio (W:H) | Stroke-Width-to-Height Ratio (SW:H) |
|---|---|---|
| 5 x 7 | 1.0 | 0.13 |
| 5 x 7 | 0.8 | 0.13 |
| 5 x 7 | 0.7 | 0.13 |
| 15 x 15 | 1.0 | 0.13 |
| 15 x 15 | 1.0 | 0.20 |
| 12 x 15 | 0.8 | 0.13 |
| 12 x 15 | 0.8 | 0.20 |

In another laboratory study using the same subjects and test apparatus, Garvey and Mace (1996) found that the fonts typically used by CMS manufacturers performed well, with the exception of "double stroke" characters within a 5 x 7 character matrix. A double-stroke font provided a LI of 43 ft/in for young observers compared to 57 ft/in for the typical CMS font. For old-old observers, the double stroke font provided a LI of 32 ft/in compared to the typical CMS font that provided 38 ft/in. Across all age groups, the double-stroke font resulted in a decrement in LI of 10 ft/in.

In the final laboratory study of CMS character legibility, Garvey and Mace (1996) found significant effects of contrast orientation on letter legibility. Positive-contrast stimuli (lighter colored letters on a dark background) produced a LI of 12 ft/in higher than negative-contrast stimuli (dark letters on a lighter background). This improvement is equal to an additional 220 ft of legibility distance for an 18-in letter height, or 2.75 s at 55 mph. White-on-black signs performed similarly to yellow-on-black signs, except for the highest-percentile old-old group, where yellow-on-black signs were significantly better than white-on-black. Red-on-black signs performed as well as the other two colors for the young observers, but were found to be significantly less legible than yellow or white on black signs for both groups of older observers. The authors point out that the reduced performance of the color red for aging subjects is likely due to its lower luminance, and as people age, they become more sensitive to changes in target luminance. The obtained LI by sign color and observer age and percentile is shown in Table 61.

In a dynamic field study, Garvey and Mace (1996) employed older and younger drivers to evaluate legibility distance and detection distance of six portable CMS's. Participants included 33 "young" subjects ages 19 to 40; 25 "old" subjects ages 59 to 72; and 26 "old-old" subjects ages 73 to 82. Other independent variables included contrast orientation (positive or negative); character height (18 in or 42 in); lighting condition (backlit, frontlit, overcast, or rain); character luminance—day (350, 570, 850, or 1,200 cd/m$^2$); character luminance—night (30, 80, 130, 200, 570, 1,200 cd/m$^2$); inter-letter spacing—night (single or double); and sign lighting—night (internal vs. external or backlight vs. LED).

**Table 61.** Legibility index obtained by Garvey and Mace (1996) in a laboratory study of CMS character legibility, as a function of driver age, sign color, and percent of drivers accommodated.

| Driver Age | Percent Accommodated | Legibility Index (ft/in) | | |
|---|---|---|---|---|
| | | Yellow on Black | White on Black | Red on Black |
| 16-40 | 50 | 61.6 | 61.6 | 63.3 |
| | 75 | 58.3 | 55.0 | 56.6 |
| | 85 | 48.3 | 51.6 | 53.3 |
| | 90 | 45.0 | 45.0 | 46.6 |
| | 95 | 40.0 | 43.3 | 35.0 |
| 62-73 | 50 | 53.3 | 55.0 | 48.3 |
| | 75 | 48.3 | 50.0 | 40.0 |
| | 85 | 46.6 | 43.3 | 38.2 |
| | 90 | 43.3 | 43.3 | 38.2 |
| | 95 | 35.0 | 41.6 | 31.6 |
| 74+ | 50 | 45.0 | 45.0 | 40.0 |
| | 75 | 41.6 | 38.2 | 33.3 |
| | 85 | 40.0 | 33.3 | 30.0 |
| | 90 | 35.0 | 31.6 | 28.3 |
| | 95 | 30.0 | 30.0 | 30.0 |

Significant findings in the field study included the following:

- At night, positive contrast messages (yellow on black) produced significantly longer legibility distances, representing a 29 percent improvement over negative contrast messages (black on yellow). The mean legibility distance for positive contrast messages was 497 ft, and the mean legibility distance for negative contrast messages was 386 ft. The "old-old" group showed significantly shorter legibility distances compared to the "young" and "old" groups, which were not significantly different from one another.
- Increasing luminance during daytime up to 850 cd/m$^2$ produced significantly longer legibility distances; however, increasing the luminance from 850 to 1,200 cd/m$^2$ did not significantly increase legibility distance. At night, the effects of increasing luminance were random, with the lowest and highest luminances both producing legibility distances of approximately 800 ft. Also, there was no significant interaction between character luminance and age group. Note: Important guidance on procedures for valid measurement of CMS character luminance is provided by Garvey and Mace (1996).

Next, the "target value," legibility, and viewing comfort of light-emitting diodes (LEDs) and fiber-optic CMS technologies were compared with flip-disk and conventional overhead guide signs in a field study conducted by Upchurch, et al. (1991). Younger (ages 18 to 31) and older (ages 60 to 79) subjects in this study demonstrated mean daytime target values for fiber-optic, LED, and flip-disk technologies that all were significantly better (longer) than the values for conventional overhead signs. Under nighttime conditions, however, the poorest performance (shortest distances) was demonstrated by both age groups for the flip-disk technology, falling below the conventional sign values as well. The fiber-optic and LED signs again exceeded the conventional signs, based on nighttime mean target value, with the fiber-optic technology showing a slight superiority for aging drivers. Under backlight (sun behind sign) and washout (sun behind driver) conditions, target values for all sign types decreased substantially and the differences among sign types diminished, but the fiber-optic technology still resulted in the best overall performance, across age groups.

Legibility distance results tended to favor the conventional signs, followed by the fiber-optic signs, LED signs, and flip-disk technology. Mean daytime legibility distances for each sign type in this study were as follows: fiber-optic—61 ft/in; LED—42 ft/in; flip-disk—39 ft/in and conventional—88 ft/in. Under nighttime conditions, the conventional signs again could be read at the longest mean distances, followed closely by the fiber-optic and LED signs, with the flip-disk technology showing the poorest performance. Backlight conditions favored the fiber-optic technology, and washout conditions favored the conventional signs; in both cases, however, the flip-disk technology resulted in the shortest legibility distances. Using a threshold for minimal acceptable legibility distance of 628 ft, the study concluded that flip-disk signs are deficient under all conditions except midday daytime viewing, LED signs are deficient under both backlight and washout sun conditions, and fiber-optic signs are deficient only with the sun glare present under backlight conditions.

Mean discomfort ratings were consistent with these patterns of results. Fiber-optic and conventional signs were assigned the best (lowest discomfort) ratings under daytime conditions, by younger and older drivers alike. LED signs caused slightly more discomfort for aging subjects, and flip-disk signs resulted in the highest discomfort ratings, especially for aging drivers. Under nighttime conditions, only the flip-disk technology resulted in high discomfort ratings. Discomfort ratings were more even, and much higher, across sign types under backlight conditions where the sun was behind the sign, though flip-disk signs still were rated the worst by both age groups. Under washout conditions, subjects reported little discomfort for either the fiber-optic or conventional signs, but much greater and roughly equivalent levels of discomfort with the LED and flip-disk technologies.

Table 62 contains legibility distances from the Upchurch et al. (1991) study. For aging drivers, the legibility distances are lower due to the well-documented degradation of visual performance with age. Unfortunately, this is the only study that has assessed legibility distances for aging observers. The legibility distances for conventional bulb matrix and LED/flip-disk hybrid CMS's were estimated from the results of the Upchurch data and data cited in Dudek (1991).

**Table 62.** Day and night predicted legibility distances for various sign technologies (Upchurch et al., 1991).

| Sign Technology (Character Height) | Daytime Legibility Distances | | Nighttime Legibility Distances | |
|---|---|---|---|---|
| | Younger Observers | Older Observers | Younger Observers | Older Observers |
| Fiber-optic<br>16 in | 1,006 ft | 959 ft | 687 ft | 667 ft |
| Light-emitting diodes<br>17.8 in * | 812 ft | 681 ft | 794 ft | 602 ft |
| Flip-disk<br>18 in | 731 ft | 667 ft | 363 ft | 348 ft |
| Bulb matrix<br>18 in | 800 ft | 671 ft | 750 ft | 569 ft |
| Hybrid LED/flip-disk<br>18 in | 731 ft | 667 ft | 794 ft | 602 ft |

* *Legibility distance of this technology decreases over time, because as LED's age, they become less bright.*

The aging driver legibility distances in Table 62 should be assumed to represent the legibility distances for the various types of technology represented. This ensures that the needs of aging drivers have been met. The results suggest that flip-disk CMS's should not be used at night along roadways where average speeds reach or exceed about 55 mph.

Although the bulb matrix CMS was assessed by Upchurch et al. (1991), no legibility distances for that sign were reported. Legibility distances for this type of CMS have been obtained; however, it is unknown whether any aging observers have been used in assessing legibility distances. Dudek (1991) cited a study in which bulb matrix CMS's provided legibility distances of 800 ft during the day and 750 ft at night. These distances are similar to the legibility distances obtained by Upchurch et al. (1991) for LED-type CMS's using younger observers. Until psychophysical data can be obtained for aging observers viewing bulb matrix signs, the legibility distances for aging observers are assumed to be roughly 671 ft during the day and 569 ft at night. These estimates are based on applying the ratio of older-to-younger legibility distances for the LED-type display.

There are also a number of hybrid CMS's that were not included in the Upchurch et al. study. Hybrid CMS's apply various combinations of sign technologies listed in Table 62 within a single sign. Product literature for one manufacturer's hybrid LED/flip-disk sign states that the sign provides 900 ft of legibility distance during the day and greater than 900 ft at night, using character heights of 18 in. Unfortunately, the methods used to obtain these legibility distances are unknown. Since the sign uses the reflective flip-disk technology during daytime and the LED's at night, the legibility distances for aging observers for the daytime flip-disk in Table 62 (667 ft) should be used as a more realistic estimate of legibility distance with LED/flip-disk hybrids. For nighttime viewing, use the nighttime LED legibility distance (602 feet) in Table 62.

CMS placement affects information acquisition under heavy traffic conditions where a center lane driver's view of a roadside device may be obscured for lengthy intervals. If a facility has more than two lanes, a consideration may be given to placement of a portable CMS in the median—space permitting and where glare from opposing vehicles is absent or minimal due to a large glare angle—rather than on the right shoulder, since lane control practices for heavy trucks are common throughout many corridors. Aging drivers participating in focus groups have reported difficulty seeing portable changeable message signs positioned on the shoulders of multilane roadways, unless they are driving in the right lane. This suggests that signs be elevated as high as possible so that they can be seen across multiple lanes of traffic, and that multiple CMS's be used with the same message — the first to attract attention, and the second further downstream to communicate the message (Kihl, 2005; Kihl, et al., 2004).

A motorist's reading time for a CMS message dictates the required exposure time at a given speed. Exposure time is the length of time a driver is within the legibility distance of the message. The minimum recommended exposure time per page (phase) for a three-line CMS is 3 s, aside from a consideration of any particular set of driver characteristics. However, while some jurisdictions have selected briefer exposure times, the increasing numbers of aging drivers on limited-access highways makes an even stronger case for the 3 s minimum per page. Reading time is the time it actually takes a driver to read a sign message. In instrumented vehicle studies conducted in light traffic with familiar drivers on a rural freeway, reading times averaged 1 to 1.5 s per unit of information (Mast and Ballas, 1976). Reading times under "loaded" driving conditions would be higher, such as under extreme geometry, heavy traffic volumes, large volume of truck traffic, traffic conflicts, or poor climatological conditions. Field research using unfamiliar drivers has indicated that a minimum exposure time of 1 s per short word (four to eight characters) or 2 s per unit of information, whichever is larger, should be used (Carvell, Turner, and Dudek, 1978; Messer, Stockton, and Mounce, 1978; Weaver, et al., 1978; Dudek, et al., 1981). A unit of information is a data item given in a message, which can answer one of the following questions: (1) what happened? (2) where? (3) what is the effect on traffic? (4) for whom is the advisory intended? and (5) what driver action is advised? Thus, the exposure time for a three-line message could vary from 3 s to as much as 6 s, with each phase of a portable CMS at the lower end of this range and with each permanent CMS phase (page) at the upper end, due to differences in the number of characters per line. Reducing the exposure time per phase is warranted only when information is being repeated. For example, a three-line message may be displayed for only 2.5 s if it is a second phase of a two-phase message which repeats one or two lines from the first phase. If the second phase presents new information, the recommended minimum exposure time for both phases remains 3 s.

For a given operating speed, exposure will increase with increasing legibility distance. For example, an overhead sign message that is legible at 650 ft will be exposed to drivers traveling at 55 mph for approximately 8 s. With a legibility distance of 1,000 ft, the message will be exposed for about 12 s. Permanent CMSs generally have legibility distances in the higher range of 900–1,200 ft. However, there is a point at which a sign becomes unreadable during a driver's approach to a CMS, which reduces the legibility distance, particularly for side-mounted CMSs. This unreadable distance, which is dependent on the number of lanes and the sign technology, as well as how far the sign is set back from the roadway edge or how high above the roadway it is mounted, ranges from 280 ft to 420 ft. In an existing system, therefore, required exposure times dictate the maximum length of message that can be displayed, and in all cases, it is desirable that motorists be able to read the entire message on an (unobstructed) CMS twice.

The calculated maximum exposure duration of a message should not exceed 9 s. For two-phase messages, a separate requirement is needed to meet the needs of drivers. In this case, 3 s is added to the required exposure time because of the asynchrony between the time the driver can read the CMS and the onset of CMS phase displayed. In other words, the phase that the driver reads initially may have already been displayed for 2 s by the time he or she can read it. Thus, the driver will not have enough time to read this phase and will need to view that phase again. The net result is that 3 s needs to be added to the required exposure time to allow drivers to read the phase that first came into view a second time. Since the maximum recommended exposure time is 9 s, only 6 s of actual message reading time is allowed on a two-phase CMS, whereas the full 9 s can be used for a single-phase message. The important point here is that single-phase messages can more efficiently convey information to drivers. When use of a single-phase CMS is not possible because of message length, multiple devices with a single phase on each device will be superior to multiple phases on a single device. Part 6 of the 2009 *MUTCD* (Section 6F.60) states that when multiple portable changeable message signs are needed, they should be placed on the same side of the roadway and they should be separated from each other by a distance of at least 1,000 feet on freeways and expressways, and by a distance of at least 500 feet on other types of highways.

For these reasons, the maximum number of phases used to display a message on a permanent CMS should be two. The most effective format for CMS message presentation is a single phase which consists of a maximum of three units of information, but if two phases are required, each should be worded so that it can stand alone and still be understood. Portable CMS devices, though limited to fewer characters per line, should also be restricted to two phases. At high speeds (55 mph), a driver may only have 2.8 to 4.6 s to read a message on a side-mounted CMS, depending on the available legibility distance. For this reason, messages should be restricted to one phase at high speeds.

Recommendations against the use of flashing messages and message elements have been made, based on the findings of a driving simulator study using older and younger drivers (Dudek, et al., 2006). In this study, 64 drivers ages 18 to 80 viewed CMS messages presented on the right side of a simulated roadway, while following a lead vehicle that varied its speed before, during, and after the display of a CMS, as well as at times when there was no CMS. One-phase, three-line messages were presented on the CMS in one of three formats: 1) all three lines flashing; (2) flashing the top line of a three-line message; and (3) all three lines static. The flash rate for the dynamic messages was 1.5 s on and 0.5 s off. There were no significant differences in average reading time between signs with all three lines flashing (7.2 s) and static messages (7.2 s), but average reading time for messages where the top line flashed were significantly longer than for static messages (7.8 s vs. 7.1 s). Comprehension for three-line flashing messages was lower (but not significantly) than for three-line static messages, for subjects' first exposure to the flashing display, which suggests that flashing all three lines may have an adverse effect on drivers unfamiliar with this mode of CMS display. Comprehension was even lower on signs where only the top line flashed, but the differences were not statistically significant. Significantly more participants preferred the static message over the three-line flashing message (60% to 40%). The most common reason cited by participants who preferred the flashing mode was that it caught their attention. The most common reason for those who preferred a static message was that it gave the driver more time to read the message and was easier to read. Participants were evenly split (50-50) in their preference for three-line static vs. first line flashing on a three-line message, but opponents of the first-line flashing message indicated that the flashing line was distracting. There were no significant differences in driver performance measures collected in the simulator (e.g., acceleration noise, lane positioning, or headway) as a function of message display format. There were no age effects on reading time, message comprehension, display preference, or driver performance.

The motorist's need for rapid understanding and integration of message components also focuses attention on the formatting of multiword text displays. The main concern is with "units of information" (i.e., where and how to divide phrases) and with the use of abbreviations and contractions in CMS messages. These formatting issues are discussed below.

Work zones constitute driving situations that require a high amount of controlled processing, and data show that cognitive ability scores that measure processing efficiency decline with age (Ackerman, 1987). In fact, sensory memory, working memory, and divided attention all show a decline with aging and must be considered in the display of messages on CMSs. This reinforces the conclusion that a message should be limited to a single phase, or certainty no more than two, because multiple phases will interfere with message comprehension. There is also considerable evidence that aging adults have poorer working memory function than younger adults (Salthouse, 1991; Salthouse and Babcock, 1991). This indicates that message length should be limited to the fewest, most relevant units possible.

Finally, aging adults are particularly disadvantaged when they are required to use working memory to manage multiple tasks (Ponds, Brouwer, and van Wolffelaar, 1988).

Van Wolffelaar, Brouwer, and Rothengatter (1990) found that there is a disproportionately greater problem for aging adults in divided attention situations and directly linked this to a higher crash rate for aging adults in time-pressured, complex traffic situations.

The minimum required information for traffic management includes: (1) a statement of the problem; and (2) the action statement(s) (i.e., a driver needs to know what to do and one good reason for doing it). Additional elements are included as needed for a specific situation. The key here is not to burden the driver with unnecessary information. Only about two-thirds of drivers are able to recall completely four pieces of information (problem, effect, attention, and action); however, 80–90 percent can recall the action message (Huchingson, Koppa, and Dudek, 1978). Two problems in message presentation must be avoided: (1) providing too much information in too short a time; and (2) providing ambiguous information that leaves either the intent of the message or the desired driver response uncertain.

The first problem does not refer solely to reading time difficulties, as discussed above; instead, it refers to the number of ideas, or "information units," contained in a message. Certainly, the number of words displayed on a sign is important, but so is the manner in which words are grouped. Units containing one word (DELAY), two words (DELAY AHEAD), or many words (MAJOR DELAY AT HIGH STREET) are equally difficult to remember when the display is no longer in sight. However, a series of, say, six units of information in a message displayed on a permanent CMS will be easier to remember if presented in two phases of three units each than if all six units are presented on a single phase. Studies have concluded that no more than three units of information should be displayed on one sequence when all three units must be recalled by drivers (Huchingson et al., 1978; Dudek et al., 1981; Gish, 1995).

Gish (1995) conducted a human factors laboratory study addressing the perceived timeliness, accuracy, and credibility of CMS messages using both younger (ages 16 to 33) and older (ages 65 to 84) test subjects. Results showed that correct recall of the first CMS phase (a downstream speed advisory) was nearly 100 percent for both age groups. However, successive phases of information (containing downstream delay and route diversion information) were recalled less accurately. For the delay information (second phase), correct recall for the younger subjects was about 82 percent, versus 60 percent for the older subjects. For route numbers (third phase), correct recall was 55 percent for the younger subjects and 19 percent for older subjects. These results reinforce the earlier recommendation that a maximum of two phases should be used.

Aging drivers participating in focus groups stated that CMS's with multiple phases were difficult, if not impossible to read. They stated that even when there was enough time to read two phases, once both were read, it was easy to forget what the first phase indicated (Kihl, 2005). Further, these focus group participants indicated that there was no need to offer explanations on the signs; just provide direction to the driver.

When a message must be divided into two phases, it is desirable to repeat key words from the first phase on the second phase, to provide assurance that all drivers see the message at least once. This also allows information rehearsal, as provided by an additional "learning trial," which will facilitate message recall when the device is no longer in sight.

A recommended standard practice is therefore to put the problem on line 1, the location on line 2, and alternate either the effect and action or diversion information on line three, repeating lines 1 and 2 on both phases.

The second type of problem can occur when an unfamiliar word or abbreviation is used, when a word is hyphenated or a phrase is divided inappropriately, or when an abbreviation or a word can mean different things in different word pairings or contexts. Ambiguity occurs, for example, when CENTER LANE is used on a freeway with four or more lanes in one direction. Another example is the use of LANE CLOSED versus LANE BLOCKED, to denote a prolonged closure for construction/maintenance versus a temporary blockage due to a crash or stall. To foster the most simple and consistent practice for motorists, LANE CLOSED is recommended under both roadwork and incident conditions, because at the time the message is displayed, the lane is effectively closed. Finally, neither FREEWAY BLOCKED nor FREEWAY CLOSED should ever be used when at least one lane is open to traffic.

Abbreviations also have the potential to be misunderstood by some percentage of drivers, exacerbating message comprehension problems for individuals with (age-related) diminished capabilities. It has been determined that certain abbreviations are understood by at least 85 percent of the driving public independent of the specific context (e.g., BLVD = boulevard). A second category of abbreviations are understood by at least 75 percent of the driving population but only with a prompt word, (e.g., LOC means "local" when shown with "traffic"). Other abbreviations are prone to be frequently confused with another word (e.g., WRNG could mean either "warning" or "wrong") and should be avoided. Following are lists of abbreviations in three categories, extracted from Dudek et al. (1981) and Durkop and Dudek (2001):

1 those that are acceptable (understood by at least 85 percent of the driving population) when shown alone (Table 63);
2. those that are not acceptable and, therefore, should not be used (Table 64); and
3. those that require a prompt word (Table 65). Table 63 also includes abbreviations taken from the *MUTCD*, as well as common contractions used in the English language.

Most of the abbreviations in these tables have been incorporated into the *MUTCD* (FHWA, 2009), as Tables 1A-1 to 1A-3 in section 1A.15; Section 6F.60 of the *MUTCD* states that when abbreviations are used on CMS's, they should be easily understood, and refers the practitioner to section 1A.15.

**Table 63.** "Acceptable" abbreviations and phrases for frequently used words. Source: Dudek, et al. (1981), Durkop and Dudek (2001).

| Word | Abbreviation | Word | Abbreviation |
|---|---|---|---|
| Alternate | ALT | Left Lane | LFT LN |
| Avenue | AVE | Major Accident | MAJ ACCDT |
| Boulevard | BLVD | Maintenance | MAINT |
| Can Not | CAN'T | Normal | NORM |
| Center | CNTR | Parking | PKING |
| Center Lane | CTR LN | Parking Lot | PRK LOT |
| Do Not | DON'T | Right Lane | RGT LN |
| Emergency | EMER | Road | RD |
| Emergency Vehicle | EMER VEH | Service | SERV |
| Entrance, Enter | ENT | Shoulder | SHLDR |
| Expressway | EXPWY | Slippery | SLIP |
| Freeway | FRWY, FWY | Speed | SPD |
| Highway | HWY | Street | ST |
| Information | INFO | Traffic | TRAF |
| It Is | IT'S | Travelers | TRVLRS |
| Junction | JCT | Warning | WARN |
| Lane Closed | LN CLSD | Weight Limit | WT LIMIT |
| Left | LFT | Will Not | WON'T |

**Table 64.** Abbreviations and phrases that are "not acceptable." Source: Dudek, et al. (1981); Durkop and Dudek (2001).

| Abbreviation | Intended Word | Common Misinterpretation |
|---|---|---|
| ACC | Accident | Access (Road) |
| ALT RT | Alternate Routes | Don't know meaning |
| CLRS | Clears | Colors |
| DLY | Delay | Daily |
| EX | Exit | Don't know meaning |
| FDR | Feeder | Federal |
| FEED RD | Feeder Road | Feed Road |
| FRNTG RD | Frontage Road | Front Road |
| L | Left | Lane (Merge) |
| LT | Light (Traffic) | Left |
| MAJ CONG | Major Congestion | Major Construction |
| PARK | Parking | Park |
| POLL | Pollution (Index) | Poll |
| RD WK | Road Work | Road Walk |
| RED | Reduce | Red |
| STAD | Stadium | Standard |
| VIC OF | Vicinity of | Don't know meaning |
| WRNG | Warning | Wrong |

**Table 65.** Abbreviations that are "acceptable with a prompt." Source: Dudek, et al. (1981), Durkop and Dudek (2001).

| Word+ | Abbreviation | Prompt |
|---|---|---|
| Access | ACCES | Road |
| Ahead | AHD | Fog* |
| Blocked | BLKD | Lane* |
| Bridge | BRDG | [Name]* |
| **Condition** | **COND** | **Traffic*** |
| **Congested** | **CONG** | **Traffic*** |
| Construction | CONST | Ahead |
| **Downtown** | **DWNTN** | **Traffic*** |
| **Eastbound** | **E-BND** | **Traffic** |
| Exit | EXT | Next* |
| Express | EXP | Lane |
| Hazardous | HAZ | **Road** |
| Interstate | I | [Number] |
| **Local** | **LOC** | **Traffic** |
| Major | MAJ | Accident |
| Mile | MI | [Number]* |
| Minor | MNR | Accident |
| Minute(s) | MIN | [Number]* |
| **Northbound** | **N-BND** | **Traffic** |
| Oversized | OVRSZ | Load |
| Prepare | PREP | To Stop |
| Pavement | PVMT | Wet* |
| Quality | QLTY | Air* |
| **Roadwork** | **RDWK** | **Ahead [Distance]** |
| Route | RTE | Best*, Detour* |
| **Southbound** | **S-BND** | **Traffic** |
| **Temporary** | **TEMP** | **Route** |
| **Township** | **TWNSHP** | **Limits** |
| Turnpike | TRNPK | [Name]* |
| Upper, Lower | UPR, LWR | Level |
| Vehicle | VEH | Stalled* |
| **Westbound** | **W-BND** | **Traffic** |
| Cardinal Directions | N, E, S, W | [Number] |

* Prompt word should precede abbreviation.

\+ The words and abbreviations shown in normal type are understood by at least 85 percent of the driving population. Those shown in boldface type are understood by at least 75 percent of the driving population, and public education is recommended prior to their usage.

# 45 Channelization (Path Guidance)

Channelization systems include the use of cones, posts, tubular markers, barricades, panels, drums, amber-flashing and steady-burn lights, and standard and raised/recessed pavement markings. They are used to direct motorists into the open lanes and to guide them through the work area. They must provide a long detection distance and be highly conspicuous under both day and night conditions. Using data collected by the police, it has been estimated that anywhere from 80 to 86 percent of the crashes in work zones can be attributed to driver error (Nemeth and Migletz, 1978; Hargroves and Martin, 1980). Hargroves and Martin (1980) found that crashes with fixed objects within a work zone account for a greater percentage than other crash types, such as rear-end or sideswipe. Nemeth and Migletz (1978) found that nighttime crashes are concentrated in the taper area. Humphreys, Maulden, and Sullivan (1979) identified the most significant problems with channelization in work zones as: (1) failure to use, or hazardous use of, temporary concrete barriers; and (2) inadequate or inconsistent use of devices and methods in closing roadways and establishing lane-closure tapers.

Aging drivers, like alcohol-impaired and fatigued drivers, show reduced sensitivity to contrast. Olson (1988) pointed out that the brightness of a traffic control device is the main factor in its attention-getting capability: in a visually complex environment, the brightness must be increased by a factor of 10 to achieve conspicuity equivalent to that found in a low-complexity environment. A major problem at night is reduction in contrast sensitivity, which makes it difficult to see even large objects when they cannot be distinguished from their background. Aging drivers also have difficulty processing information due to less effective scanning behavior and eye movements, diminished visual field size, difficulty in selective attention, and slower decision making. Inconsistent use of drums and traffic cones to delineate the travel path may be a particular problem for aging drivers, especially when applied in the presence of remnants of old lane markings, because such inconsistency is confusing and aging drivers (and inattentive drivers) are not able to react as quickly to conflicting traffic cues (National Transportation Safety Board, 1992). To compensate for their slower information-processing capabilities, their

**Table 66.** Cross-references of related entries for channelization (path guidance).

| Applications in Standard Reference Manuals | | |
|---|---|---|
| ***MUTCD*** **(2009)** | **NCHRP 500-Volume 9 (2004)** | **Traffic Engineering Handbook (2009)** |
| Sect. 6B.01<br>Sects. 6C.05, 6C.08, 6D.01, 6F.13, 6F.14, 6F.21 through 6F.24, 6F.32, & 6F.63 & 6F.81<br>Sects. 6G.04 & 6G.07<br>Sect. 6G.10 through 6G.18<br>Figs. 6H-3, 6H-5 through 6H-7, 6H-10 through 6H-12, 6H-15, 6H-18, 6H-21 through 6H-34, 6H-36 through 6H-44, & 6H-46 plus associated notes for each fig. | Pgs. V-26-V-27, Sect. on *Strategy 3.1 B11: Improve Traffic Control at Work Zones (T)* | Pg. 663 Paras. 6-7 |

reduced visual capabilities, and their slower reaction time, aging drivers often drive more slowly. Although driver age was not studied, Hargroves and Martin (1980) found that slow-moving vehicles were overrepresented in work-zone crashes. Aging drivers also show reductions in lane-keeping ability, which is further compromised when they are required to attend to other tasks, in unfamiliar surroundings. Finally, steering abilities may be adversely affected by physical problems such as arthritis.

McGee and Knapp (1979) performed an analytic study to develop a performance requirement/standard for the detection and recognition of retroreflective devices (cones, drums, panels, and barricades) used in work zones. The performance standard developed in this study, presented in terms of visibility requirements (i.e., the distance at which motorists should be able to detect and recognize the devices at night) and established using the principles of driver information needs and the requirement for decision sight distance, calls for a minimum visibility distance of 900 ft when illuminated by the low beams of standard automobile headlights at night under normal atmospheric conditions.

Pain, McGee, and Knapp (1981) evaluated the effectiveness of traffic cones and tubular markers, vertical panels, drums, barricades, and steady-burn lights in laboratory studies, in controlled field studies, and at actual construction sites. Two-hundred fifty-four subjects between the ages of 17 and 60+ participated; over half of the subjects were between ages 21 and 40, and 7 percent of the subjects were age 60 or older. Overall, there were no major differences between the device categories in the daytime. At night, barricades, panels, drums, cones, and tubular markers were also equivalent when the optimized cone and tubular marker retroreflectorization was used (two bands of retroreflective material for cones and one band for tubular markers totaling 150 to 200 in$^2$, or roughly the amount provided by a 12- to 14-in collar) of retroreflective material with SIA of at least 250. However, tubular markers and cones with 6 in of collar resulted in diminished nighttime performance. The variables manipulated in the cone optimization study included amount of retroreflectorization (69, 138, 207, 276, and 345 in$^2$), [corresponding to single bands measuring 6-, 10-, 14-, 17-, and 20-in wide; number of bands of retroreflective material (1, 2, or 3); 3 types of retroreflectorization plus 1 internally illuminated cone (polycarbonate Reflexite with SIA of 2000 at entrance angle -4° and observation angle 0.1°, high intensity with SIA of 300 at entrance angle -4° and observation angle 0.1°, and polycarbonate Reflexite plus vinyl Reflexite); color of retroreflectorization (white and yellow), 3 sizes (18-, 28-, and 36- in tall); 3 device spacings (half, regular, and double-speed limit). The variables manipulated in the tubular marker study included amount of retroreflectorization (14, 28, 43, 57, and 71 percent of area covered, corresponding to bands measuring 150-, 300-, 450-, 600-, and 950-mm wide); number of bands (1, 2, 4, 6, or 8); the same retroreflectorization levels and colors as for the cone study, 3 sizes (18-, 28-, and 42-in tall); and the same device spacings as described for the cone study.

In comparing the meaning of chevrons versus stripes, Pain et al. (1981) found that diagonal, horizontal, and vertical stripes conveyed no consistent directional information; chevrons, though less easily detected than the stripe patterns, effectively and unambiguously indicated that a movement to the left or right was required. Since diagonal, horizontal, and vertical stripes conveyed no consistent direction information; Pain et al. (1981) concluded that there was no reason to have a diagonal stripe pattern for left and right "sidedness." They pointed out, however, that only one direction of diagonal should be allowed in an array so there is always a consistent pattern or image on devices.

In terms of device spacing, comparisons of regular speed-limit spacing (55 ft in the test), half-spacing (27.5 ft), and double-spacing (110 ft) of Type I barricades and 8-in x 24-in) panels showed that changes in spacing produced little impact on driver behavior. There was no significant speed or lateral placement differences between half, regular, and double speed-limit spacing during the day. At night, however, when devices were placed at half-spacing, they produced a speed reduction, apparently from the illusion that the motorist was going faster than he or she actually was. Devices placed at double-spacing tended not to perform as well as when they were placed at regular speed-limit spacing, as drivers made lane changes and detected arrays of traffic control devices sooner with shorter spacing. From these findings, Pain et al. (1981) recommended that: (1) all devices be placed at speed limit spacing for most conditions and, in all cases, along the taper or transition section; (2) if there is no construction work or hazard in the closed lane for a substantial length, or traffic delays, the spacing can be increased to no more than twice the speed limit; and (3) shorter spacing may prove to be useful where speed reduction is desired.

Device-specific findings by Pain et al. (1981) are as follows:

- **Traffic cones**. (1) They perform as well as other devices during daytime, with long detection distance and adequate lane-change distances. (2) Bigger is better: 36-in cones are more effective than 28-in cones; 28-in cones are better than 18-in) cones (and 18-in cones should not be used on high-speed facilities); (3) At night, 150 to 200 $in^2$, or roughly the amount in a 12- to 14-in collar of highly retroreflective material (with specific intensity per unit area [SIA] of at least 250), is needed for effectiveness. Even higher brightness materials enhance driver response characteristics and are preferable. (4) Under both day and night conditions, the 2-band configuration outperformed the 3-band configuration, and both outperformed the 1-band configuration; therefore, two bands of retroreflective material are preferable on cones.
- **Tubular Markers**. (1) During daytime, 28-in and 42-in tubular markers are as effective as cones, but 18-in tubular markers are ineffective and not recommended for lane closures or diversions on high-speed facilities. (2) At night, tubular markers with at least a 12-in highly retroreflective band are equally as effective as cones. (3) The 1-band configuration outperformed the 2- and 3-band configurations for tubular markers
- **Vertical panels**. (1) Laboratory results showed that compared with the barricade, the vertical panel is more easily detectable. (2) Vertical panels are equally as effective (detectable) as Type I barricades, and vertical panels promote earlier lane changing than barricades. (3) The minimum width dimensions of the panel should be 300 mm (12 in) rather than 200 mm (8 in), especially when used at night and on high-speed facilities.
- **Drums**. (1) Drums are highly visible and detectable from long distances, during both day and night. (2) Drums promote lane changing further upstream of the taper than other devices. (3) Drums are associated with a speed reduction. (4) Drums are a dangerous object when hit.

- **Barricades**. (1) The Type I barricade is as effective as other devices. (2) The Type II barricade is no more detectable than the Type I barricade. (3) The 12-in x 36-in barricade is more conspicuous than the 8-in x 24-in barricade.

Other findings were reported for comparisons of steady-burn lights and Type II and Type III sheeting. The steady-burn lights provided the longest detection distances at night compared with all other materials, and they more than tripled the distance (or zone) in which lane changing occurred before the taper. In comparisons of Type II sheeting and Type III sheeting on cone and tubular marker optimization tests, Type III was significantly better at night on a flat road. Narrow-angle sheeting, even though offering high brightness, was not effective under certain sight geometry characteristics, such as hills and curves. Type III sheeting and steady-burn lights were comparable in terms of point-of-lane-change and array detection distance; however, the authors noted that the effect of vertical or horizontal curvature must be considered.

There have been mixed results regarding the effectiveness of steady-burn lights in highway work zones. The use of steady-burn lights mounted on channelizing devices has been shown to significantly influence driver behavior in some work-zone configurations, and they are particularly effective in left-lane closures (KLD Associates, 1992). Although drivers age 55 and older consistently showed poorer performance than younger drivers in all study conditions, evidence was found that the use of lights improved the performance of aging test subjects. The variables manipulated in this study included work-zone configuration (left-lane, right-lane, and shoulder closures), device type (panels versus drums), and light placement (every device, alternate devices, no lights). Drivers of all ages were able to identify lane and shoulder closures from greater distances when lights were used on channelization devices, as opposed to when the channelizing devices were used alone. Steady-burn lights produced a higher percentage of correct responses (determining the direction the channelizing devices were leading) for all driver age groups when used in left-lane closures than in right-lane closures. Interestingly, the use of lights on every other drum or vertical panel (placement on alternate devices) generated more correct responses than the use of lights on consecutive devices. More generally, the literature suggests that in environments characterized by high-speed operations, compromised visibility due to inclement weather, and/or complex maneuvers required as a result of work-zone configuration, the deployment of steady-burn lights should be considered on all channelizing devices used for right-lane closures.

However, Pant, Huang, and Krishnamurthy (1992) obtained a different result when they examined the lane-changing behavior of motorists in advance of tapered sections as they drove an instrumented vehicle through work zones during the day, at night when steady-burn lights were placed on drums, and at night when the steady-burn lights were removed. They measured the traffic volume at several locations in each lane in advance of the taper. Results showed that the steady-burn lights had little effect on driver behavior in the work zones studied. It was concluded by Pant et al. that steady-burn lights have little value in work zones that employ drums with high intensity sheeting and a flashing arrow panel as channelizing devices.

Opiela and Knoblauch (1990) conducted laboratory and field studies to determine the optimal spacing and use of devices for channelization purposes in the taper or tangent sections of work zones. In the laboratory study, the recognition distances of eight different device types, spaced at the standard distance and at 1.5 and 2.0 times the standard distance, were measured for 240 subjects. Results indicated variability between the performance of most channelizing devices across the spacings tested. Right- and left-lane closures were then used at six actual work zones, to test the various device spacings under both day and night conditions. Field data were collected at four points equally spaced over 2,000 ft before the work zone and the activity at the start of the taper for the lane closure, according to the premise that the most effective treatment would minimize the percentage of traffic in the closed lane at the start of the taper. Statistical analysis of 2,100 observation periods lasting 5 minutes each showed that neither type of device (round drums, oblong drums, Type II barricades, and cones with retroreflective collars) nor device spacings (55, 80, and 110 ft) had a significant effect on driver lane-changing behavior.

Cottrell (1981) also found that driver lane-change response was not strongly dependent on the channelizing device employed in a work-zone taper. The objective of this study was to evaluate the effectiveness of alternative orange-and-white chevron patterns on vertical panels and barricades that form an arrow pointing in the direction in which traffic is being diverted, compared with traffic cones, simulated drum vertical panels, and Type II barricades and vertical panels with standard orange-and-white striping patterns. The measure of effectiveness was the position of lane changing relative to the transition taper. Although the subjective evaluation revealed that chevron patterns were preferred over the presently used patterns because of their clear directional message, the positions of lane changing were similar for the stripes and chevrons. With respect to the spacing of devices, it was generally found that lane changes occurred more frequently at greater distances from the taper when the devices were spaced every 40 ft, as opposed to every 80 ft.

In a supplemental test, the effectiveness of the concrete safety-shaped barrier (CSSB), also referred to as a “Jersey” barrier in some jurisdictions, was compared with that of the channelizing devices studied (Cottrell, 1981). The barrier was marked with steady-burn warning lights and 6-in reflectors and had a slope of 16:1 for the 192-ft taper. The CSSB was rated equal to the cone during the daytime and lower than all other devices based on the lane-change positions. It was recommended that a supplemental taper of channelization devices be used with the CSSB. In a study of concrete barrier visibility, Pain et al. (1981) found that retroreflectors were superior to retroreflectorized tape. Logically, the most conspicuous types of retroreflective devices, such as those containing cube-corner lenses, will be potentially the most effective in this regard.

Overall, Pain et al. (1981) concluded that most devices show relatively successful detection and path guidance performance. However, a major deterrent to effectiveness is not the device itself; instead, poor positioning, dirt, and overturned devices destroy the visual line or path created by the channelizing devices. Therefore, although use of appropriate devices is important, of equal importance is conscientious set-up and care of channelizing devices used in the work zones.

In consideration of the threat posed to drivers by passenger compartment intrusion or interference with vehicle control, or the threat to workers and other traffic from impact debris, plastic drums, cones, tubular markers, and vertical panels used as channelizing devices presented no hazards in full-scale vehicle crash tests (Bryden, 1990). However, Types I and II barricades and portable signs and supports formed impact debris, which was often thrown long distances through work zones, posing a threat to workers and other traffic. The American Traffic Safety Services Association (ATSSA) is opposed to the use of metal drums in work zones as channelizing devices, as they pose a hazard to motorists as well as workers in the zone (TranSafety, 1987). They suggest the use of plastic drums, which are safer. Riedel (1986) described studies showing that a substantial number of work-zone crashes occur in the taper and the crossover where channelization devices are located. The frequency of crashes involving drums has led to the use of forgiving devices such as plastic drums, which in tests have been shown to be safer than steel drums. Juergens (1972) noted that because barricades are inherently fixed-object hazards, they should not be used as primary delineation to guide traffic. Further, they should not be used unless the construction hazard the motorist may encounter is greater than the hazard of striking the barricades. A concern with the use of steady-burn lights mounted on channelizing devices was highlighted in full-scale vehicle crash tests evaluating the performance of work-zone traffic control devices, where warning lights attached to these devices were thrown free, posing a potential threat to workers and other traffic (Bryden, 1990).

# 46 Delineation of Crossovers/ Alternate Travel Paths

Studies have established that: (1) a substantial proportion of construction work-zone crashes occur in the taper and the crossover, where channelizing devices are usually located; (2) darkness is associated with an increase in the frequency of crashes in these areas; and (3) construction zones are associated with increases in the incidence of fixed-object, rear-end, and head-on crashes (Graham, Paulsen, and Glennon, 1977). Nemeth and Rathi (1983), studying crash types in construction zones on the Ohio Turnpike, found that 52.4 percent of the crashes were with fixed objects, and 68.3 percent of the

**Table 67.** Cross-references of related entries for delineation of crossovers/alternative travel paths.

| Applications in Standard Reference Manuals | |
|---|---|
| ***MUTCD*** **(2009)** | **AASHTO** *Green Book* **(2011)** |
| Sects. 6F.80 through 6F.83<br>Sects. 6F.76, 6F.84, 6F.85<br>Sects. 6F.69, 6F.70, & 6F.79<br>Sect. 6G.04<br>Sect. 6G.11<br>Sect. 6G.12<br>Sect. 6G.14<br>Figs. 6H-7, 6H-9, 6H-19, 6H-20, 6H-39 through 6H-41, & 6H-45 plus associated notes for each fig.<br>Ch. 6I | Pgs. V-26-V-27, Sect. on *Strategy 3.1 B11: Improve Traffic Control at Work Zones (T)* |

crossover crashes involved collisions with channelizing devices or other objects. In this study, 69.4 percent of the crashes at the first curve of a crossover occurred at night. Nemeth and Migletz (1978) found that 60.7 percent of single-vehicle fixed-object crashes were collisions with drums and 29.8 percent of all crashes involved collisions with drums. They also found that the proportion of crashes involving construction objects (drums) at night is significantly higher than the proportion of daylight construction object crashes. The results of these studies highlight the need for highly conspicuous and properly installed and maintained channelizing devices.

The relationships between functional capabilities of aging drivers and their performance that are likely to be of greatest operational significance as they approach and negotiate a crossover in a work zone can be summarized as follows. Age-related declines in acuity (both static and dynamic) and contrast sensitivity will delay recognition of channelizing devices and pavement markings and will delay comprehension of the information provided by advance warning signs. This information loss in the early stages of the driver's vehicle control task will be compounded by attentional and decision making deficits shown to increase with increasing age, with age differences in performance magnified as serial processing demands for conflict avoidance and compliance with traffic control messages increase during the approach to the work zone. Age-related decrements in the "useful field of view," selective attention, and divided attention, and attention-switching capabilities will slow the initiation of a driver's response when a lane change is required prior to the transition zone, or maneuvering through channelization across the median. In addition, less efficient working memory processes may translate into riskier operations for aging drivers in unfamiliar areas if concurrent search for and recognition of navigational cues is required, as such demands disproportionately tax "spare capacity" for lanekeeping and conflict avoidance for aging operators. Finally, the execution of vehicle-turning movements becomes more difficult for aging drivers as bone and muscle mass decrease, joint flexibility is lost, and range of motion diminishes. Simple reaction time, while not significantly slower for aging drivers responding to expected stimuli under nominal operating conditions, suffers operationally significant decrements with each additional response to an unexpected stimulus, e.g., as required in emergency situations. In addition, aging drivers' increased sensitivity to glare and reduced dark adaptation ability will compound the difficulties described above while driving at night.

The National Transportation Safety Board (NTSB) has expressed concern about the lack of positive separation of opposing traffic in work zones (NTSB, 1992). The NTSB uses "positive barrier," or "positive separation of traffic," to refer to the use of concrete barriers to separate traffic. (A number of States distinguish between these terms, using "positive separation" to describe various channelization treatments which do not necessarily involve use of a physical concrete barrier.) The NTSB (1992) emphasizes that, "Fatal crash rates increase significantly when an interstate highway is switched from a four-lane, divided operation to a two-lane, two-way operation (TLTWO) during construction work." Research on the use of channelization and barrier delineation for TLTWO's is described below.

A crossover requires a change in direction and may require a reduction in speed. This requires adequate advance warning of the lane and speed reduction, conspicuous and unambiguous delineation/channelization in the transition zone, and conspicuous separation of opposing traffic the length of the TLTWO. One survey of drivers in Houston and Dallas, Texas by Hawkins, Kacir, and Ogden (1992) found that only half of the respondents correctly understood that they should turn before reaching the CROSSOVER sign (D13-1) when this device was shown in a field placement in an arterial work zone. Of course, the D13-1 sign panel is identified in the *MUTCD* as a device used in permanent installations on divided highways, not as a temporary device for use in construction zones. The poor comprehension of motorists for such an explicit message is alarming, nevertheless, and suggests the need for heightened conspicuity of guidance information in this situation. Hawkins et al. recommended that the spacing of channelizing devices be decreased in the vicinity of a crossover to reduce drivers' confusion.

Next, Pang and Yu (1981) conducted a study to verify whether concrete barriers were justified at transition zones adjacent to TLTWO's on normally divided highways, based on crash experience in several construction zone TLTWO's. They found that 34 of the 44 total crashes that occurred in TLTWO's were within the transition zone. Four head-on crashes occurred on two-way, two-lane segments away from the transitions. The transition zone was defined as the roadway section at which traffic flow was converted from a four- to a two-lane operation and vice versa. The absence of opposing traffic precluded the occurrence of head-on crashes during the study period; however, more than one-half of the crashes (56 percent) had the potential of becoming head-on collisions. The authors concluded that on relatively low-volume highways, delineation devices appear to be adequate at transition zones, assuming they are placed properly. A regression analysis provided by Pang (1979) indicated that as annual average daily traffic increases, the crash rate at transition zones also increases, with a concurrent increase in the head-on crash rate at the transition zone.

Project duration and approach speed are two other variables that appear to affect the head-on crash rate at transitions (Pang and Yu, 1981). Graham (1977) concluded that as project duration increases, the crash rate at the transitions decreases. Expectancy issues were highlighted as a plausible explanation. Pang and Yu (1981) reported that because the crash rate in the transition zone increases with shorter project duration, concrete barriers may be necessary for short-term projects. However, long-term projects are expected to have a greater number of crashes owing to a longer period of exposure. Thus, installation of concrete barriers would be more economically justified for long-term projects than for short-term ones. With regard to approach speed, it can be expected that as speed to the transition increases, the chances of a head-on collision would also increase, due to the tendency of vehicles to stray out of their lanes at curves such as those present in transition zones. Pang and Yu (1981) suggested that concrete barriers appear to be justified at transition zones where approach speeds are high.

The conspicuity of concrete safety shaped barriers (CSSB's) is an important issue. Their composition provides little contrast with the roadway pavement, making them difficult to see at night, particularly in the rain, and under opposing headlight glare conditions. Proper barrier delineation treatments will provide drivers with a defined path during darkness and adverse weather conditions. Standard barrier delineation treatments include Type C steady-burn warning lights on top of the barrier, retroreflective devices on the top or side of the barrier, vertical panels placed on top of the temporary concrete barrier, and retroreflective pavement markings on the side of the barrier. The results of studies of barrier delineation in work zones have been mixed (Ullman and Dudek, 1988). For instance, Mullowney (1978) suggested that delineation should be mounted on the top of the barrier so it will retain its reflectivity longer and require less maintenance. However, Ogwoaba (1986) recommended side-mounted concrete barrier delineation so that the delineators are not masked by oncoming headlight glare. The size and brightness of delineators is another controversial topic, with some studies suggesting the use of larger but less bright devices (Davis, 1983; Bracket, et al., 1984; Kahn, 1985) and others recommending smaller, brighter reflectors (Mullowney, 1978; Ogwoaba, 1986). Kahn (1985) found that the delineation of portable concrete barriers improved considerably through the use of cylindrical reflectors on top and smaller units on the side of the barrier at 25-ft intervals. Delineator spacings ranging from 25 ft to 200 ft (7.6 m to 61 m) have been recommended by various studies.

Ullman and Dudek (1988) conducted a study of five barrier delineation treatments, using observations of driver performance to determine how different delineator types, spacings, and mounting positions on the barrier affect nighttime traffic operating in the travel lane next to the barrier. An additional objective of the study was to determine how the visibility and brightness of different types of delineators deteriorate over time because of dirt and road film; in a controlled field study, drivers ages 18 to 56 were asked to provide subjective evaluations of delineator brightness. The study was not conducted at a work zone, but was conducted on an illuminated urban freeway with four lanes in each direction. The CSSB was located 1 ft from the inside travel lane. The five delineation treatments were: (1) top-mounted cube-corner lenses at 200-ft spacing; (2) side-mounted cube-corner lenses at 50-ft spacing; (3) top-mounted retroretroreflective brackets at 50-ft spacing; (4) side-mounted retroreflective brackets at 200-ft spacing; and (5) top-mounted retroreflective cylinders at 50-ft spacing. The cube-corner reflector (treatments 1 and 2) had a diameter of 3.25 in. The brackets (treatments 3 and 4) were 3 in (75 mm) high and 4.25 in wide, and were covered with high intensity sheeting. The cylindrical tube (treatment 5) had a diameter of 3 in and was 6 in high, and was wrapped with high intensity sheeting. Before-and-after data were obtained for the following measures of effectiveness: lane distribution, lane straddling, and lateral distance from the left rear tire to the bottom of the CSSB.

Results of the driver performance data collected by Ullman and Dudek (1988) showed that the treatments had very little practical effect on lane distribution. Lane-straddling rates at all of the treatment segments were low during the higher volume nighttime hours; however, a significant increase in lane straddling occurred for Treatment 2. The data suggested that the combination of close delineator spacing and the side-mounted position may make some drivers too apprehensive of driving near the barrier. Lateral distance data showed significant differences during the higher volume nighttime hours for Treatment 4 and Treatment 5. Lateral distance distributions shifted away from the barrier at Treatment 4 and closer to the barrier at Treatment 5. Subjective evaluations for clean delineators showed brightness rankings to be the same for all treatments. Treatments 1–4 received adequate ratings from at least 80 percent of the subjects, while Treatment 5 was rated adequate by only 50 percent of the subjects. With respect to each treatment's relative effectiveness in helping drivers maintain a safe travel path next to the CSSB, the rankings did not differ significantly; however, Treatment 5 again received the worst score. Subjects stated that side-mounted delineators were preferable to top-mounted delineators because side-mounted delineation provided a more direct line of sight, a better indication of the location of the wall, and a more realistic perception of the lane width. For dirt-covered delineators, Treatment 2 was rated as brightest and most effective, while Treatment 5 was rated as dimmest and least effective. Although further research was deemed necessary, the study authors recommended the use of cube-corner lenses for delineating CSSB's in narrow freeway median applications, because these delineators do not lose their reflectivity due to dirt and grime as quickly as those covered with high intensity sheeting. In addition, for situations with limited lateral clearance, as is common with TLTWO's, top-mounted delineation is recommended, because side-mounted close delineator spacing results in lane straddling if the barrier is located close to the travel lanes. Although subjects indicated a preference for close spacings, driver performance data did not show any differences between 50-ft and 200-ft spacing. The authors recommended that a 200-ft spacing be considered maximum, and that closer spacings may be necessary for CSSB's on sharp curves. The treatments were also deemed appropriate for CSSB's in work zones.

On divided highways with narrow medians, which are often created when barriers are used in crossover situations in work zones, drivers are subject to blinding glare from opposing vehicle headlights. This is particularly problematic for aging drivers who have a reduction in their dark adaptation ability and increased sensitivity to glare. This results in reduced visibility of roadway alignment and channelization, and increases the possibility of crashes. Glare screens can solve the problem, as well as reduce rubbernecking and its associated problems. The Pennsylvania Department of Transportation discontinued the use of the standard glare-control mesh screen in 1976, based on maintenance difficulties, and has employed a paddle-type system in its place (Maurer, 1984). The system consists of plastic airfoil-shaped paddles, which when mounted resembles a picket fence. Results of a 5-year study have shown that the paddle-type system reduces headlight glare satisfactorily and is more cost-effective, both in terms of installation and maintenance, than metal mesh screen. The system was also found to be beneficial as a temporary control for channelizing traffic around a construction work zone, when screening was placed at the transition or the taper zone at the ends of the work zone (Maurer, 1984). Kelly and Bryden (1983) reported that a glare screen consisting of individual plastic louvers 36 in high, mounted vertically on a guiderail or median barrier spaced at 24-in centers, performed as expected in two safety improvement projects.

# 47 Temporary Pavement Markings

Preconstruction centerlines and edge lines that are not obliterated may confuse drivers about the exact locations of lanes. The National Transportation Safety Board (1992) has reported that although guidelines exist for proper signing and striping in construction areas, the traffic control techniques used in many jurisdictions are not in compliance with the guidelines. Lewis (1985) stated that if drivers are presented with conflicting information (as may be the case in a work zone), they will generally choose to follow the pavement, as the pavement itself is a primary source of information for drivers. This points to a need for unambiguous pavement delineation patterns in work zones, to provide clear guidance—particularly at night and under adverse weather conditions—and to accommodate drivers with visual limitations such as those associated with normal aging.

The research findings that have the greatest bearing on age differences in drivers' ability to acquire and use information provided by roadway delineation are a decline in spatial contrast sensitivity and acuity for aging drivers, and a general slowing of responses because of deficits in visual search ability that slows discrimination of more important from less important information in a driving scene.

Discrimination of the boundaries of the traveled way often involves only slight differences in the brightness of the road surface versus the shoulder or surrounding land. The ability to obtain such "edge information" depends upon a driver's sensitivity to contrast. Age differences in contrast sensitivity, beginning at approximately age 40 and becoming progressively more exaggerated with advancing age, demonstrate significant decrements in performance for aging persons (Owsley, Sekuler, and Siemsen, 1983). Under constant viewing conditions, aging observers have lower contrast sensitivity especially in situations where there is a reduction in ambient light levels. A 60-year-old driver requires 2.5 times the contrast needed by a 23-year-old driver (Blackwell and Blackwell, 1971).

Age decrements in visual search and scanning capabilities are widely reported in gerontological research. Rackoff and Mourant (1979) measured visual search patterns for 10 young (ages 21–29) and 13 older (ages 60–70) subjects as they drove on a freeway under day and night conditions in low to moderate traffic. They reported that differences

**Table 68.** Cross-references of related entries for temporary pavement markings.

| Applications in Standard Reference Manuals | | |
|---|---|---|
| ***MUTCD* (2009)** | **NCHRP 500-Volume 9 (2004)** | **Traffic Engineering Handbook (2009)** |
| Sects. 6F.63, 6F.64, 6F.65<br>Sects. 6F.77, 6F.78, 6F.79<br>Sect. 6G.06<br>Figs. 6H-7, 6H-12, 6H-14, 6H-24, 6H-29, 6H-32 through 6H-34, 6H-36, 6H-38 through 6H-42, & 6H-44 plus associated notes for each fig.. | Pgs. V-26-V-27, Sect. on *Strategy 3.1 B11: Improve Traffic Control at Work Zones (T)* | Pg. 669, Sect. on *Pavement Markings* |

between young and older test subjects' performance were most apparent at night, and that older subjects required more time to acquire the minimum information needed for vehicle control. Thus, older drivers require delineation information that is optimal from the standpoints of both attention conspicuity and search conspicuity downstream, and that provides unambiguous path guidance cues for moment-to-moment steering control. Uncertainty about roadway heading and lane position has been cited by older driver focus group members as reasons for driving slower, for erratic maneuvers caused by last-second steering corrections, and for simply avoiding nighttime operations (Staplin, Lococo, and Sim, 1990). An exaggeration of the difficulties older drivers have in rapidly discerning the correct travel path may be expected in construction zones, where drivers must respond to temporary pavement markings that are often in competition with preexisting stripes and/or misleading informal cues provided by variation in the surface characteristics of the road, shoulder, or median.

These diminished capabilities must be considered in relation to specific information needs, when negotiating work zones, while also taking into account the time (distance) in which these needs must be satisfied. The information needs may be loosely contrasted according to the discrimination of continuous versus discrete roadway features (i.e., the perception and recognition of the boundaries of the traveled way, as opposed to a singular location which must be avoided (e.g., an island, barrier, or abutment) or where a path selection decision must be acted upon (e.g., a ramp gore, pavement width transition point, or intersection)). Furthermore, delineation must provide information to a driver permitting roadway feature recognition both at "long" preview distances up to and sometimes exceeding 5 s travel time, and at the more immediate proximities (i.e., within 1 s travel time) where attention is directed for instant-to-instant vehicle control responses.

An investigation of age-related differences in the required contrast for pavement delineation showed that an aging driver (ages 65–80) test sample required a level of contrast 20–30 percent higher than a young/middle-aged (ages 19–49) comparison group (Staplin et al., 1990). The differences became exaggerated with glare as an independent variable. An inevitable consequence of these age differences is an increased reliance on delineation elements for path guidance by aging drivers under nighttime conditions, especially against oncoming glare. The "long preview" and the instant-to-instant steering control cues provided by pavement markings are critical to aging drivers under these circumstances.

Raised pavement markers (RPMs) used for delineation of the centerline and edge lines in construction zones have been found to provide improved wet weather and nighttime reflectivity, and are particularly useful when lanes are diverted from their original path (Spencer, 1978). Davis (1983) reported that, compared with conventional pavement markings (e.g., paint), day-night/wet-night visible RPMs improved construction zone traffic performance significantly. In this study, the markers were associated with decreased lane-change frequency and night lane encroachments. In before-and-after comparisons of crash frequencies in two construction projects, the number of crashes and fatalities decreased as a function of RPM installation (Niessner, 1978). In a study investigating vehicle guidance through work zones, Shepard (1989) recommended that closely spaced RPMs should be used as a supplement to existing pavement striping in areas where the roadway alignment changes.

Dudek, Huchingson, and Woods (1986) conducted a study on a test track to examine the effectiveness of temporary pavement markings for use in work zones. Ten candidate treatments were tested during the day, and the most effective treatments were examined at night. All treatments were tested only under dry weather/dry road conditions. The candidate treatments are presented in Table 69 and included patterns with stripes, RPM's, and combinations of stripes and RPM's. Treatment 1 was the control condition in the study.

**Table 69.** Temporary pavement marking treatments evaluated by Dudek, Huchingson, and Woods (1986).

| Treatment | Description |
|---|---|
| 1* | 4-ft stripes (4 in wide) with 36-ft gaps (control condition) |
| 2* | 2-ft stripes (4 in wide) with 38-ft gaps |
| 3* | 8-ft stripes (4 in wide) with 32-ft gaps |
| 4* | 2-ft stripes (4 in wide) with 18-ft gaps |
| 5* | Four nonreflective RPM's at 3-1/3-ft intervals with 30-ft gaps and one retroreflective marker centered in alternate gaps at 80-ft intervals |
| 6* | Three nonretroreflective and one retroreflective RPM at 3-1/3-ft intervals with 30-ft gaps |
| 7 | 2-ft stripes (4 in wide) with 48-ft gaps |
| 8 | Treatment 2 plus RPM's at 80-ft intervals |
| 9* | Two nonretroreflective RPM's at 4-ft intervals with 36-ft gaps plus one retroreflective RPM centered in each 36-ft gap |
| 10 | 1-ft stripes (4 in wide) with 19-ft gaps |

** Treatments evaluated both day and night*

Results of both daylight and nighttime testing indicated that there were no practical differences between treatments when comparing measures of effectiveness developed from speed and distance measurements. Practical differences were arbitrarily defined as at least 4 mph for speed measures and 1 ft for distance measures. The greatest number of erratic maneuvers during daylight occurred for treatments 7 and 8, which consisted of 2-ft stripes and long gaps. Drivers referred to 2-ft stripes as dots. The subjective data indicated that Treatments 5, 6, and 9 were preferred, under both daylight and nighttime conditions. Reasons given were that RPMs clearly identify curves, are highly visible at a great distance, provide noise and vibration when drivers cross them, and stand out more than tape markings. Of the treatments without RPMs, Treatment 3 was the drivers' choice, for both lighting conditions, while Treatment 2 was rated as least effective.

It should be noted that for temporary pavement markings, the *MUTCD* specifies in section 6F.78 that the same cycle length as permanent markings be used (30 ft), with markings at least 2 ft long, and that half-cycle lengths with a minimum of 2-ft stripes may be used for roadways with severe curvature.

Because subjects tend to perform best when in a controlled, test-track setting and because the range of performance measures are not always sensitive enough to discern small differences between candidate treatments, Dudek, et al. (1988) conducted field studies to compare the safety and operational effectiveness of 1-ft, 2-ft, and 4-ft temporary broken line pavement markings on 40-ft centers in work zones. The study was conducted at night on rural two-lane, two-way highways with 2.0-degree horizontal curvatures, level to rolling terrain, and average speeds between 50 mph and 62 mph. In terms of speed, lateral distance, encroachment, erratic maneuver, and speed profile data for the sample of vehicles with headways of 4 s or more, there were no differences in driver performance between the 1-ft, 2-ft, and 4-ft striping patterns. Analysis of subjective evaluations of the effectiveness of the markings found that the 1-ft stripe was generally rated as poorest, but its mean ranking was not significantly different from that of the 2-ft and 4-ft stripes. Drivers generally preferred the longer stripes, but there was no evidence that the 2-ft or 4-ft stripes were superior to the 1-ft stripe.

In a discussion of the conditions present during this research, Ward (1988) stated that all sites had 12-ft lanes with 4-ft to 10-ft shoulders, the marking material was highly retroreflective yellow tape laid over very black new pavement overlays, and there were no edge lines; therefore, the drivers' focus was a "brilliant ribbon of yellow to follow," resulting in no difference in driver performance between the three stripe lengths. Most important was that none of the treatments were judged as extremely effective, although the 1-ft stripe was rated as poorest, and there was a slight preference for the 4-ft lengths. This is consistent with results obtained by Dudek et al. (1986), where subjects rated 8-ft stripes with 32-ft gaps as the best striping treatment (when RPM's were not available). In the Dudek et al. (1986) study, drivers preferred the treatments with longer stripes, shorter gaps, and RPM's. Hence, the results of the Dudek et al. (1988) study may be applicable only to pavement overlay projects on two-lane, two-way rural roadways, and may not translate to other highway work-zone situations.

Harkey, Mera, and Byington (1992) conducted a study to determine the effects of short-term (interim) pavement markings on driver performance under day, night, wet, and dry weather conditions. The three marking patterns tested included: (1) 2-ft stripes with 38-ft gaps and no edge lines; (2) 4-ft stripes with 36-ft gaps and no edge lines; and (3) 10-ft stripes with 30-ft gaps and edge lines. The measures of effectiveness included lateral placement of the vehicle on the roadway, vehicle speed, number of edge line and lane line encroachments, and number of erratic maneuvers (e.g., sudden speed or directional changes and brake applications). For each operational measure, the 10-ft markings resulted in better driver performance than either the 2-ft or 4-ft temporary marking patterns. Drivers traveled 0.76 mph slower on segments with 4-ft markings and 2.02 mph slower on segments marked with 2-ft markings than on segments marked with 10-ft stripes and edge lines. In addition, compared with the 10-ft pattern, drivers encroached over the lane or edge line 66 percent more often in the presence of the 4-ft temporary marking and 139 percent more often in the presence of the 2-ft markings. These values increased dramatically under night and wet-weather conditions. Comparisons of driver performance between the 4-ft and 2-ft markings showed the following: (1) the speed at which drivers traveled decreased as the length of the lane line decreased; (2) drivers positioned their vehicles closer to the center of the lane as the length of the line increased; (3) the variability of vehicle placement within the lane increased as the length of the lane line decreased; (4) the number of encroachments increased as the length of the lane line decreased; and (5) all operational measures were negatively affected by adverse weather conditions. Results provided evidence of significant decreases in driver performance associated with both the 2-ft and the 4-ft markings, but drivers performed better with the 4-ft stripes compared to the 2-ft stripes. The results suggested that while it may not be practical to place full markings (10-ft segments with 30-ft gaps as specified by *MUTCD* Section 3A.06) on a temporary basis, measures should be taken to prevent reductions in driver performance which result in increased crash potential. Such measures include the use of longer temporary markings, the addition of RPM's for improved performance under adverse weather conditions, and the appropriate use of warning signs to indicate a change in the pavement marking pattern.

# PROMISING PRACTICES

## 48 Increased Letter Height for Temporary Work Zone Signs

**Description of Practice**: Studies have shown that 25-30 percent of crashes within a work zone happen in the advance warning area or transition area. Most of them are rear-end or side-swipe types of crashes. Some of them are preventable with more perception/reaction time. A Caltrans sign comparison study concluded that for aging drivers, early recognition of the proposed sign could result in an additional 1.5 seconds of response time (Caltrans 2012).

Work zone warning signs notify road users of specific situations or conditions on or adjacent to a roadway that might not otherwise be apparent. A solution is needed to improve sign legibility without increasing the cost of providing temporary traffic control. To improve and enhance roadway safety in and around work zones, the largest warning signs practical should be used. However, due to the limitations of the most commonly available portable sign stands, the work zone warning signs are limited to a maximum of 48 in by 48 in. If larger sign sizes are used, they will require larger portable sign stands resulting in a significant increase in cost to provide traffic control in and around work zones.

The California MUTCD recommends the use of larger-than-standard sign, symbol and legend sizes where roadway or road user conditions require greater emphasis. In order to increase sign legibility for TTC zone warning signs, a suggested solution was to identify signs that can have larger legends displayed on some "action" words without increasing the overall sign size maximum of 48 in by 48 in. The proposal calls for increasing the number patch from 8-in to 10-in numbers, and the words "LEFT", "RIGHT", and "CLOSED" from 6-in to 8-in letters. (See Figure 95.)


**Figure 95.** Current (left) and proposed modified (right) temporary work zone sign in California. (Caltrans 2012)

**Anticipated Benefits to Aging Road Users**: As with signs in other driving environments, larger legend size would increase sign legibility and improve work zone safety. Initial results of a Caltrans study indicate that drivers were able to read the modified signs from approximately 100 ft further away. While benefitting all road users, it may especially help aging road users as the larger legend size of action words will gain quicker comprehension of the sign message and from a longer distance, increasing their decision making and response time to the intended action required by the sign.

# 49 Work Zone Road Safety Audits

**Description of Practice:** Work zones have increased potential for violating a driver's expectations, which can be especially hazardous for the aging population because of their diminished visual acuity. According to the Fatality Analysis Reporting System (FARS), 609 people were killed in motor vehicle crashes in work zones in 2012. Of those 609 fatalities, 45 were age 65 and older. A Work Zone Road Safety Audit (WZRSA) is a tool agencies can use to help reduce fatalities and serious injury crashes in work zones. It is the formal safety performance evaluation of a work zone by an independent, multidisciplinary team. It detects and reports on potential road safety issues and identifies opportunities to improve the safety of workers and all roadway users, including the aging population.

A Work Zone RSA follows the eight-step process of an RSA combined with characteristics of a typical work zone inspection or process review.

Step 1: Identify Project or Active Work Zone to be Audited

Step 2: Select the WZRSA Team

Step 3: Conduct a Pre-audit Meeting to Review Project Information and Drawings

Step 4: Conduct a Review of Project Data and Perform a Field Review

Step 5: Conduct Audit Analysis and Prepare Report of Findings

Step 6: Present Audit Findings to Road Owner

Step 7: Road Owner Prepares Formal Response

Step 8: Incorporate Findings into the Project and Evaluate Results

One of the key features of a WZRSA is that it is performed by a multidisciplinary team focused on safety issues. Team members with various backgrounds and experiences can identify issues that may otherwise be overlooked. WZRSA teams may review the potential for safety enhancements to roadway and work zone elements, human factor considerations, enforcement and emergency services issues, and facility operations, whether they currently exist or are planned.

**Anticipated Benefits to Aging Road Users:** Recommendations from a WZRSA can potentially affect roadway users and workers immediately, improve the safety of the work zone being audited, and improve an agency's overall work zone development and deployment process. The *Work Zone Road Safety Audit Guidelines and Prompt Lists* is a publication that includes guidance on how to conduct an RSA at all phases of work zone planning, design and deployment. The document explains the importance of the Work Zone RSA and navigates practitioners through the RSA process. Executing WZRSAs can make a work zone safer, mitigate the potential for risk claims, reduce the societal cost of crashes, reduce project costs, mitigate congestion, and lessen crash severity levels, including those that particularly affect aging drivers.

# CHAPTER 11
# Highway-Rail Grade Crossings

The following discussion presents the rationale and supporting evidence for *Handbook* treatments pertaining to these two proven practices.

## Proven Practices

50. Passive Traffic Control Devices
51. Lighting

# PROVEN PRACTICES

## 50 Passive Traffic Control Devices

For the approximately two-thirds of highway-rail grade crossings that are controlled by passive devices, "recognition errors" have been cited as the most frequent error type, accounting for 77 to 85 percent of the errors at Crossbuck-only crossings (Berg, Knoblauch, and Hueke, 1982). This category of driver error was defined broadly by the study authors as "a breakdown in the detection and/or perception of the necessary information to negotiate the crossing safely." Given the vast body of evidence that sensory and perceptual capabilities decline as a function of age, it is reasonable to assert that the tasks of detecting an approaching train and judging its distance and speed pose exaggerated difficulty for aging drivers. Older drivers are also slower than their younger counterparts to process information (Berg et al., 1982), which was cited as a significant contributing factor by these researchers in decision errors—i.e., the "breakdown in the analysis of information or an incorrect choice of action"—at rail crossings by elderly and inexperienced drivers. Fambro (1999) similarly underscores these problems which disproportionately affect aging road users in his comprehensive literature review, while summarizing a large body of research directed at engineering countermeasures to improve driver understanding of and behavior at grade crossings.

Studies in this area have examined how changes in signing, delineation, the use of

**Table 70.** Cross-References of Related Entries for Passive Traffic Control Devices.

| Applications in Standard Reference Manuals | | | | |
|---|---|---|---|---|
| *MUTCD* (2009) | NCHRP 500 – Volume 9 (2004) | Railroad-Highway Grade Crossing Handbook (1986) | | Traffic Engineering Handbook (2009) |
| Sect. 1A.13, *Highway-Rail Grade Crossing*<br>Sects. 8A.01 & 8A.04<br>Figs. 8B-8 & 8B-9<br>Sects. 8B.03 through 8B.12<br>Fig. 8B-2, 8B-3<br>Sects. 8B.17, 8B.20 through 8B.23, 8B.27, 8B.28<br>Fig. 8B-4<br>Sects. 8A.06, 8B.16, 8B.19, 8B.26. | Pg. 5-10, Sect. 5.2.6 *Railroad-Highway Grade Crossings*<br>Pgs. 5-21 through 5-22, Sect. 5.3.6 *Railroad-Highway Grade Crossings*<br>Pg. 6-10, Sect. 6.2.6 *Railroad-Highway Grade Crossings*<br>Pg. 6-19, Sect. 6.3.6 *Railroad-Highway Grade Crossings*<br>Pg. 7-26, Sect. 7.2.16 *Railroad-Highway Grade Crossings*<br>Pg. 7-39, Sect. 7.3.7 *Railroad-Highway Grade Crossings*<br>Pgs. 9-185 through 9-192, Sect. 9.12.3 *Crossing Design* | Pg. 10, Para. 3<br>Pg. 11, Para 4<br>Pg. 12, Para. 2<br>Pg. 29, Para. 3<br>Pg. 30, Table 8<br>Pg. 31, Paras. 5-6<br>Pg. 33, Paras. 2 & 4<br>Pg. 53, Fig. 7<br>Pg. 57-58, Figs. 9-10<br>Pgs. 66-69, Sects. on *New Hampshire Index & NCHRP 50*<br>Pg. 71, Tables 19-20<br>Pg. 78, Para. 2<br>Pgs. 80-81, Para. 6 & Fig. 15<br>Pg. 83, Para. 5<br>Pg. 84, Para. 5, 4th bullet<br>Pg. 87, Para. 4, Last bullet | Pgs. 96-103, Sect. on *Passive Traffic Control Devices*<br>Pgs.173-176, Item 1 of each economic type analysis<br>Pgs. 177-180, Sect. on *Resource Allocation Procedure*<br>Pg. 188, Para. 4<br>Pgs. 196-199, Part of Sect. on *Traffic Control Devices*<br>Pgs. 201-202, Figs. 100-103<br>Pg. 206, Paras. 2-3<br>Pg. 215, Para. 4<br>Pg. 217, Para. 5<br>Pg. 219, Para 4, 2nd bullet<br>Pg. 220, Sect. on *Improved Signing*<br>Pg. 226, Paras. 4 & 8<br>Pg. 227, Para. 1 | Pgs. 147, Table 5-7<br>Pg. 398, Item 1<br>Pg. 425, Final Paragraph<br>Pgs. 634-635, Sect. on *Railroad-Highway Grade Crossing Control* |

rumble strips and the introduction of nighttime illumination can variously affect drivers' allocation of attention; looking behaviors; braking/deceleration during approach to a highway-rail grade crossing; and maneuver decisions to negotiate the crossing; as well as the actual vehicle-train crash experience at a site.

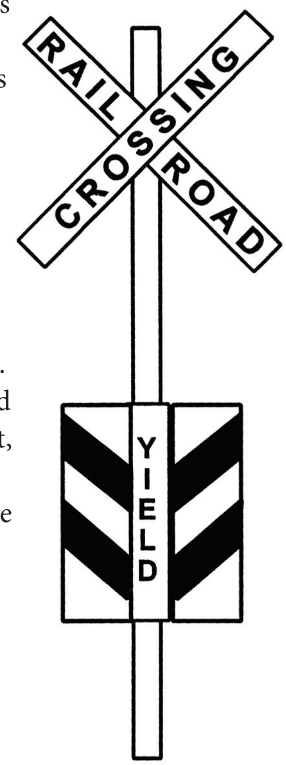



**Figure 96.** Experimental Enhanced Crossbuck Sign, Referred to as the "Buckeye Crossbuck" or "Conrail Shield"

To begin, simply detecting the presence of a passive crossing, where the need to slow and look for a train is indicated, can be problematic, especially at night. Fambro (1999) cites the work of Russell and Konz (1980) who found that placement of the Crossbuck sign (R15-1) does not make the best use of the vehicle's headlight beam pattern, which is aimed to the right and down. They state that certain combinations of headlight angle and roadway geometry at the crossing may result in a Crossbuck sign luminance of zero. The *MUTCD* states that the sign height above the ground (9 ft) may be varied as required by local conditions. Russell and Konz (1980) recommend lowering the Crossbuck by 2 ft, which would increase the illuminance by 50 percent at 150 ft and 69 percent at 250 ft. Russell and Rys (1994) conducted a small field study that confirmed that, from a distance of 350 ft, a Crossbuck at a height of 9 ft measured to the center and 6 ft from the right pavement edge received 8.4 percent of the vehicle headlight illuminance, compared to 14.2 percent if the Crossbuck were lowered to 7 ft above ground level, and 44 percent if the Crossbuck were lowered to 3 ft above the ground. Russell and Rys conclude that placement of the Crossbuck as low as possible and using retroreflective tape on the full length of the Crossbuck posts would make the best use of the greater headlight illuminance levels present near the ground.

Related work by Russell and Kent (1993) indicates that the conspicuity of passive grade crossings may be affected by adopting more effective delineation practices. These researchers conducted a before-after study to evaluate the effectiveness of five low-cost passive warning systems, implemented at six different sites. The warning systems included combinations of conventional signing (YIELD) and an enhanced delineation treatment; experimental signing (the "Buckeye Crossbuck," also termed the "Conrail Shield") as shown in Figure 96, plus an enhanced delineation treatment; two systems utilizing signing alone; and the enhanced delineation treatment alone. The enhanced delineation treatment included Type VII (ASTM D 4956-01) retroreflective tape that provides for high brightness on straight approaches as well as at wide observation angles (with SIA values ranging between 800 and 1,000), placed on both sides of both Crossbuck posts, and Type 2, flexible roadside retroreflective delineators with high intensity sheeting, placed on the right side of each approach, spaced 50 ft apart from the advance warning sign to the Crossbuck post (a total distance of 1,200 ft), and extending an equal distance beyond the Crossbuck post.

The measures of effectiveness in the Russell and Kent (1993) study included: approach speeds; brake light activations; and head movements toward the tracks. One "before" study was conducted prior to installation of the new treatments, and two "after" studies were conducted, one at 2 months and the other at 7 months after treatment installation. Each observation period lasted for 3 to 4 days, from 2:30 p.m. until 5:30 p.m., and from 9:00 p.m. until 12 midnight. Results indicated that only the locations where the delineation system alone (roadside delineators and high-brightness tape on both sides of the crossbuck posts) was installed showed statistically significant, long-term positive changes in more than one variable (deceleration rates and looking behavior). The researchers indicated that the added retroreflective devices and tape on the Crossbuck posts provide high values of reflected light at all distances, especially under low-beam headlight conditions, concluding that the delineation treatment showed the most permanent improvement in driver behavior of the low-cost systems tested, and would be effective at grade crossings on highways in rural areas, particularly at night.

Brich (1995) similarly concluded that the use of very high intensity retroreflective sheeting (e.g., ASTM D 4956-01 Type IX) applied to both the front and back sides of the Crossbuck posts for the entire length of the post, plus double-sided Crossbucks (blades) also with very high intensity retroreflective sheeting resulted in superior conspicuity of the crossing, compared to systems that contained double-sided Crossbucks with Type IX sheeting, plus Type IX sheeting on only the back side of the posts (full length); or double-sided Crossbucks with Type IX sheeting, plus Type IX sheeting placed on the back of the posts in a 4-ft long strip; or single-sided Crossbucks with a strip of Type IX sheeting on the back side of the Crossbuck blades and also on the front and back of the posts (full length); or single-sided Crossbucks with a strip of Type VII sheeting on the back of the Crossbuck blades and also on the back side of the posts (applied 3 ft above ground level to the center of the Crossbuck blades). Both the Type VII and IX sheeting materials provide high brightness at wide observation angles, but Type IX is designed to provide high brightness at shorter viewing distances (in the 300- to 600-ft range). To delineate the Crossbuck posts, a strip of 2-in wide sheeting was applied to a 3-in wide, 9-ft tall aluminum strip that was mounted on the front and the back of the Crossbuck post, or to the back of the post only, depending on the treatment being evaluated. The study by Brich (1995) was conducted in a laboratory using videotaped images of varying treatments filmed under low- and high-beam headlight illumination at night, during the approach to rail grade crossings. A train was also filmed traveling through each crossing.

Comments obtained from the subjects in the Brich (1995) study indicated that marking the full length of the Crossbuck posts on the front and the back results in: (1) visually stabilizing the Crossbuck and tying it to the ground, which provides a valuable reference point; and (2) it makes the part of the far-side post below the undercarriage of a moving train in the crossing visible, causing a flickering effect that alerts a motorist of the presence of a train. It was concluded that using double-sided Crossbucks and marking the full length of both sides of both posts increases the visibility of the crossing; increases driver depth perception of the crossing; and increases the ability of a driver to detect a train in the crossing. The cost of a double-sided Crossbuck with Type IX sheeting in 1995 was $87.50 and the cost of sheeting and aluminum to apply to the post was $18.74 per Crossbuck assembly. Since most crossings use two Crossbuck assemblies, the cost per crossing (Crossbuck, post, aluminum strip, and retroreflective material) was $212.48, in 1995 dollars.

The *MUTCD* (FHWA, 2009) includes the requirement to use a strip of retroreflective sheeting that is at least 2-in wide, on the front and back of each Crossbuck support post, for the full length of the post. In addition, it states that a strip of retroreflective sheeting shall be applied to the back of the Crossbuck blades, except in locations where Crossbuck signs are installed back-to-back.

The largest body of work has been directed toward improving performance under daytime conditions, seeking to improve conspicuity for advance warning devices as well as devices at the crossing, but principally focusing upon motorists' understanding of signs at highway-rail grade crossings. Uses of novel sign designs, combinations, materials, and placements have been evaluated, plus expanded applications of conventional devices—particularly STOP signs.

Research has indicated that driver comprehension of highway-rail grade crossing signs is poor. Even when the signs are conspicuous, they don't provide any information about what drivers should do when approaching or crossing the tracks. The *MUTCD* (2009) specifies that a railroad crossing sign (Crossbuck, R15-1) is a regulatory sign, and indicates that as a minimum, one sign shall be used on each roadway approach to every grade crossing, alone or in combination with other traffic control devices. Although the Crossbuck is, in effect, a YIELD sign, and motorists have the obligation to so interpret it, drivers do not have a clear understanding of what their responsibilities are when encountering the Crossbuck sign (Fambro et al., 1997). Lerner, Ratte, and Walker (1990) indicate that across studies, the majority of subjects (54 to 84 percent) believe that the appropriate behavior at a passive crossing is to stop; however, observational studies indicate that drivers routinely disregard this "rule."

One area of research has attempted to enhance the conspicuity and comprehensibility of the Crossbuck sign. Two enhanced Crossbuck signs have been evaluated in the State of Ohio (Zwahlen and Schnell, 2000). The Buckeye Crossbuck (also known as the Conrail Shield) is a standard Crossbuck sign with a supplemental reflectorized aluminum shield with a red vertical YIELD legend, mounted at headlight level. The 38-in high shield (reflectorized with white microprismatic sheeting on both sides) contains a 9-in wide center section (YIELD) with two 12-in side panels that are bent away from the center panel at 45-degree angles (see Figure 96). These panels contain alternating stripes of red and white highly retroreflective sheeting, with narrow mirrored strips between the stripes. This device costs approximately $300 per crossing. The Buckeye Crossbuck and the Standard Improved Crossbuck were evaluated on a statewide basis in Ohio with respect to their potential to alter driver risk taking behavior, their crash reduction potential, user acceptance, and photometric performance at night. The Standard Improved Crossbuck consists of a wooden post that is reflectorized on all four sides and aluminum blades that are reflectorized on both front and back with white microprismatic long-distance performance (Type VII) sheeting and the standard black legend. The Standard Crossbuck consists of a non-reflectorized wooden post and aluminum blades equipped with white encapsulated retroreflective sheeting material (Type III) and the standard black legend.

For the driver risk-taking portion of the study, motorist near-collision and violation video data were collected along four selected rail corridors during 1995 in the before-condition (Standard Crossbuck condition). In the after-condition (1996-1997) half of the Current Standard Crossbucks were replaced with the Buckeye Crossbuck and the other half were replaced with the Standard Improved Crossbuck. A total of 3,833 passive railroad crossing approaches were recorded under both the before and after condition. Motorists were categorized as either compliant (yielded to an approaching train blowing its whistle) or non-compliant (drove over the crossing although an approaching train was blowing its whistle). Results of the driver risk-taking study indicated that the new crossbuck devices did not provide increased compliance over the standard crossbuck (56.1 percent non-compliant vs. 54.6 percent non-compliant). However, none of the driver violations in the before or after period were closer than 5 seconds. Both new crossbuck designs provided temporal distributions that were slightly shifted towards longer risk acceptance times (median value = 25 seconds) when compared to the temporal distributions obtained with the Current Standard Crossbuck design (median value = 20 seconds). The increased time difference for the Buckeye Crossbuck compared to the Standard Crossbuck was significantly significant ($p<0.0186$). The crash analysis showed a statistically significant superiority ($p<.0.047$) of the Buckeye Crossbuck (157 crashes) over the Standard Improved Crossbuck (192 crashes) from 1994 to 1999, a 22.3 percent decrease. The crash analysis included every public passive railroad/highway grade crossing in Ohio; all crossings were equipped with either the Buckeye Crossbuck or the Standard Improved Crossbuck, which were evenly matched in terms of their number of installations. The user acceptance survey included 374 returned surveys out of 1,009 sent to randomly sampled licensed Ohio drivers. Findings indicated an overwhelming preference of the Buckeye Crossbuck over the Standard Improved Crossbuck. The majority of road users perceived that the additional area of the shield with the vertical "Yield" legend was useful in warning an approaching driver about the presence of a public passive railway/highway crossing. Road users indicated that the Buckeye Crossbuck should be adopted as a warning device at public passive crossings. The Buckeye Crossbuck provided the strongest visual signal among the measured crossbucks at night and during the day.

Based on their study findings, Zwahlen and Schnell (2000) recommended amending the National standard for crossbucks at passive railroad/highway grade crossings in the *MUTCD*, including the Buckeye Crossbuck as an alternative design, with the following modification. They recommended that the sheeting material of choice for the whole Buckeye Crossbuck should be a microprismatic sheeting material with a high angularity (Type VII Visual Impact performance, instead of Type VII Long Distance Performance).

Bridwell, et al. (1993) conducted a laboratory study that employed 42 young/middle-aged subjects (ages 25 to 45 years) and 42 older subjects (ages 65 to 85) who viewed slides of 7 railroad crossing signs. The signs included the standard Crossbuck sign (R15-1); the standard Crossbuck sign with a red and white striped (barber) pole; the standard Crossbuck sign with a standard YIELD sign mounted below; the standard Crossbuck with the Conrail Shield mounted below; the Canadian Crossbuck (Crossbuck with white panel, red border, and no text); the Canadian Crossbuck with the Conrail Shield mounted below; and a standard YIELD sign with a black and white regulatory sign below reading "TO TRAINS." Sign recognition distance, conspicuity distance (except for the YIELD TO TRAINS sign) and driver comprehension data were collected. Although there were no significant differences in recognition distance between the signs, the authors suggest that this may be more a result of the testing conditions (laboratory) than of the signs themselves. They recommend that a field study be conducted to measure actual recognition distances. In terms of conspicuity distance, the worst performing signs were the two that contained only the Crossbuck (standard R15-1 and the Canadian Crossbuck). The standard Crossbuck when supplemented with the YIELD sign, or the Conrail Shield, or a barber-striped pole was noticed significantly more often.

For the comprehension portion of the Bridwell et al. (1993) study, drivers were asked about what they thought the sign meant, and what they should do if they encountered such a sign on the roadway. Drivers who didn't know what the meaning of a sign was (i.e., "there is a railroad crossing") were shown the Advanced Railroad Crossing (W10-1) warning sign to help put the Crossbuck sign "in context." Several drivers required this "in context" information to correctly identify the meaning of the Canadian Crossbuck, the Canadian Crossbuck with the Conrail Shield, and the YIELD TO TRAINS sign. Data were therefore presented for percent-correct for sign meaning before and after being shown the Advance Railroad Crossing sign. Responses were always correct (100 percent comprehension) before the Advance sign for three of the signs: the standard Crossbuck, the standard Crossbuck sign with the barber pole, and the standard Crossbuck with the YIELD sign. For the other four signs, the "before" data for percent correct responses were as follows: standard Crossbuck with Conrail Shield (83.3 percent), Canadian Crossbuck (91.7 percent); Canadian Crossbuck with Conrail Shield (58.3 percent); and YIELD TO TRAINS sign (66.7 percent). After presentation of the Advanced Railroad Crossing sign, comprehension improved for three signs: all drivers understood the meaning of the Canadian Crossbuck and the YIELD TO TRAINS sign (100 percent correct comprehension), and comprehension improved from 58.3 percent correct to 83.3 percent correct for the Canadian Crossbuck with the Conrail Shield. In terms of knowing what to do when encountering such a sign, the two best signs (83.3 percent correct for the standard Crossbuck with the YIELD sign and the YIELD TO TRAINS sign) significantly outperformed the two worst signs (the standard Crossbuck [41.6 percent correct] and the Canadian Crossbuck [33.3 percent correct]). The other three signs were understood correctly half of the time. After being shown the Advance Railroad Crossing sign, the only sign that showed significant improvement in driver understanding of the correct action was the YIELD TO TRAINS sign, which increased to 100 percent identification of the correct action.

Bridwell et al. (1993) conclude that a change in the current standard Crossbuck sign for passive crossings appears necessary, based on study findings that it is neither well understood nor well noticed. They recommend further testing in the field for the standard Crossbuck sign supplemented with the standard YIELD sign, the standard Crossbuck sign supplemented with the Conrail Shield (which has the words "YIELD"), and the standard YIELD sign with the supplemental plaque that reads "TO TRAINS." The Canadian Crossbuck should be omitted from further testing, as it performed worse than the standard Crossbuck.

Fambro (1999) conducted five focus groups containing 10 participants each, who were selected to provide a range of ages. Focus groups were conducted in College Station, Corsicana, and Arlington, Texas and in De Kalb and St. Charles, Illinois. During the sessions, participants were asked to provide their reactions to the following eight traffic control devices described as proposed enhancements to passive warning devices at highway-rail grade crossings: (1) Buckeye Crossbuck; (2) LOOK FOR TRAINS sign; (3) YIELD TO TRAINS sign; (4) a vehicle-activated strobe light; (5) illumination; (6) rumble strips; (7) additional retroreflective material and/or devices on Crossbuck and support posts; and (8) roadway traffic signals. None of the passive signing systems were recommended by focus group participants as promising, although the Buckeye Crossbuck was rated as an excellent alternative in one of the five focus groups.

In the Fambro et al. (1997) survey of 1,010 drivers conducted to determine driver understanding of traffic control devices at highway-rail crossings, 82 percent of the respondents correctly identified the meaning of the "YIELD TO TRAINS" experimental sign (i.e., "Yield the right-of-way if a train is approaching a crossing"). In the focus group sessions conducted by Fambro (1999), the "YIELD TO TRAINS" signs were not rated as promising alternative traffic control devices. However, he recommends their use at passive grade crossings in rural areas, to alert and warn drivers that they are approaching a critical safety decision point. The sign consists of a standard YIELD sign, with a supplemental panel with the phrase, "TO TRAINS." The sign combination can be placed on the standard Crossbuck sign or used on a separate pole at the crossing. Fambro's recommendation is based on a before-after study conducted in Texas, which found a significant decrease in approach speed at two of six sites; significant increases in looking behavior at three of eight sites; and no significant decrease in looking behavior at any of the eight sites evaluated (Fambro, Beitler, and Hubbard, 1994).

The above recommendations with combinations involving the standard R1-2 sign focuses attention on the use of traffic control devices whose meanings are familiar to drivers. Section 8B.04 of the *MUTCD* (2009) indicates that, while the Crossbuck Assembly is required, STOP or YIELD signs may be used in addition to the Crossbuck Assembly at passive grade crossings at the discretion of the responsible State or Local jurisdiction. It further states that a YIELD sign shall be the default traffic control device for Crossbuck Assemblies on all highway approaches to passive grade crossings unless an engineering study performed by the regulatory agency or highway authority having jurisdiction over the roadway approach determines that a STOP sign is appropriate. Engineering studies should take into account such factors as the line of sight to approaching rail traffic (giving due consideration to seasonal crops or vegetation beyond both the highway and railroad or LRT rights-of-ways), the number of tracks, the speeds of trains or LRT equipment and highway vehicles, and the crash history at the grade crossing. The YIELD or STOP sign may be installed on the same support as the Crossbuck sign or it may be installed on a separate support; in either case the YIELD or STOP sign is considered to be a part of the Crossbuck Assembly.

The use of STOP signs at passive crossings has been a controversial issue for over 40 years (Russell and Burnham, 1999). One camp (including Russell and Burnham) maintains that the indiscriminate use of STOP signs at all passive crossings would serve to breed driver disrespect for STOP signs as well as for highway-rail grade crossings. Russell and Burnham (1999) cite the research of Bezkorovainy-Holsinger (1966) and Burnham (1994) who observed that approximately 84 percent of drivers at STOP-controlled highway-rail grade crossings violated the law, and either did not stop at all, or performed a rolling stop.

This view is contrasted against that of the National Transportation Safety Board (NTSB), who in 1998 recommended that States install STOP signs at all passive grade crossings unless a traffic engineering analysis determines that installation of a STOP sign would reduce the level of safety at a crossing. Farr and Hitz (1985) found that STOP signs reduced crossing crashes by approximately 35 percent, based on analysis of data included in the Department of Transportation (DOT)-Association of American Railroads (AAR) Rail-Highway Crossing Inventory and the Federal Railroad Administration (FRA) Railroad Accident/Incident Reporting System for the years 1975 through 1980. Eck and Shanmugam (1987) used the National Rail-Highway Crossing Inventory and FRA crash files to compare low-volume road grade crossing characteristics with high-volume road grade crossing characteristics. They found that exposure-based crash rates at low-volume road grade crossings were much higher than at higher-volume road grade crossings, and that magnitudes of crash reductions following upgrades from no signs or Crossbucks only to STOP signs were higher for the low-volume crossings.

Earlier work in this area has also influenced current thinking, particularly the Sanders, McGee, and Yoo (1978) study which determined advantages and disadvantages of the selective use of highway STOP signs as safety improvements at highway-rail grade crossings, and developed guidelines for their use. They performed crash analyses to compare crash rates for crossings with Crossbucks only to crash rates for crossings with Crossbucks and standard highway STOP signs. Results indicated that crash rates for STOP-sign crossings were lower than rates for Crossbuck-only crossings, given higher vehicle-train exposure. Sanders et al. (1978) also performed field studies to compare driver behaviors for Crossbuck-only crossings to driver behaviors for similar crossings where a standard highway STOP sign was installed in addition to the Crossbuck. Driver behaviors included looking behavior, speed profiles, and observance of STOP signs. Looking behavior was obtained by Sanders et al. (1978) for 1,413 drivers at 8 Crossbuck-only sites in 4 States, and for 3,073 drivers at 18 sites with both a STOP sign and a Crossbuck sign in 5 States. They found that 83 percent of the drivers looked for trains at the locations with STOP signs, but only 42 percent looked for trains at the Crossbuck-only sites. Speed profile measures indicated that drivers approaching a STOP-sign crossing began their deceleration closer to the crossing than did drivers approaching a Crossbuck crossing. Also, vehicle speeds just prior to the crossing were considerably lower at the STOP-sign crossing. Sanders et al. (1978) observed that while STOP sign observance (compliance) at stop-controlled highway-rail crossings was less than at highway intersections (60 percent vs 80 percent), there was no transfer of adverse stopping behavior between the rail-grade crossing and a nearby stop-controlled highway intersection.

Applying the results of Sanders et al. (1978) to the goal of accommodating age-related driver difficulties is hampered by lack of knowledge about the age of drivers sampled in their research. In addition, the driver behaviors adopted as outcome variables were affected by factors other than signing practices and site characteristics. For example, looking behavior was affected by the level of enforcement at STOP sign controlled crossings. Their principal conclusion still is worth noting: STOP signs should be applied selectively only at hazardous passive grade crossings (restricted sight triangle; ADT<2000; 3+ train crossings per day) and should not be used indiscriminately at all passive grade crossings.

Fambro, et al. (1997) conducted a field study using 10 younger drivers (ages 18 to 25), 10 middle-aged drivers (ages 30 to 45), and 10 older drivers (ages 55 and older), to document looking behavior and deceleration at rail grade crossings. This study was predicated upon the belief that looking behavior in both directions and a significant reduction in speed are the key safety goals at passive crossings, because no warning devices are activated when a train is approaching the crossing. The passive site with the greatest percentage of drivers who looked in both directions before crossing (97 percent) was a site controlled by a STOP sign. All of the young and middle-aged drivers looked both ways at this site, and 9 of the 10 older drivers looked both ways. Three of the 30 drivers did not stop at the STOP sign (although they slowed considerably), and 10 drivers performed a rolling stop. At the other two passive sites (marked with Crossbuck signs only, and no advance railroad crossing sign), 70 percent of the drivers did not look in both directions at one site (70 percent of younger, 80 percent of middle-aged, and 60 percent of older drivers), and 17 percent did not look in both directions at the other site (20 percent of the younger, 10 percent of the middle-aged, and 20 percent of the older drivers).

It may be noted that stopping before reaching the tracks provides the driver who may have difficulty dividing attention (e.g., the aging driver), with the ability to focus on the single task of looking for a train. For example, Lerner, Ratte, and Walker (1990) note that in the Knoblauch et al. (1982) study, relatively few crashes occurred at a roadway-rail grade crossing because a driver who was stopped (at a passive crossing or at an active crossing with flashing lights) misjudged a gap and proceeded to cross. The large majority of decision errors were made by drivers in moving cars. Expecting to stop and seeing a STOP sign at a passive crossing would also remove the potential for vehicle-to-vehicle (rear-end) crashes. Related is the fact that 15 to 25 percent of drivers expect all crossings to be actively controlled (Fambro, 1999; Lerner et al., 1990). This erroneous perception results in drivers assuming that it is safe to cross (without slowing or looking both ways) when there are no lights flashing, even when there are no lights present at the crossing. A STOP sign at a passive crossing will eliminate this expectancy and provide positive and unambiguous guidance, removing the need to look for the absence of active warnings for clues about what behavior is appropriate. Also, as Lerner et al. (1990) note, response time is faster to detect the presence of a TCD as opposed to its absence.

Together, the findings and conclusions in the paragraphs above should provide guidance for the selective use of the R1-1 sign at highway-rail grade crossings, by informing the engineering judgment called out in the *MUTCD* for application of these devices.

As described in Chapter I (Design Element 12 Stop and Yield Signing), highway signs with fluorescent sheeting have been found to be more conspicuous and can be detected at a further distance than signs with standard sheeting of the same color. Of particular interest is a study by Burns and Pavelka (1995), who found that signs with fluorescent red sheeting had greater detection and color recognition distances at dusk than signs made with standard red sheeting. The results of this study suggest that the use of fluorescent red sheeting on YIELD signs at highway-rail grade crossings (and on STOP signs, where they are deemed appropriate), would serve to increase their conspicuity both under daytime and low luminance conditions, and would be of particular benefit to aging drivers, who suffer from decreases in contrast sensitivity.

Other research pertaining to signing for highway-rail grade crossings for which data from aging drivers has been obtained has addressed comprehension of the Railroad Advance Warning sign and the Parallel Railroad Advance Warning sign. Picha, Hawkins, and Womack (1995) conducted a survey of 747 drivers ranging in age from 16 to 65 and older who were renewing their drivers' licenses in seven Texas cities. Of the 747 participants, 54 were ages 55 to 64 (7.3 percent of the sample) and 31 were age 65 or older (4.2 percent of the sample). A multiple choice question was included regarding the meaning of the W10-1 (Railroad Advance Warning) sign and the W10-3 (Parallel Railroad Advance Warning) sign. No advantages for alternative designs to the standard W10-1 were demonstrated in this research; however, an alternative to the current W10-3 was recommended.

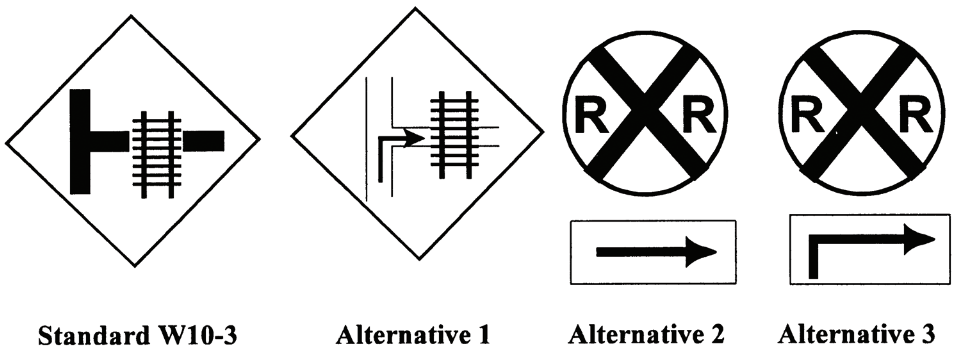



**Figure 97.** Standard *MUTCD* W10-3 Sign and Alternative Sign Designs Evaluated by Picha, Hawkins, and Womack (1995)

The standard Parallel Railroad Advance Warning sign (W10-3) and three Alternative designs were shown to the same driver sample. (See Figure 97.) Alternative 1 was a yellow diamond sign that consisted of the same elements present in the standard design, except that the roadway outline was drawn (as opposed to thick solid lines), and a bent right arrow was drawn within the roadway lines to indicate that a right turn would lead to railroad tracks. Alternative 2 was the standard W10-1 sign (Advance RR Crossing) with a supplemental plaque containing an arrow that pointed to the right. Alternative 3 was the same as Alternative 2 except the supplemental panel contained a bent right-pointing arrow. The correct response, "you will cross a railroad track if you turn right at the intersection," was provided by 84.1 percent of the participants who saw the standard sign; 88.1 percent of the respondents who saw Alternative 1; 90.5 percent of the respondents who saw Alternative 2; and 87.2 percent of the respondents who saw Alternative 3. A higher percentage of respondents indicated that they did not know what the standard sign meant (10.2 percent) than the alternative designs (6.2 percent for Alternative 1; 3.2 percent for Alternative 2; and 1.6 percent for Alternative 3). Thus, the standard W10-3 sign had the lowest correct response rate and the highest "not sure" rate, although these differences did not reach statistical significance. While suggestive, further work is deemed necessary to justify a treatment in this *Handbook*.

The next category of countermeasures reviewed, targeting speed reductions by drivers approaching highway-rail grade crossings, is the application of rumble strips. Fambro's (1999) review indicates that in Kentucky, rumble strips were effective in reducing collisions and near misses, with no indication of motorists avoiding the rumble strips; however, in Georgia, about 12 drivers per day "drove around" the strips (Skinner, 1971; Parsonson and Rinalducci, 1982). Parsonson and Rinalducci (1982) recommend that at grade crossings, rumble strips should be applied only at nonresidential locations where unfamiliar drivers are the prevalent group. Fambro states that the potential benefits of rumble strips at roadway-rail grade crossings include: decreased approach speeds; increased awareness of warning signs; and increased awareness of a potentially hazardous intersection. He recommends their use for passive crossings on rural, low-volume roadways and provides the following guidelines:

- Three to four rumble strip pads of 5 to 20 rumble strips should be used, with the first pad placed 2 to 3 s before the advance warning sign to direct the driver's attention to the sign.

- Subsequent pads should be placed with decreasing spacing and numbers to create the sensation of acceleration.
- The last pad should be placed at least 250 ft before the crossing to avoid creating a pavement condition that might interfere with braking.

Another view is provided by Lerner, Ratte, and Walker (1990), who caution that distorting the driver's perception of approach speed with progressively decreasing spacings of rumble strips, in an effort to encourage slowing on the approach to a crossing, could actually encourage a driver to speed up and try to beat a train. While this behavior has not typically been associated with aging drivers either in the research literature or anecdotally, it raises a more general concern that any present recommendation regarding the use of rumble strips would be premature.

Finally, a novel treatment to attract motorists' attention to highway-rail grade crossings is the use of a vehicle-activated strobe light on a sign assembly. The vehicle-activated strobe light causes short bursts of flashing light when a vehicle passes over detectors placed in the roadway. In research conducted by the Texas Transportation Institute, the strobe is mounted on top of a standard railroad advance warning sign, and the vehicle detector is placed approximately 8 seconds before the advance warning sign (Fambro, Schull, Noyce, and Rahman (1997). The strobe flashes three to five times to direct the driver's attention toward the advance warning sign, and it should stop flashing 2 to 3 seconds before the driver reaches the sign to allow time to read the sign.

Fambro et al. (1997) evaluated this treatment in a controlled field study using 7 younger drivers (age 25 or younger), 12 middle-aged drivers (ages 25 to 54) and 7 older drivers (age 55 and older). Head movements toward the sign and braking reactions were recorded by in–vehicle observers to the advance railroad crossing sign alone, to the advance railroad crossing sign supplemented with a strobe light, and to an advance railroad warning sign supplemented with a standard flashing beacon. The sign sheeting was engineering grade, making it retroreflective. There were no differences in head movements (indicating no differences in attention-getting value) as a function of the sign system; however, 54 percent of the drivers exhibited braking in response to signs enhanced with either the strobe light or the flashers, compared to 31 percent who exhibited braking to the standard sign without enhancements. Drivers also responded to a questionnaire and participated in a focus group discussion. Three drivers (11 percent) thought that the strobe-enhanced sign indicated that a train was ahead, and 9 drivers (35 percent) thought that the flashing beacon indicated the presence of a train. The authors mention a concern with this interpretation; drivers at passive crossings who do not see trains approaching after encountering strobe- or flasher-enhanced warning signs may begin to disrespect active devices at crossings that do indicate the presence of a train. Seven drivers (27 percent) indicated that the strobe light was confusing, and 11 drivers (42 percent) thought the flasher-enhanced sign was confusing. With special attention to the problems of aging drivers, including the difficulties in decision making and delays in response time when confronted with unusual or unexpected situations, such results were not sufficiently encouraging to warrant a recommendation in this *Handbook*.

# 51 Lighting

Aging drivers, with their decreased contrast sensitivity, and need for increasing levels of light for night driving tasks, would be expected to benefit disproportionately from increasing the detectability and conspicuity of railroad crossing signing, and of the crossing itself. Another strategy is to add illumination to passive crossings. In one before-after study of 52 highway-rail grade crossings (Russell and Konz, 1980), adding illumination to passive crossings resulted in an 85 percent reduction in the mean number of crashes per week (where the vehicle ran into a train already at the crossing). The importance of illumination at passive highway-rail grade crossings was also highlighted by Fambro (1999).

Mather (1991) evaluated the 7-year crash history of 35 passive highway-rail grade crossings in Oregon that were illuminated as a low-cost alternative for improving crossing safety at night. The eligibility criteria for the installation of illumination were: (1) the crossing must have regular nighttime train movements (4 p.m. to 7 a.m.), and (2) the crossing is too low on the statewide crossing priority list (low train or vehicle traffic volumes) to qualify for automatic warning devices. Crash data indicate that before illumination, 18 train-vehicle crashes occurred at 13 crossings during the hours of darkness. After illumination, only 3 train-vehicle crashes occurred at two crossings during the hours of darkness.

The cost of installation across the 34 crossings averaged $1,931 per crossing, and ranged from $386 to $9,384 (where a 1-mi long ditch was dug to provide electrical power to the site). The goal was $2,000 per crossing (a substantial reduction of the costs associated with installing active warning devices, estimated to be in excess of $100,000 per crossing, according to Bridwell et al., 1993). Monthly maintenance costs averaged $15 per luminaire per pole.

The installation specifications for illumination at the crossings reported on by Mather (1991) are as follows.

At least one luminaire shall be mounted on each side of the track at the crossing. Luminaires should be located so that protective devices at the crossing will be directly illuminated.

- Luminaires shall be oriented toward the railroad track to provide at least 10.76 lux [1 footcandle (fc)] of illumination on the vertical plane 5 ft from the centerline of the track. Maximum permissible level of illumination and exact orientation of the

**Table 71.** Cross-References of Related Entries for Lighting.

| Applications in Standard Reference Manuals | | |
|---|---|---|
| *MUTCD* (2009) | NCHRP 500 – Volume 9 (2004) | Traffic Engineering Handbook (2009) |
| Pgs. V-22-V-23, Sect. on Strategy 3.1 B8: Improve Roadway Delineation (T) | Pgs. 55-56, Sect. on *Control of Distribution Above Maximum Candlepower* | Pgs. 140-143, Sects. on *Illumination & Miscellaneous Improvements* |

luminaire will be determined on a case-by-case basis. Factors at the site, including the ambient level of nighttime illumination, need to be considered. The maximum level of illumination is related to the level of lighting on the roadway approaches. The level of illumination should be sufficient to alert drivers to the crossing ahead and to any railroad equipment occupying the crossing, but should not be so bright as to create a blinding effect for motorists in the area immediately beyond the crossing. Cutoffs will normally be used on luminaires to minimize this blinding effect.

Luminaires should illuminate an area along the track that is 50 percent wider than the traveled width of the road. The illumination should cover a distance equal to the normal height of rail equipment (at least 15 ft above the top of the rail).

Poles holding luminaires should be located so that they can be maintained from the roadway right-of-way.

Mather (1991) states that it was difficult to convince highway authorities and electrical companies that the luminaires should be aligned toward the railroad tracks instead of the roadway. However, through meetings and demonstrations, all parties eventually agreed that the luminaires were more effective if they were aligned toward the track. Light readings taken at all tracks showed that a higher percentage of the installations complied with the 10.76 lux (1 fc) standard for illumination where the luminaires faced the railroad tracks. Mather provided the following specifications for the installations. For single-track crossings, poles were located 25 ft from both the road and the centerline of the railroad track. Two-hundred-watt, high-pressure sodium luminaires were placed at least 30 ft above the top of the rail on 6- to 16-ft long arms. If a railroad signal system was involved, full cutoff luminaires were used. For multiple-track crossings, 400-watt, high-pressure sodium luminaires were placed at least 40 ft above the top of the rail. If a considerable distance separated the tracks, it was desirable to install a luminaire between the tracks. Semicutoff luminaires were used because they spread the light over a larger area of the crossing. This treatment was needed at crossings with three or more tracks, and those with severe angles of intersection.

## APPENDIX A

# Supplemental Technical Notes

## Aging And Driver Capabilities

Many aspects of sensory and cognitive function needed to drive safely deteriorate in later adulthood. In fact, recent data indicate that aging adults are in the highest risk category for crashes when figures are based on crashes per number of miles driven. Among the senses, the importance of vision is paramount. To respond appropriately to all manner of stimuli in the roadway environment, a driver must first detect and recognize physical features of the roadway, traffic control devices, other vehicles, non-motorized users, and a wide variety of other objects and potential hazards of a static and dynamic nature. On rare occasions, critical information concerning the presence or position of traffic is conveyed to a road user solely through an auditory signal; in the vast majority of cases, however, the visual system is preeminent at this (input) stage of processing.

Age-related changes in the lens of the eye, combined with pathology (for example, glaucoma, cataracts, diabetic retinopathy, and macular degeneration), result in the diminished capabilities that are described below.

### Reductions in Acuity

This is the ability needed to discriminate high contrast features; it is necessary for reading information on road signs. Visual acuity of 20/40 with or without corrective lenses for both eyes or one blind eye is the predominant minimum standard for driver licensing for passenger car drivers throughout the U.S. However, there are an increasing number of states (including Pennsylvania, Maryland, New Jersey, Florida, Illinois, and others) that will grant a restricted license to low-vision drivers with acuities as poor as 20/70 to 20/100. Restrictions may include daytime only, area, and speed limitations. Added to reductions in acuity, aging is also associated with yellowing of the eyes' lenses and increased density (or thickening). This affects the way color is perceived and also reduces the amount of light that reaches the retina, which makes seeing in low light conditions more difficult.

### Reductions in Contrast Sensitivity

This is the ability needed to detect low-contrast features; it is necessary to see worn lane lines, detect (non retroreflectorized) curbs and median boundaries, and see other road users at dusk. Some people have 20/20 acuity but still have "cloudy" or washed-out vision. Contrast sensitivity makes it possible to distinguish an object from its background. It begins to decline after about age 40, as a result of normal aging. Individuals age 61+ have an increasing risk for the development of cataracts and other sight-threatening or visually disabling eye conditions that reduce contrast sensitivity. Many people with reductions in contrast sensitivity are not aware that their vision is impaired, and contrast sensitivity is not a standard test in most DMVs for licensing.

## Reductions in Visual Field

This is the ability to see objects in the periphery; it is necessary for detecting signs, signals, vehicles, pedestrians, cyclists, etc., outside of a limited field of view directly ahead. A limitation in visual field size is a physiological limitation—the person's visual system is not capable of detecting a stimulus outside of his or her visual field.

## Restrictions in the Area of Visual Attention

This is the ability to see potential conflicts in the periphery, and to discriminate relevant from irrelevant information; it is necessary for responding quickly and appropriately to a constantly changing traffic scene. Sometimes termed "useful field of view," "functional field of view," or "attentional window," this refers to a subset of the total field of view. Restrictions in the area of visual attention can lead to "looked but didn't see" crashes, where stimuli can be detected, but cannot be recognized and understood sufficiently to permit a timely driver response. As such, this term represents a limitation at the attentional stage of visual information processing, rather than a physiological limitation.

## Increased Sensitivity to Glare

This refers to the ability to see in the presence of oncoming headlights, at night, or in the presence of sun glare in daytime. Glare introduces stray light into the eye; it reduces the contrast of important safety targets.

## Slower Dark Adaptation

This is the ability needed to see targets when moving from areas of light to dark, which may occur at highway interchanges or moving from commercialized areas to non-commercialized areas.

## Decreased Motion Sensitivity

This ability is needed to accurately estimate closing speeds and distances; it is necessary, for example, for judging gaps to safely perform left turns at intersections with oncoming traffic, to cross an intersecting traffic stream from a minor road or driveway, or to merge with traffic.

## Hearing Sensitivity

While driving is primarily a visual task, sounds sometimes give drivers the first awareness that a problem or condition demanding a timely driver response exists, including not only emergency sounds such as sirens, but also sounds that signify problems with brakes, tires, or other mechanical problems. In addition, it is to be expected that hearing will play an increasingly important role in the future, as new technologies are introduced in vehicles to provide aging drivers with navigational assistance or early warning of hazards. Pedestrians with visual impairments, regardless of age, also depend on auditory cues to detect approaching traffic at intersections, and rely on auditory signals at crosswalks if they are present. A decreased sensitivity to sound, particularly at higher frequencies, accompanies normal aging.

Compounding the varied age-related deficits in visual performance that are a part of normal aging, an overall slowing of mental processes occurs as individuals continue to age into their seventies and beyond. Declines have been demonstrated in a number of specific mental activities that are related to driver and pedestrian safety, such as attentional, decisional, and response-selection functions. These are described below.

### Selective Attention

This refers to the ability to filter out less critical information and continuously re-focus on the most critical information (for example, detecting a lane-use restricted message on an approach to a busy intersection; detecting a pedestrian crossing while watching oncoming traffic to locate a safe gap).

### Divided Attention

This refers to the ability to perform multiple tasks simultaneously and process information from multiple sources (for example, lane-keeping, reading signs, noticing traffic signals and changing phases, while maintaining a safe headway with other traffic during an intersection approach).

### Perception-Reaction Time

This is the time required to make a decision about what response is appropriate for specific highway design elements and traffic conditions, and then make a vehicle control movement such as steering and/or braking. As the overall speed of mental processing of information slows with aging, PRT increases. As the complexity of the driving situation increases, PRT increases disproportionately for aging motorists.

### Working Memory

This refers to the ability to store, manipulate, and retrieve information for later use while driving (e.g., carrying out a series of navigational instructions while negotiating in heavy traffic; or remembering, integrating, and understanding successive phases of a changeable message sign).

Finally, it has been well established that physical capabilities decline as a function of age and also as a function of general health. Aging (as well as disease and disuse) brings about changes in the components and structure of the cartilage near the joints, underlying bones, ligaments and muscles. These changes impair the ability of the musculoskeletal system to perform driving acts. The physical capabilities (motor functions) needed for safe and effective vehicle control are described below.

### Limb Strength, Flexibility, Sensitivity, and/or Range of Motion

These abilities are needed to quickly shift (the right foot) from accelerator to brake pedal when the situation demands, to apply correct pressure for appropriate speed control, and for arm movements to safely maneuver the car around obstacles.

## Head/Neck and Trunk Flexibility

A key ability of a driver is to rapidly glance in each direction from which a vehicle conflict may be expected in a given situation; this includes the familiar “left-right-left” check before crossing an intersection, as well as looking over one’s shoulder before merging with traffic or changing lanes.

## APPENDIX B

# Photograph and Image Credits

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| 1 | Elements included for each Handbook treatment | Debbie Murillo, Texas A&M Transportation Institute |
| 2 | Percentage of crashes involving drivers and pedestrians by age at intersections (Hauer, 1988). | Ezra Hauer, TRB Special Report 218 (1988) |
| 3 | Example 90° angle of intersection. | Debbie Murillo, Texas A&M Transportation Institute |
| 4 | Example 75° angle of intersection. | Debbie Murillo, Texas A&M Transportation Institute |
| 5 | Skewed signalized intersection with prohibition of right turn on red | Debbie Murillo, Texas A&M Transportation Institute |
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| 10 | Pedestrian Crossing Island (or Refuge Area) | Debbie Murillo, Texas A&M Transportation Institute |
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| 12 | Comparison of curb radii | Debbie Murillo, Texas A&M Transportation Institute |
| 13 | MUTCD R10-12 sign adjacent to left-turn signal face. | Marcus Brewer, Texas A&M Transportation Institute |

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| 14 | (MUTCD R10-31P) | Federal Highway Administration, *Manual on Uniform Traffic Control Devices for Streets and Highways*, 2009 Edition. |
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| 16 | Skewed signalized intersection with prohibition of right turn on red | Debbie Murillo, Texas A&M Transportation Institute |
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| 18 | (MUTCD D3-1) | Federal Highway Administration, *Manual on Uniform Traffic Control Devices for Streets and Highways*, 2009 Edition. |
| 19 | Intersection Warning W2-1 Sign and W16-8P Supplemental Advance Street Name Plaque | Federal Highway Administration, *Manual on Uniform Traffic Control Devices for Streets and Highways*, 2009 Edition. |
| 20 | (MUTCD D3-2) | Federal Highway Administration, *Manual on Uniform Traffic Control Devices for Streets and Highways*, 2009 Edition. |
| 21 | (MUTCD W4-4P) | Federal Highway Administration, *Manual on Uniform Traffic Control Devices for Streets and Highways*, 2009 Edition. |
| 22 | (MUTCD W3-1) | Federal Highway Administration, *Manual on Uniform Traffic Control Devices for Streets and Highways*, 2009 Edition. |
| 23 | Mast-arm mounted lane-use control signs | Alan Pate, Battelle |
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| 27 | Recommended placement of MUTCD R10-15 sign. | Debbie Murillo, Texas A&M Transportation Institute |
| 28 | Countdown pedestrian signal | David Harkey, Highway Safety Resource Center, University of North Carolina |
| 29 | Key geometric design elements and traffic control devices for roundabouts | Debbie Murillo, Texas A&M Transportation Institute |

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| 33 | Right-Turn Channelization Design | Debbie Murillo, Texas A&M Transportation Institute |
| 34 | Combination Lane Use/Destination Guide Sign (MUTCD D15-1). | Federal Highway Administration, *Manual on Uniform Traffic Control Devices for Streets and Highways*, 2009 Edition. |
| 35 | Example of one signal head per lane | Marcus Brewer, Texas A&M Transportation Institute |
| 36 | High-visibility ("ladder") crosswalk | Kay Fitzpatrick, Texas A&M Transportation Institute |
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| 39 | Diagram of Restricted Crossing U-Turn Intersection | Debbie Murillo, Texas A&M Transportation Institute |
| 40 | (MUTCD R10-32P) | Federal Highway Administration, *Manual on Uniform Traffic Control Devices for Streets and Highways*, 2009 Edition. |
| 41 | Typical arrangements of signal faces with flashing yellow arrow indications for permissive left-turn movements | Flashing Yellow Arrow information page, City of Bryan website, Bryan, Texas (2014) www.bryantx.gov |
| 42 | Example Overhead Arrow-per-Lane Sign. | Federal Highway Administration, *Manual on Uniform Traffic Control Devices for Streets and Highways*, 2009 Edition. |
| 43 | (MUTCD D13-3) | Federal Highway Administration, *Manual on Uniform Traffic Control Devices for Streets and Highways*, 2009 Edition. |
| 44 | Recommended signs and markings for adjacent entrance/exit ramps at a crossroad intersection | Debbie Murillo, Texas A&M Transportation Institute |
| 45 | Advance ground-mounted diagrammatic sign. | David Harkey, Highway Safety Resource Center, University of North Carolina |
| 46 | Recommended raised pavement markers and post-mounted delineators at an exit gore | Debbie Murillo, Texas A&M Transportation Institute |

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| 49 | Recommended signing for restricted movements on an exit ramp | Debbie Murillo, Texas A&M Transportation Institute |
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| 51 | White edge lines, centerline RPMs, and chevrons on a horizontal curve | Adam Pike, Texas A&M Transportation Institute |
| 52 | (MUTCD W7-6 and W13-1P). | Federal Highway Administration, *Manual on Uniform Traffic Control Devices for Streets and Highways*, 2009 Edition. |
| 53 | (MUTCD W3-4 and W16-13). | Federal Highway Administration, *Manual on Uniform Traffic Control Devices for Streets and Highways*, 2009 Edition. |
| 54 | (MUTCD W14-3) | Federal Highway Administration, *Manual on Uniform Traffic Control Devices for Streets and Highways*, 2009 Edition. |
| 55 | Lane Control Signal (adapted from Ullman et al. 1996) | Ullman, G.L., Parma, K.D., Peoples, M.D., Trout, N.D., and Tallamraju, S.S. *Visibility, Spacing, and Operation of Freeway Lane Control Signals*. (1996) |
| 56 | Dotted Lane Line Markings at Freeway Lane Drop | Marcus Brewer, Texas A&M Transportation Institute |
| 57 | Contrast Markings on Light Colored Pavement | Marcus Brewer, Texas A&M Transportation Institute |
| 58 | Curve Warning Markings | Marcus Brewer/Debbie Murillo, Texas A&M Transportation Institute |
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| 66 | Traffic cone for nighttime work zone operations. | Debbie Murillo, Texas A&M Transportation Institute |
| 67 | Temporary work zone sign with increased letter height. | Caltrans, Office of Signs, Markings and California MUTCD. *Challenge Area: CA-14 — Improve Work Zone Safety*. (2012) |
| 68 | Recommended placement of post-mounted delineators | Debbie Murillo, Texas A&M Transportation Institute |
| 69 | Turning Path Taken by Left-Turning Vehicles (from Staplin et al., 1997). | Staplin, L., Harkey, D., Lococo, K., and Tarawneh, M. *Intersection Geometric Design and Operational Guidelines for Older Drivers and Pedestrians, Volume I: Final Report*. (1997) |
| 70 | Intersection Geometries Examined in a Field Study of Right-Turn Channelization (Staplin et al., 1997). | Staplin, L., Harkey, D., Lococo, K., and Tarawneh, M. *Intersection Geometric Design and Operational Guidelines for Older Drivers and Pedestrians, Volume I: Final Report*. (1997) |
| 71 | Sight Distance for Left and Right Turns for Passenger Car Drivers at Yield-Control Intersections (Harwood et al., 1993). | Harwood, D.W., Mason, J.W., Jr., Pietrucha, M.T., Brydia, R.E., Hostetter, R.S., and Gittings, G.L. *Intersection Sight Distance*. (1993) |
| 72 | Spatial relationships that determine available sight distance | McCoy, P.T., Navarro, U.R., and Witt, W.E. "Guidelines for Offsetting Opposing Left-Turn Lanes on Four-Lane Divided Roadways." *Transportation Research Record 1356*. (1992) |
| 73 | Comparison of Required Intersection Sight Distance Values from the Modified AASHTO Model (with J = 2.5 S) and the Gap Acceptance Model (with Gap Values of 5.5 S, 7.0, 7.5 S, and 8.0 S). | Staplin, L., Harkey, D., Lococo, K., and Tarawneh, M. *Intersection Geometric Design and Operational Guidelines for Older Drivers and Pedestrians, Volume I: Final Report*. (1997) |
| 74 | Alignment of Left-Turn Lanes for Negative and Positive Offset | David Harkey, Highway Safety Resource Center, University of North Carolina |
| 75 | Alternative Left-Turn Treatments for Rural and Suburban Divided Highways | Bonneson, J.A., McCoy, P.T., and Truby, J.E. "Safety Improvements at Intersections on Rural Expressways: A Survey of State Departments of Transportation." *Transportation Research Record 1385*. (1993) |
| 76 | Sight Distance Restrictions for a Positioned and Unpositioned Left-Turning Driver at an Aligned Intersection with an Opposing Left-Turning Vehicle. | Staplin, L., Harkey, D., Lococo, K., and Tarawneh, M. *Intersection Geometric Design and Operational Guidelines for Older Drivers and Pedestrians, Volume I: Final Report*. (1997) |
| 77 | Left-Turn Lane Offset Design Values Necessary to Achieve Unrestricted Sight Distances Calculated with Either the Modified AASHTO Model (J = 2.5 s) or the Gap Acceptance Model (G = 8.0 s). | Staplin, L., Harkey, D., Lococo, K., and Tarawneh, M. *Intersection Geometric Design and Operational Guidelines for Older Drivers and Pedestrians, Volume I: Final Report*. (1997) |

| Figure # | Caption | Credit |
|---|---|---|
| 78 | Alternative Curb Radii Evaluated in Laboratory Preference Study of Intersection Geometries | Staplin, L., Harkey, D., Lococo, K., and Tarawneh, M. *Intersection Geometric Design and Operational Guidelines for Older Drivers and Pedestrians, Volume I: Final Report*. (1997) |
| 79 | Novel Sign Tested as a Countermeasure to Reduce RTOR Violations and Pedestrian Conflicts | Zegeer, C.V. and Cynecki, M.J. "Evaluation of Countermeasures Related to RTOR Accidents that Involve Pedestrians." *Transportation Research Record 1059*. (1986) |
| 80 | Recommended Wording For Educational Placards For One-Stage And Two-Stage Crossings | Knoblauch, R., Nitzburg, M., Dewar, R., Templer, A. and Pietrucha, M. *Older Pedestrian Characteristics for Use in Highway Design*. (1995) |
| 81 | One Way and Chevron Sign Combination Used in Central Island of Roundabout | Jacquemart, G. Synthesis of Highway Practice 264: Synthesis of Roundabout Practice in the United States. (1998) |
| 82 | Roundabout Advance Warning Sign Recommended by Lord et al | Lord, D., Van Schalwyk, L., Chrysler, S., and Staplin, L. "A Strategy to Reduce Older Driver Injuries at Intersections Using More Accommodating Roundabout Design Practices." *Accident Analysis and Prevention*, 39(3), pp 427-432. (2007) |
| 83 | Lane Control Sign Recommended by Lord et al | Lord, D., Van Schalwyk, L., Chrysler, S., and Staplin, L. "A Strategy to Reduce Older Driver Injuries at Intersections Using More Accommodating Roundabout Design Practices." *Accident Analysis and Prevention*, 39(3), pp 427-432. (2007) |
| 84 | Roundabout Sign Recommended by Lord et al | Lord, D., Van Schalwyk, L., Chrysler, S., and Staplin, L. "A Strategy to Reduce Older Driver Injuries at Intersections Using More Accommodating Roundabout Design Practices." *Accident Analysis and Prevention*, 39(3), pp 427-432. (2007) |
| 85 | Yield Sign Treatment Recommended by Lord et al | Lord, D., Van Schalwyk, L., Chrysler, S., and Staplin, L. "A Strategy to Reduce Older Driver Injuries at Intersections Using More Accommodating Roundabout Design Practices." *Accident Analysis and Prevention*, 39(3), pp 427-432. (2007) |
| 86 | Exit Treatment Recommended by Lord et al | Lord, D., Van Schalwyk, L., Chrysler, S., and Staplin, L. "A Strategy to Reduce Older Driver Injuries at Intersections Using More Accommodating Roundabout Design Practices." *Accident Analysis and Prevention*, 39(3), pp 427-432. (2007) |

| Figure # | Caption | Credit |
|---|---|---|
| 87 | Example of continental crosswalk markings | K. Fitzpatrick, S.T. Chrysler, V. Iragavarapu, E. Park. (2010) *Crosswalk Marking Field Visibility Study*. Research Report. FHWA-HRT-10-068. Federal Highway Administration, Washington, DC. |
| 88 | Example of bar pairs crosswalk markings | K. Fitzpatrick, S.T. Chrysler, V. Iragavarapu, E. Park. (2010) *Crosswalk Marking Field Visibility Study*. Research Report. FHWA-HRT-10-068. Federal Highway Administration, Washington, DC. |
| 89 | Diagram of Median U-Turn Intersection | Debbie Murillo, Texas A&M Transportation Institute |
| 90 | Diagram of Restricted Crossing U-Turn Intersection | Debbie Murillo, Texas A&M Transportation Institute |
| 91 | Supplemental Plaque Used with Extended Crossing Time Feature for APS | Federal Highway Administration, *Manual on Uniform Traffic Control Devices for Streets and Highways*, 2009 Edition. |
| 92 | Example of MUTCD diagrammatic sign (a) and modified diagrammatic sign (b) used in comprehension evaluation | Brackett, Q., Huchingson, R.D., Trout, N.D., and Womack, K. "Study of Urban Guide Sign Deficiencies." *Transportation Research Record 1368*. (1992) |
| 93 | Ground-Mounted Diagrammatic Guide Sign for Urban Multilane Arterial, Used by Zwahlen et al | Zwahlen, Helmut T., Russ, Andrew, Roth, James M., and Schnell, Thomas. (2003) "Evaluation of the Effectiveness of Ground Mounted Diagrammatic Advance Guide Signs For Freeway Entrance Ramps", Paper No. 03-3315, presented at the 82nd Annual Transportation Research Board Meeting, National Academy of Sciences, Washington, DC. |
| 94 | Pixel layout of LCD Heads employed in research conducted by Ullman et al. | Ullman, G.L., Parma, K.D., Peoples, M.D., Trout, N.D., and Tallamraju, S.S. *Visibility, Spacing, and Operation of Freeway Lane Control Signals*. (1996) |
| 95 | Current (left) and proposed modified (right) temporary work zone sign in California. | Caltrans, Office of Signs, Markings and California MUTCD. *Challenge Area: CA-14 — Improve Work Zone Safety*. (2012) |
| 96 | Experimental Enhanced Crossbuck Sign, Referred to as the "Buckeye Crossbuck" or "Conrail Shield". | Russell, E.R. and Kent, W. *Highway-Rail Crossing Safety Demonstrations*. (1993). |
| 97 | Standard MUTCD W10-3 Sign and Alternative Sign Designs Evaluated by Picha, Hawkins, and Womack | Picha, D.L., Hawkins, H.G., and Womack, K.N. *Motorist Understanding of Alternative Designs for Traffic Signs*. (1995) |

# APPENDIX C
# Glossary

**AAAFTS.** American Automobile Association Foundation for Traffic Safety.

**AADT.** Annual Average Daily Traffic.

**AASHTO.** American Association of State and Highway Transportation Officials.

**Ambient conditions.** The visual background or surrounding atmospheric and visibility conditions.

**Angular motion sensitivity.** The ability of an observer to detect changes in the apparent distance and direction of movement of an object as a function of the change in the angular size of the visual stimulus on the observer's retina.

**Angular velocity threshold.** The rate of change in angular size of a visual stimulus that is necessary for an observer to discern that an object's motion has increased or decreased.

**Annual average daily traffic (AADT).** The total volume passing a point or segment of a highway facility in both directions for 1 year divided by the number of days in the year.

**Apron.** The mountable portion of the central island of a roundabout that is adjacent to the circulatory roadway. An apron is generally required on smaller roundabouts to accommodate the wheel tracking of large vehicles.

**ASTM.** American Society for Testing and Materials.

**ATSSA.** American Traffic Safety Services Association.

**Attraction signing.** Information/supplemental signs featuring logos or verbal messages pointing out places to visit or food, gas, and rest stop locations.

**Barnes Dance timing.** Type of exclusive signal timing phase where pedestrians may also cross diagonally in addition to crossing either street. Also referred to as scramble timing.

**Brake reaction time.** The interval between the instant that the driver recognizes the presence of an object or hazard on the roadway ahead and the instant that the driver actually applies the brakes.

**Brightness.** A term that refers to human perception of luminance. Whereas luminance is a photometrically measured quantity, brightness describes how intense a light source or lighted surface appears to the human eye.

**Buttonhook ramp.** J-shaped ramp that connects to a parallel or diagonal street or frontage road, which is often well removed from the interchange structure and other ramps.

**Candela (cd).** A measure of luminous intensity.

**Central island.** The raised area in the center of a roundabout around which traffic circulates.

**Changeable message sign (CMS).** Sometimes called portable changeable or variable message sign. This traffic control device has the flexibility to display a variety of messages to fit the needs of the traffic and highway situation.

**Channelization.** The separation or regulation of conflicting traffic movement into definite paths of travel by the use of pavement markings, raised islands, or other suitable means, to facilitate the safe and orderly movement of both vehicles and pedestrians.

**Chevron signs.** A chevron symbol (sideways "V") in black, against standard yellow background, on a vertical rectangle. Used as an alternate or supplement to standard delineators and to large arrow signs.

**CIE.** Commission Internationale de l'Éclairage (International Commission on Street/ Highway Lighting).

**Circulatory roadway.** The curved path used by vehicles to travel in a counterclockwise fashion around the central island of a roundabout.

**Circulatory roadway width.** The width between the outer edge of the circulatory roadway and the central island, not including the width of any apron.

**Cloverleaf interchange.** A form of interchange that provides indirect right-turn movements in all four quadrants by means of loops. Generally used where the turning and weaving volumes are relatively low. This type of interchange eliminates all crossing conflicts found in a diamond interchange but requires more area. The cloverleaf type of interchange can have one or two points of entry and exit on each through roadway.

**Coefficient of luminous intensity ($R_I$).** The ratio of the luminous intensity (I) of a retroreflectometer in the direction of observation to the illuminance E at the retroreflectometer on a plane perpendicular to the direction of the incident light, expressed in candelas per lux.

**Coefficient of retroreflected luminance ($R_L$).** A measure of retroreflection most often used to describe the retroreflectivity of pavement markings. Coefficient of retroreflected luminance is defined as the coefficient of luminous intensity per unit area.

**Coefficient of retroreflection ($R_A$).** A measure of retroreflection used more often to refer to the retroreflectivity of highway signs. Coefficient of retroreflection is defined as the ratio of the coefficient of luminous intensity ($R_I$) of a plane retroreflecting surface to its area (A), expressed in candelas per lux per square meter.

**Complete interchange lighting (CIL).** Includes lighting in the interchange area on both the acceleration and deceleration areas plus the ramps through the terminus.

**Composite photometry.** Light measurement applied to a high-mast lighting system that employs a counterbeam arrangement, to take advantage of the efficiency with which pavement luminance can be increased with light directed upstream, while enhancing positive contrast through additivity of vehicle headlighting with the light directed downstream.

**Concrete safety-shaped barrier (CSSB).** A tapered concrete barrier used as a highway divider in narrow medians to prevent vehicle crossovers into oncoming traffic. It is referred to as a Jersey Barrier in some jurisdictions, as its first application was on the New Jersey Turnpike. CSSB's can be either permanent barriers or temporary portable barriers used in work zone applications.

**Conspicuity.** A measure of the likelihood that a driver will notice a certain target at a given distance against a certain background.

**Contrast.** See luminance contrast.

**Contrast sensitivity.** Ability to perceive a lightness or brightness difference between two areas. Frequently measured for a range of target patterns differing in value along some dimension such as pattern element size and portrayed graphically in a contrast sensitivity function in which the reciprocal of contrast threshold is plotted against pattern spatial frequency or against visual angle subtended at the eye by pattern elements (such as bars).

**Critical gap.** The gap (distance to nearest vehicle) in oncoming or cross traffic that a driver will accept to initiate a turning or crossing maneuver 50 percent of the time it is presented, typically measured in seconds.

**Crossbuck.** White X-shaped retroreflectorized highway-rail grade crossing sign with the words RAILROAD CROSSING in black lettering, located alongside the highway at the railroad tracks. At multiple track crossings a sign indicating the number of tracks will be on the post of the Crossbuck.

**Cutoff.** A luminaire light distribution is designed as cutoff when the candlepower per 1,000 lamp lumens does not numerically exceed 25 (2.5 percent) at an angle of 90 degrees above nadir (horizontal); and 100 (10 percent) at a vertical angle of 80 degrees above nadir. This applies to any lateral angle around the luminaire.

**Dark adaptation.** Adjustment of the eye to low levels of illumination, which results in increased sensitivity to light.

**Decision sight distance (DSD).** The distance required for a driver to detect an unexpected or otherwise difficult-to-perceive information source or hazard in a roadway environment that may be visually cluttered, recognize the hazard or its threat potential, select an appropriate speed and path, and initiate and complete the required safety maneuver safely and efficiently.

**Deflection.** The change in trajectory of a vehicle imposed by geometric features of the roadway.

**Depth perception.** The ability to distinguish the relative distance of objects in visual space, used to interpret their motion over multiple observations.

**Diamond interchange.** The simplest and perhaps most common type of interchange. This type of interchange contains a one-way diagonal-type ramp in one or more of the quadrants. The diamond interchange provides for all movements to and from the intersecting road.

**Diverge steering (DS) zone.** Used with interchange/ramp exit models, it is the distance upstream from the exit gore at which a driver begins to diverge from the freeway.

**Divided attention.** The ability of a driver to allocate attention among tasks or stimuli in the roadway environment, where more than one task or stimulus is perceived to be important to safe performance at a given time.

**Divided highway.** Roadway that is separated by a median.

**Downstream.** The direction toward which traffic is flowing.

**Dynamic visual acuity.** Acuteness or clarity of vision for an object that has angular movement relative to the observer. Acuity depends on sharpness of retinal focus, sensitivity of nervous elements, oculomotor coordination, interpretative faculty of the brain, and contextual variables.

**Edgeline visibility.** The detection/recognition of painted pavement surface delineation along roadway edges demarcating the outside edge of the travel lane.

**Entry width.** The width of the entry to a roundabout, where it meets the inscribed circle, measured perpendicularly from the right edge of the entry to the intersection point of the left edge line and the inscribed circle.

**Exit gore area.** The area located immediately between the left edge of a ramp pavement and the right edge of the mainline roadway pavement at a merge or diverge area.

**Flared approach.** The widening of an approach at a roundabout, resulting in multiple lanes at entry to provide additional capacity at the yield line and storage.

**FARS.** Fatal Analysis Reporting System.

**FHWA.** Federal Highway Administration.

**Footcandle.** The English system's unit of illuminance. One footcandle is the illuminance on a surface that is everywhere one foot from a uniform point source of light of one candle and equal to one lumen per square foot. One footcandle equals 10.76 lux.

**Footlambert.** A unit of luminance equivalent to 1 lumen per square foot.

**Full diamond interchange.** Interchange with a one-way diagonal-type ramp in each quadrant.

**Gap acceptance.** The decision by a driver that there is sufficient time and/or distance ahead of an approaching vehicle to allow safe performance of a desired crossing or merging maneuver.

**Gap judgments.** The judgment of a driver of the time and/or distance ahead of an approaching vehicle traveling in a lane that the driver wishes to turn across or merge into.

**Gap search and acceptance (GSA) zone.** Used with interchange/ramp entry models, it is the zone in which the driver searches, evaluates, and accepts or rejects the available lags or gaps in the traffic stream for execution of a merging maneuver.

**Guard (guide) rail.** Protective barrier along a roadway to prevent vehicles from leaving the roadway.

**Half-diamond interchange.** An interchange with a one-way diagonal-type ramp in two adjacent quadrants. This type of interchange is appropriate to situations in which traffic demand is predominantly in one direction.

**High-mast lighting.** Illumination of a large area by means of a cluster of 3 to 12 luminaires which are designed to be mounted in fixed orientation at the top of a high mast (generally 18 to 46+ m [80 to 150+ ft] or higher).

**High-spatial-frequency stimulus.** A visual target characterized by fine detail.

**Highway-rail grade crossing.** The general area where a highway and a railroad's right-of-way cross at the same level, including the railroad tracks, highway, and traffic control devices for highway traffic traversing the area.

**Horizontal alignment.** The linear (tangent) character or specific degree of curvature describing the geometry of a defined section of highway in plain view.

**IIHS.** Insurance Institute for Highway Safety.

**Illuminance.** The density of luminous flux (rate of emission of luminous energy flow of a light source in all directions) incident on a surface; the quotient of the flux divided by the area of the surface, when the surface is uniformly illuminated.

**Illumination.** The amount of light falling onto a surface.

**Initial acceleration (IA) zone.** Used with interchange/ramp entry models, it is the zone in which the driver accelerates to reduce the speed differential between the ramp vehicle and the freeway vehicles to an acceptable level for completing the merge process.

**Inscribed circle diameter.** The basic parameter used to define the size of a roundabout, measured between the outer edges of the circulatory roadway. It is the diameter of the largest circle that can be inscribed within the outline of the intersection.

**In-service brightness level (ISBL).** The brightness level of a delineation treatment at an intermediate point in its anticipated service life; this value varies by type of delineator, type of wear (traffic level), and environmental conditions.

**Interchange (grade separation).** A system of interconnecting roadways that provides for the movement of traffic between two or more highways on different levels.

**Intersecting angle (skew).** The angle formed by the intersection of two roadways (other than a 90-degree angle).

**Intersection (at grade).** The general area where two or more highways join or cross without grade separation, including the roadway and roadside facilities for traffic movements within it.

**Intersection sight distance (ISD).** The unobstructed view of an entire (at-grade) intersection and sufficient lengths of the intersecting highway to permit control of the vehicle to avoid collisions during through and turning movements.

**ISTEA.** Intermodal Surface Transportation Efficiency Act.

**TEH.** Institute of Transportation Engineers.

**Joint flexibility.** An aspect of the physical condition of the driver that can be assessed to determine whether the driver has sufficient strength to turn the steering wheel, apply the brakes, and generally control the vehicle.

**Lane control signals.** Special overhead signals that permit or prohibit the use of specific lanes of a street or highway or that indicate the impending prohibition of their use.

**Leading pedestrian interval (LPI).** Also known as, "pedestrian head start," and "delayed vehicle green," an LPI allows pedestrians to begin crossing an intersection a few seconds before the vehicular green interval begins. This allows pedestrians to establish their presence in the crosswalk before the turning vehicles, thereby enhancing the pedestrian right of way.

**Legibility index (LI).** Used to describe the relative legibility of different letter styles, it is calculated from the distance at which a character, word, or message is legible divided by the size of the letters on the sign.

**Limited sight distance.** A restricted preview of the traveled way downstream due to a crest vertical curve or horizontal curvature of the roadway, or to blockage or obstruction by a natural or manmade roadway feature or by (an)other vehicle(s).

**Luminaire.** A complete lighting unit consisting of a lamp or lamps together with the parts designed to distribute the light, to position and protect the lamps, and to connect the lamps to the power supply.

**Luminance.** The luminous intensity or brightness of any surface in a given direction, per unit of projected area of the surface as viewed from that direction, independent of viewing distance. The SI unit is the candela per square meter.

**Luminance contrast.** The difference between the luminance of a target area and a surrounding background area, divided by the background luminance alone (e.g., lane marking minus lane pavement surface, divided by pavement surface.)

**Lux.** The metric unit of illuminance. One lux is equal to the illuminance corresponding to a luminous flux density of one lumen per square meter.

**Measures of effectiveness (MOE's).** Descriptions of driver or traffic behavior which quantify the level of safety or the quality of service provided by a facility or treatment to drivers, passengers, or pedestrians; examples include vehicle speed, trajectory, delay, and similar measures, especially crashes, plus indices of performance such as reaction time. In research studies, the MOE's are the dependent measures (e.g., the effects/behaviors resulting from introduction of a treatment or countermeasure).

**Median barriers.** A longitudinal system of physical barriers used to prevent an errant vehicle from crossing the portion of a divided highway separating traffic moving in opposite directions.

**Merge steering control (MSC) zone.** Used with interchange/ramp entry models, it is the zone in which the driver enters the freeway and positions the vehicle in the nearest lane on the mainline.

**Minimum required visibility distance (MRVD).** The distance necessary to permit detection and comprehension, plus driver decision-making, response selection, and completion of a vehicle maneuver, if necessary.

**Mountable.** Geometric features (e.g., curbs) that can be driven upon by vehicles without damage, but not intended to be in the normal path of traffic.

**MUTCD.** *Manual on Uniform Traffic Control Devices for Streets and Highways*.

**NCHRP.** National Cooperative Highway Research Program.

**Nearside priority.** Priority given to drivers entering the circle of a roundabout.

**Negative offset.** A term used to describe the alignment of opposing left-turn lanes at an intersection; this geometry exists when the left boundary of one left-turn lane, when extended across the intersection, falls to the right of the right-facing boundary of the opposite left-turn lane.

**NHTSA.** National Highway Traffic Safety Administration.

**Non-cutoff.** The luminaire light distribution category when there is no candlepower limitation in the zone above maximum candlepower.

**No turn on red (NTOR).** This message on signs is used to indicate that a right turn on red (or left turn on red for one-way streets) is not permitted at an intersection.

**NTSB.** National Transportation Safety Board.

**Ocular media.** The internal structure of the eye, including the aqueous, through which light entering through the cornea must be transmitted before reaching the photosensitive retina.

**Ocular transmittance.** The amount of light reaching the retina relative to the amount incident upon the cornea.

**Offside priority.** Priority given to traffic already in the circle of a roundabout.

**Osteoarthritis.** A degenerative form of arthritis.

**Parclo loop ramp.** A (partial cloverleaf) interchange with loops in advance of the minor road with direction of travel on the freeway; and in the same interchange area, an interchange with loops beyond the minor road.

**Partial interchange lighting (PIL).** Lighting on an interchange that consists of a few luminaires located in the general areas where entrance and exit ramps connect with the through traffic lanes of a freeway (between the entry gore and the end of the acceleration ramp or exit gore and the beginning of the deceleration ramp).

**Passive crossing control devices.** Non-activated traffic control devices, including signs, pavement markings, and other devices located at or in advance of crossings to indicate the presence of a crossing and the possibility of a train.

**Peak intensity.** The maximum strength of a traffic signal maintained through a defined viewing angle; measured in candelas.

**Pedestrian control device.** A special type of device (including pedestrian signal indications and sign panels) intended for the exclusive purpose of controlling pedestrian traffic in crosswalks.

**Pedestrian crosswalk.** An extension of a sidewalk across an intersection or across a roadway at a midblock location to accommodate pedestrian movement.

**Pedestrian refuge.** An at-grade opening within a median island that allows pedestrians to safely wait for an acceptable gap in traffic.

**Perception-reaction time (PRT).** The interval between a driver's detection of a target stimulus or event and the initiation of a vehicle control movement in response to the stimulus or event.

**Positive offset.** A term used to describe the alignment of opposing left-turn lanes at an intersection; this geometry exists when the left boundary of one left-turn lane, when extended across the intersection, falls to the left of the right-facing boundary of the opposite left-turn lane.

**Post-mounted delineators (PMD's).** Retroreflective devices located in a series at the side of a roadway to indicate alignment. Each delineator consists of a flat reflecting surface, typically a vertical rectangle, mounted on a supporting post.

**Raised.** Geometric features (e.g., curbs) with a sharp elevation change that are not intended to be driven upon by vehicles at any time.

**Raised pavement markers (RPM's).** Used as positioning guides and/or as supplements or substitutes for other types of markings, these markers conform to the color of the marking for which they serve as a positioning guide, can be mono- or bi-directional, and are fastened into the pavement with the reflector surface visible above the road surface.

**Reaction time (RT).** The time from the onset of a stimulus to the beginning of a driver's (or pedestrian's) response to the stimulus, by a simple movement of a limb or other body part.

**Retroreflective.** Capable of returning light to its source.

**Rheumatoid arthritis.** A usually chronic disease of unknown cause characterized by pain, stiffness, inflammation, swelling, and sometimes destruction of joints. Drivers with this condition sometimes require compensatory equipment for their vehicle. In acute conditions, individuals should not drive because of weakness and extreme tenderness in the joints of the wrists and hands.

**Right turn on red (RTOR).** Unless otherwise specified by traffic signal control signing, this practice permits a driver to proceed with a right turn on a red signal after stopping at signalized intersections. It provides increased capacity and operational efficiency at a low cost.

**Roundabouts.** Circular intersections with specific design and traffic control features that include yield control of entering traffic, channelized approaches, and appropriate geometric curvature to ensure that travel speeds on the circulating roadway are typically less than 50 km/h (30 mph).

**Route marker reassurance assembly.** Consists of a cardinal direction marker (i.e., east, west, north, and south) and a route marker.

**Saccadic movement.** A change in visual fixation from one point to another by means of a quick, abrupt movement of the eye.

**Scissors off-ramp.** A condition where one-way traffic streams cross by merging and diverging maneuvers onto exit ramps. Drivers tend to go straight ahead onto an off-ramp instead of turning left.

**Selective attention.** The ability, on an ongoing moment-to-moment basis while driving, to identify and allocate attention to the most relevant information, especially embedded when within a visually complex scene and in the presence of a number of distractors.

**Senile miosis.** An aging characteristic involving an excessive smallness or contraction of the pupil of the eye.

**Short range delineation.** Delineation that is useful to the driver for tracking the roadway at night under poor visibility conditions.

**Sight distance.** The length of highway visible to the driver.

**Sight triangle.** In plan view, the area defined by the point of intersection of two roadways, and by the driver's line of sight from the point of approach along one leg of the intersection, to the farthest unobstructed location on another leg of the intersection.

**Situational awareness.** The selective attention to and perception of environmental elements within a specified space and time envelope, the comprehension of their meaning, and the projection of their status in the near future.

**Slip ramp.** A diagonal ramp, more properly called a cross connection, which connects with a parallel frontage road.

**Small target visibility (STV).** A proposed criterion for roadway lighting. The concept assumes that increased target visibility results in both increased nighttime safety and improved nighttime driver performance, a surrogate for reduced crash risk.

**Speed-change lane (SCL).** Used in interchange/ramp exit models, it refers to the speed-change maneuver on deceleration lanes segmented components.

**Splitter island.** A raised or painted area on an approach to a roundabout used to separate entering from exiting traffic, deflect and slow entering traffic, and provide storage space for pedestrians crossing the road in two stages. It is also referred to as a median island or separator island.

**Steering control (SC) zone.** Used with interchange/ramp entry models, it is the zone where positioning of the vehicle along a path from the controlling ramp curvature onto the speed-change lane is accomplished.

**Stereopsis.** Binocular visual perception of three-dimensional space based on retinal disparity.

**Stopping sight distance (SSD).** The sight distance required to permit drivers to see an obstacle soon enough to stop for it under a defined set of reasonable worst-case conditions, without the performance of any avoidance maneuver or change in travel path; the calculation of SSD depends upon speed, gradient, road surface and tire conditions, and assumptions about the perception-reaction time of the driver.

**Temporary pavement marking treatment.** This treatment primarily involves the application of paint or tape striping and has been shown to be important for effective vehicle guidance at highway work sites.

**Threshold contrast.** The minimum difference in luminance of a target and luminance of that target's background at which the target is visible. Also defined as the luminance contrast detectable during some specific fraction of the times it is presented to an observer, usually 50 percent.

**T-intersection.** An intersection that involves three legs, where one leg is perpendicular to the other two legs. There are several types of this intersection, such as plain, with turning lanes, and channelized.

**Traffic control device (TCD).** The prime, and often the only, means of communicating with the driving public. These devices (e.g., signs, markings, signals, islands) must be used discriminately, uniformly, and effectively to ensure correct driver interpretation and response.

**Transient adaptation factor.** A reduction in target contrast caused by the process of transient visual adaptation.

**Transient visual adaptation (TVA).** The process in which the (driver's) eye fixates upon roadway locations or surrounding environments at different luminance levels, continuously adapting to higher and lower levels; this process temporarily reduces contrast sensitivity.

**TRB.** Transportation Research Board.

**Trumpet interchange.** A three-leg interchange where a connecting highway terminates and where only a small amount of traffic moves between the terminating highway and one of the two legs of the freeway. The trumpet is laid out so that this minor traffic moves via a 200-degree loop.

**Two-quadrant cloverleaf interchange.** A type of partial cloverleaf where most traffic leaving one highway turns to the same leg of the intersecting highway.

**TWLTL.** Two-way, left-turn lane.

**Two-way stop-control.** Stop signs are present on the approaches of the minor street and drivers on the minor street (or a driver turning left from the major street) must wait for a gap in the major-street traffic to complete a maneuver.

**Upstream.** The direction from which traffic is flowing.

**Useful field of view.** Also known as the "functional field of view", or "attentional window," this area refers to a subset of the total field of view where stimuli can not only be detected, but can be recognized and understood sufficiently to permit a timely driver response. As such, this term represents an aspect of visual information processing, rather than a measure of visual sensitivity.

**Variable message sign (VMS).** See changeable message sign.

**Veiling glare.** Stray light entering the eye that reduces the contrast of a target upon which the driver has fixated; this may result from the driver's direct view of light sources, such as opposing headlights or roadway luminaires, or from light reflected from surfaces near the target's location.

**Vertical curve.** The parabolic curve connecting the two approach grades on either side of a hill.

**Visual accommodation.** The process by which the eye changes focus from one distance to another

**Visual acuity.** The ability of an observer to resolve fine pattern detail. Acuity is usually specified in terms of decimal acuity, defined as the reciprocal of the smallest resolvable pattern detail in minutes of arc of visual angle. "Normal" or average acuity is considered to be 1.0 (a resolution of 1-min arc).

**Visual adaptation.** The process by which the retina becomes accustomed to more or less light than it was exposed to during an immediately preceding period. It results in a change in the sensitivity of the eye to light.

**Visual clear (VC) zone.** Used with interchange/ramp entry models, this refers to the zone that provides a buffer between the driver and the end of the acceleration lane, where the driver can either merge onto the freeway in a forced maneuver or abort the merge and begin to decelerate at a reasonable rate.

**Yield line.** A pavement marking used to mark the point of entry from an approach into the circulatory roadway of a roundabout, and is generally marked along the inscribed circle. Entering vehicles must yield to any circulating traffic coming from the left before crossing this line into the circulating roadway.

**Zebra crossing.** A crossing marked by transverse white stripes where vehicles are required to yield to pedestrians.

## Appendix D
# References

Abdulsattar, H., Tarawneh, M., and McCoy, P. (1996). "Effect on Vehicle-Pedestrian Conflicts of 'Turning Traffic Must Yield to Pedestrians' Sign." *Transportation Research Record*, 1553, pp. 38-45. Transportation Research Board: Washington, D.C.

Ackerman, P.L. (1987). "Individual Differences in Skill Learning: An Integration of Psychometric and Information Processing Perspectives." *Psychological Bulletin*, 102, pp. 3-27.

Adams, A., Wong, L., Wong, L., and Gould, B. (1988). "Visual Acuity Changes With Age: Some New Perspectives." *American Journal of Optometry and Physiological Optics*, 65, pp. 403-406.

Adrian, W.K. (1963). "Uber die Sichbarkeit von Stassenverkehrs - Signalen (On the Visibility of Traffic Signals)." *Lichttechnik*, 15(3).

Administration on Aging. (2007). A Profile of Older Americans: 2007. Available at http://www.agingcarefl.org/aging/AOA-2007profile.pdf.

Agent, K.R. (1979). *Delineation of Stop-Sign Approaches. Kentucky Department of Transportation*. Bureau of Highways, Division of Research, Report No. RR-527.

Agent, K.R. (1987). "Guidelines for the Use of Protected/Permissive Left-Turn Phasing." *Institute of Transportation Engineers Journal*, *July*, pp. 37-42. Institute of Transportation Engineers: Washington, D.C.

Agent, K.R. (1988). "Traffic Control and Accidents at Rural High-Speed Intersections." *Transportation Research Record*, 1160, pp. 14-21. Transportation Research Board: Washington, D.C.

Agent, K.R. and Deen, R.C. (1975). "Relationship Between Roadway Geometrics and Accidents." *Transportation Research Record*, 541, pp. 1-11. Transportation Research Board: Washington, D.C.

Alexander, G.J. (1989). "Search and Perception-Reaction Time at Intersections and Railroad Grade Crossings." *Institute of Transportation Engineers Journal*, 59(11), pp. 17-19. Institute of Transportation Engineers: Washington, D.C.

Alexander, G.J. and Lunenfeld, H. (1986). *Driver Expectancy in Highway Design and Traffic Operations*. Publication No. FHWA-TO-86-1. Federal Highway Administration, Washington, D.C.

Allen, R.W., O'Hanlon, J.F., and McRuer, D.T. (1977). *Driver's Visibility Requirements for Roadway Delineation, Vol I: Effects of Contrast and Configuration on Driver Performance and Behavior*. Publication No. FHWA-RD-77-165. Federal Highway Administration, Washington, D.C.

Allen, T.M. and Straub, A.L. (1955). "Sign Brightness and Legibility." *Highway Research Board Bulletin*, 127, pp. 1-14.

American Association of State Highway and Transportation Officials. (1984). *An Informational Guide for Roadway Lighting.* Washington, D.C.

American Association of State Highway and Transportation Officials. (1984). *A Policy on Geometric Design of Highways and Streets*. Washington, D.C.

American Association of State Highway and Transportation Officials. (1990). *A Policy on Geometric Design of Highways and Streets*. Washington, D.C.

American Association of State Highway and Transportation Officials. (1994). *A Policy on Geometric Design of Highways and Streets*. Washington, D.C.

American Association of State Highway and Transportation Officials. (2004). *A Policy on Geometric Design of Highways and Streets*. Washington, D.C.

American Association of State Highway and Transportation Officials. (2010). *Highway Safety Manual, Volumes 1, 2 and 3.*. Washington, D.C.

American Association of State Highway and Transportation Officials. (2011). *A Policy on Geometric Design of Highways and Streets*. Washington, D.C.

American Automobile Association Foundation for Traffic Safety. (1995). *Safety Effects Resulting From Approval of the National Highway System*. Bellomo-McGee, Inc., Vienna, VA.

American Society for Testing and Materials. (2001). *Standard Specification for Retroreflective Sheeting for Traffic Control. Designation: D 4756-01.*

Anders, T.R., Fozard, J.L., and Lillyquist, T.D. (1972). "The Effects of Age upon Retrieval from Short-Term Memory." *Developmental Psychology*, 6.

American Traffic Safety Services Association. (2012). Emerging Safety Countermeasures for Wrong-Way Driving. Washington, D.C.

American Traffic Safety Services Association. (2013). Safety Opportunities in High Friction Surfacing. Available at https://s3.amazonaws.com/media.atssa.com/default-file/1480+ATSSA+High+Friction+LoRes.pdf.

Avolio, B.J., Kroeck, K.G., and Panek, P.E. (1985). "Individual Differences in Information-Processing Ability as a Predictor of Motor Vehicle Accidents." *Human Factors*, 27, pp. 577-587. Human Factors and Ergonomics Society: Santa Monica, CA.

Bailey, I. and Sheedy, J. (1988). "Vision Screening for Driver Licensure." *Transportation in an Aging Society*, TRB Special Report 218(2), pp. 294-324. Transportation Research Board: Washington, D.C.

Bailey, S.S., Jones, S.A., Stout, R.J., Bailey, J.H., Kass, S., and Morgan, B.B. (1992). "Issues of Elderly Pedestrians." *Transportation Research Record*, 1375, pp. 68-73. Transportation Research Board: Washington, D.C.

Bali, S., Potts, R., Fee, J.A., Taylor, J.I., and Glennon, J. (1978). *Cost-Effectiveness and Safety of Alternative Roadway Delineation Treatments for Rural Two-Lane Highways. Final Report*, *Vol II*. Publication No. FHWA-RD-78-51. Federal Highway Administration, Washington, D.C.

Ball, K. and Owsley, C. (1991). "Identifying Correlates of Accident Involvement for the Older Driver." *Human Factors*, 33(5), pp. 583-595. Human Factors and Ergonomics Society: Santa Monica, CA.

Ball, K., Owsley, C., Sloane, M., Roenker, D., and Bruni, J. (1993). "Visual Attention Problems as a Predictor of Vehicle Crashes Among Older Drivers." *Investigative Ophthalmology and Visual Science*, 34, pp. 3110-3123.

Bared, J., Giering, G., and Warren, D. (1999). "Safety Evaluation of Acceleration and Deceleration Lane Lengths." TEH Journal 69(5), pp. 50-54.

Bates, L. (1974). *The Effect of Arrowboard Trucks on Merging Traffic*. Illinois Department of Transportation.

Bell, B., Wolfe, E., and Bernholtz, C.D. (1972). "Depth Perception as a Function of Age." *Human Development*, 3, pp. 77-88.

Benekohal, R.F., Resende, P., Shim, E., Michaels, R.M., and Weeks, B. (1992). *Highway Operations Problems of Elderly Drivers in Illinois*. Publication No. FHWA-IL-92-023. Illinois Department of Transportation and the Federal Highway Administration.

Bergen, W.G. (1970). *Criteria for the Design and Development of Advanced Graphic Guide Signs*. Serendipity, Inc.

Bezkorovainy, G. and Holsinger, R. (1966). "The Use of Stop Signs at Railroad Crossings." *Traffic Engineering*, Vol 37(2), pp. 54-59.

Berg, W.D., Knoblauch, K., and Hueke, W. (1982). "Causal Factors in Railroad-Highway Crossing Crashes." *Transportation Research Record*, 847, pp. 47-54. Transportation Research Board: Washington, D.C.

Bhise, V. and Rockwell, T. (1973). "Toward the Development of a Methodology for Evaluating Highway Signs Based on Driver Information Acquisition." *Highway Research Record*, 440, pp. 38-56.

Bjørnskau, T. and Fosser, S. (1996) *Car Drivers' Behavioral Adaption to the Installation Of Road Lighting: Before-And-After Study on Route E-18 in Norway* (Bilisters afterdstilpasning til innføring av vegbelysning: Resultater fra en før-og etterundersøkelse på E-18 i Aust-Agder)

Blaauw, G.J. (1985). "Vehicle Guidance by Delineation Systems at Night." *Ergonomics*, 28(12), pp. 1601-1615.

Blackwell, O.M. (1970). *Visual Performance, Effects of Age*. JERI Annual Report.

Blackwell, O.M. and Blackwell, H.R. (1971). "Visual Performance Data for 156 Normal Observers of Various Ages." *Journal of Illuminating Engineering Society, October.*

Blackwell, O.M. and Blackwell, H.R. (1980). "Individual Responses to Lighting Parameters for a Population of 235 Observers of Varying Ages." *Journal of Illuminating Engineering Society, July*, pp. 205-232.

Blackwell, H.R. and Taylor, J.H. (1969). *Survey of Laboratory Studies of Visual Detection. NATO Seminar on Detection, Recognition, and Identification of Line-of-Sight Targets*. The Hague, Netherlands.

Blomberg, R. and Edwards, J. (1990). *Development of Safety Information Materials and Media Plans for Elderly Pedestrians. Task 2 Report*. Contract No. DTNH22-89-C-07397. National Highway Traffic Safety Administration, Washington, D.C.

Boisson, H. and Pages, R. (1964). *Determination du Seuil de Perception des Signaux Routiers. (Determination of the Visual Perception of Roadway Signals)*. Commission Internationale De L'Éclairage Proceedings 15th Session, CIE Publication No. 11D.

Bonneson, J.A. and McCoy, P.T. (1994). "Driver Understanding of Protected and Permitted Left-Turn Signal Displays." *Transportation Research Record*, 1464, pp. 42-50. Transportation Research Board: Washington, D.C.

Bonneson, J.A. and McCoy, P.T. (1997). *Capacity and Operational Effects of Midblock Left-Turn Lanes*. National Cooperative Highway Research Program, Report No. 395. Transportation Research Board: Washington, D.C.

Bonneson, J.A., McCoy, P.T., and Truby, J.E. (1993). "Safety Improvements at Intersections on Rural Expressways: A Survey of State Departments of Transportation." *Transportation Research Record*, 1385, pp. 41-47. Transportation Research Board: Washington, D.C.

Botwinick, J. (1965). "Theories of Antecedent Conditions of Speed of Response." In: A.T. Welford and J.E. Birren (Eds.), *Behavior, Aging, and the Nervous System*. Springfield, IL.

Box, P.C. (1989). "Major Road Accident Reduction by Illumination." *Transportation Research Record*, 1247, pp. 32-38. Transportation Research Board: Washington, D.C.

Boynton, R.M. (1967). *Visibility Losses Caused by Sudden Luminance Changes*. Comte Rendu, 16th Session of the Commission Internationale de l'Éclairage, *A*, pp. 171-182.

Boynton, R.M., Corwin, T.R., and Sternheim, C. (1970). "Visibility Losses Produced by Flash Adaptation." *Illuminating Engineering*, 65, pp. 259-266.

Boynton, R.M. and Miller, N.R. (1963). "Visual Performance Under Conditions of Transient Adaptation." *Illumination Engineering*, 58, pp. 541-550.

Boynton, R.M., Rinalducci, E.J., and Sternheim, C. (1969). "Visibility Losses Produced by Transient Adaptation Changes in the Range of 0.4 to 4,000 Foot-Lamberts." *Illuminating Engineering*, 64, pp. 217-227.

Bracket, R., Stuart, M., Woods, D., and Ross, H. (1984). *Delineation of Temporary Barriers in Work Zones*. Texas Transportation Institute, Publication No. 4151-1.

Brackett, Q., Huchingson, R.D., Trout, N.D., and Womack, K. (1992). "Study of Urban Guide Sign Deficiencies." *Transportation Research Record*, 1368, pp. 1-9. Transportation Research Board: Washington, D.C.

Brainin, P.A. (1980). *Safety and Mobility Issues in Licensing and Education of Older Drivers*. Publication No. DOT-HS-805-492. National Highway Traffic Safety Administration, Washington, D.C.

Brainin, P.A., Bloom, R., Breedlove, R., and Edwards, J. (1977). *Older Driver Licensing and Improvement System (Final Report)*. Publication No. DOT-HS-7-01502. National Highway Traffic Safety Administration, Washington, D.C.

Brich, Steven C. (1995). *Investigation of Retroreflective Sign Materials at Passive Railroad Crossings*. Virginia Transportation Research Council. Final Report No. VTRC95-R22. Charlottesville, VA.

Bridwell, N., Alicandri, E., Fischer, D., and Kloeppel, E. (1993). *A Preliminary Laboratory Investigation of Passive Railroad Crossing Signs*. Publication No. FHWA-RD-93-153. Federal Highway Administration, McLean, VA.

Brilon, W. (1996). *Sichert von Kreisverkehrsplatzen*, unpublished paper. In Jacquemart, 1998, *Synthesis of Highway Practice 264: Synthesis of Roundabout Practice in the United States*. National Cooperative Highway Research Program. Transportation Research Board: Washington, D.C.

Brouwer, W.H., Ickenroth, J.G., Ponds, R.W., and van Wolffelaar, P.C. (1990). "Divided Attention in Old Age." In: *European Perspectives in Psychology, Volume 2*. Wiley and Sons, New York, NY.

Brouwer, W.H., Waterink, W., van Wolffelaar, P.C., and Rothengatter, T. (1991). "Divided Attention in Experienced Young and Old Drivers: Lane Tracking and Visual Analysis in a Dynamic Driving Simulator." *Human Factors*, 33(5), pp. 573-582. Human Factors and Ergonomics Society: Santa Monica, CA.

Bryden, J.E. (1979). *Effectiveness of Flashing Arrow Boards During Moving Maintenance Operations*. Publication No. FHWA-NY-RR-79-73. New York Department of Transportation and the Federal Highway Administration, Washington, D.C.

Bryden, J.E. (1990). "Crash Tests of Work Zone Traffic Control Devices." *Transportation Research Record*, 1254, pp. 26-35. Transportation Research Board: Washington, D.C.

Burg, A. (1967). *The Relationship Between Vision Test Scores and Driving Record: General Findings*. Report 67-24. Department of Engineering, University of California at Los Angeles.

Burnham, A.C., Jr. (1992). "Chapter 8: Traffic Signs and Markings." In: Pline, J.L. (Eds). *Traffic Engineering Handbook, Fourth Edition*. Institute of Transportation Engineers. Prentice Hall, Englewood Cliffs, New Jersey.

Burnham, A. (1994). "Stop Sign Effectiveness at Railroad Grade Crossings: Abuse Without Excuse." *Proceedings of the Third International Symposium on Railroad-Highway Crossing Research and Safety*. Knoxville, TN.

Burns, D.M. and Pavelka, L.A. (1995). "Visibility of Durable Fluorescent Materials for Signing Applications." *Color Research and Application*, 20, 108-116.

Bush, R.J. (1986). *Statewide Pedestrian Study Phase 3 Report–Correlation and Evaluation of Pedestrian Accident Data*. Publication No. FHWA-MD-86-01. Maryland State Highway Administration and the Federal Highway Administration.

Byrd, M. (1984). "Age Differences in the Retrieval Information from Semantic Memory." *Experimental Aging Research*, (10).

California Department of Public Works. (1967). *Evaluation of Minor Improvements: Flashing Beacons, Safety Lighting, Left Turn Channelization*.

California Department of Transportation. (1998). *Design Information Bulletin 80 - Roundabouts.*

California Department of Transportation, Office of Signs, Markings and California MUTCD. (2012). Challenge Area: CA-14 -- Improve Work Zone Safety.

Campbell, B.E. and Middlebrooks, P.B. (1988). *Wrong-Way Movements on Partial Cloverleaf Ramps*. Georgia Department of Transportation Research Project No. 8203 in cooperation with the Federal Highway Administration, Washington, D.C.

Campbell, K.L. (1993). "Recent Research in Developing Accident Typologies." *Proceedings of Human Factors Research in Highway Safety. Transportation Research Record, Circular 414*. Transportation Research Board: Washington, D.C.

Campbell, K.L., Wolfe, A.C., Blower, D.F., Waller, P.F., Massie, D.L., and Ridella, S. (1990). *Accident Data Analysis in Support of Collision Avoidance Technologies. Final Report*. Publication No. UMTRI-90-31, HS-041-104. University of Michigan Transportation Research Institute.

Carlson, P. J. (2001). *Evaluation Of Clearview Alphabet With Microprismatic Retroreflective Sheeting.* Texas Transportation Institute, Texas Department of Transportation, Federal Highway Administration. Research Report FHWA/TX-02/4049-1

Carlson, P. J., & Brinkmeyer, G. (2002). "Evaluation Of Clearview On Freeway Guide Signs With Microprismatic Sheeting." *Transportation Research Record* No. 1801, Traffic Control Devices, Visibility, and Rail-Highway Grade Crossings 2002., p. 27-38.

Carlson, P. J., & Hawkins, G. (2003). "Legibility Of Overhead Guide Signs With Encapsulated Versus Microprismatic Retroreflective Sheeting." *Transportation Research Record* No. 1844, Traffic Control Devices, Visibility, and Rail-Highway Grade Crossings 2003., p. 59-66.

Carlson, P.J., Holick, A. (2005). "Maximizing Legibility of Unlit Freeway Guide Signs with Clearview Font and Combinations of Retroreflective Sheeting Materials." *Transportation Research Record*. Volume 1918. 25-34.

Carstens, R.L. and Woo, R.Y. (1982). *Warrants for Rumble Strips on Rural Highways*. Iowa Highway Research Board, Publication No. HR-235.

Carvell, J., Turner, J., and Dudek, C. (1978). *Human Factors Requirements for Real-Time Motorist Information Displays, Vol 15: Freeway Incident Management Studies*. Publication No. FHWA-RD-78-19. Federal Highway Administration, Washington, D.C.

Case, H.W., Hulbert, S., and Beers, J. (1970). *Driving Ability as Affected by Age*. Final Report, 70-17, Institute of Transportation and Traffic Engineering, Los Angeles, CA.

Cerella, J., Poon, L., and Fozard, J. (1982). "Age and Iconic Read-Out." *Journal of Gerontology*, 36.

Choueiri, E. M. and Lamm, R. (1987). *Rural Roads Speed Inconsistencies Design Methods: Part I, Operating Speeds and Accident Rates on Two-Lane Rural Highway Curved Sections.* Department of Civil and Environmental Engineering, Clarkson University, NY.

Christian, M., Barnack, J., and Karoly, A. (1981). *Evaluation of Limited Sight Distance Warning Signs*. Traffic and Safety Division, New York State Department of Transportation.

Chrysler, S. T., Carlson, P. J., & Hawkins, H. G. (2002). *Nighttime Legibility Of Ground-Mounted Traffic Signs As A Function Of Font, Color, And Retroreflective Sheeting Type*. Texas Transportation Institute, Texas Department of Transportation, Federal Highway Administration.

Chu, X. (1994). *The Effects of Age on the Driving Habits of the Elderly: Evidence From the 1990 NPTS*. National Urban Transit Institute, University of South Florida. Publication No. NUTI93USF3.2. Supported by a grant from the U.S. Department of Transportation, University Research Institute Program.

Cirillo, J.A. (1968). "Interstate System Accident Research Study II, Interim Report II." *Public Roads*, 35(3), pp. 71-75. Federal Highway Administration: Washington, D.C.

Cirillo, J.A. (1970). "The Relationship of Accidents to Length of Speed-Change Lanes and Weaving Area on Interstate Highway." *Highway Research Record*, 312, pp. 17-32.

Cirillo, J.A. and Council, F.M. (1986). "Highway Safety: Twenty Years Later." *Transportation Research Circular*, 1068, pp. 90-95. Transportation Research Board: Washington, D.C.

Clark, R.D., Lord, S.R., and Webster, I.W. (1993). "Clinical Parameters Associated with Falls in an Elderly Population." *Gerontology*, Mar-Apr 39(2), pp. 117-123

Classen, S., Shechtman, O., Stephens, B., Davis, E., Justiss, M., Bendixen, R., Belchior, P., Sandhu, M., Posse, C., McCarthy, D., and Mann, W. (2007). "The Impact of Roadway Intersection Design on Driving Performance of Young and Senior Adults." *Traffic Injury Prevention*, 8, pp 69-77.

Coffin, A. and Morrall, J. (1995). "Walking Speeds of Elderly Pedestrians at Crosswalks." *Transportation Research Record*, 1487, pp. 63-67. Transportation Research Board: Washington, D.C.

Cole, B.L. (1966). "Distribution of Intensity for Road Traffic Signal Lights." *Journal of the Australian Road Research Board*, 2(10), pp.13-20.

Cole, B.L. and Brown, B. (1966). "Optimum Intensity of Red Road-Traffic Signal Lighting for Normal and Protanopic Observers." *Journal of the Optical Society of America*, 56(4), pp. 516-522.

Cole, B.L. and Brown, B. (1968). "Specification of Road Traffic Signal Light Intensity." *Human Factors*, 10(3), pp. 245-254. Human Factors and Ergonomics Society: Santa Monica, CA.

Cole, B.L. and Hughes, P.K. (1984). "A Field Trial of Attention and Search Conspicuity." *Human Factors*, 26(3), pp. 299-313. Human Factors and Ergonomics Society: Santa Monica, CA.

Commission Internationale de l'Éclairage. (1980). *Light Signals for Road Traffic Control*. Publication No. 48.

Commission Internationale de l'Éclairage. (1988). *A Guide for the Design of Road Traffic Lights*. Publication No. 79, 1st Edition.

Commission Internationale de l'Éclairage. (1990). *Road Lighting as an Accident Countermeasure*. CIE Technical Committee TC 4-02 of Division 4: Lighting and Signalling for Transport.

Compton, R.P. and Milton, E.V. (1994). *Safety Impact of Permitting Right-Turn-On-Red*. Publication No. DOT- HS-808. National Highway Traffic Safety Administration, Washington, D.C.

Cooner, S., Cothron, A., and Ranft, S. (2004). *Countermeasures for Wrong-Way Movement on Freeways: Overview of Project Activities and Findings*. Publication No. FHWA/TX-04/4128-1. Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation.

Cooper, P.J. (1990). "Elderly Drivers' Views of Self and Driving in Relation to the Evidence of Accident Data." *Journal of Safety Research*, 21.

Copelan, J.E. (1989). *Prevention of Wrong-Way Accidents on Freeways*. Publication No. FHWA-CA-TE-89-2. California Department of Transportation, Division of Traffic Operations.

Cornwell, M. (1987). "The Assessment of People with Arthritis Who Wish To Drive A Car." *Institute for Disability Studies*, 9, pp. 174-177.

Cottrell, B.H., Jr. (1981). "Use of Chevron Patterns on Traffic Control Devices in Work Zones." *Transportation Research Record*, 833, pp. 3-6. Transportation Research Board: Washington, D.C.

Cottrell, B.H., Jr. (1985). *Guidelines for Protected/Permissive Left-Turn Signal Phasing*." Virginia Highway and Transportation Research Council, Virginia Department of Transportation, Charlottesville, VA.

Cottrell, B.H., Jr. (1988). "Evaluation of Wide Edgelines on Two-Lane Rural Roads." *Transportation Research Record*, 1160, pp. 35-44. Transportation Research Board: Washington, D.C.

Cottrell, B.H., Jr. and Allen, G.R. (1982). *Guidelines for Exclusive/Permissive Left-Turn Signal Phasing*. VHTRC with U.S. Department of Transportation, Federal Highway Administration, Charlottesville, VA.

Council, F.M. and Zegeer, C.V. (1992). *Accident Analysis of Older Drivers and Pedestrians at Intersections—Task B Working Paper*. Contract No. DTFH61-91-C-00033. Federal Highway Administration, Washington, D.C.

Cribbins, P.D. and Walton, C.M. (1970). "Traffic Signals and Overhead Flashers at Rural Intersections, Their Effectiveness in Reducing Accidents." *Highway Research Record*, 325, pp. 1-14.

Crowley, K.W. and Seguin, E.L. (1986). *Wrong Way Traffic Control at Intersections*. Publication No. FHWA-RD-86-116. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C.

Curtis, O., Opiela, K., and Guell, D. (1988). *Signal Displays for Left-Turn Control*. Publication No. DTFH61-85-C-00164. Federal Highway Administration, Washington, D.C.

Dahlstedt, S. (undated). *Walking Speeds and Walking Habits of Elderly People*. National Swedish Road and Traffic Research Institute, Stockholm, Sweden.

Darzentas, J., McDowell, M.R., and Cooper, D.F. (1980). "Minimum Acceptable Gaps and Conflict Involvement in a Simple Crossing Maneuver." *Traffic Engineering and Control*, 21(2), pp. 58-61.

David, N.A. and Norman, J.R. (1979). *Motor Vehicle Accidents in Relation to Geometric and Traffic Features of Highway Intersections: Volume II-Research Report*. Publication No. FHWA-RD-76-129. Federal Highway Administration, Washington, D.C.

Davis, T.D. (1983). *Construction Zone Safety and Delineation Study*. Publication No. FHWA-NJ-83-005. New Jersey Department of Transportation and the Federal Highway Administration, Washington, D.C.

Deacon, J.A. (1988). "Potential Improvements in Roadway Delineation for Older Drivers." In: *Transportation in an Aging Society*. TRB Special Report 218. Transportation Research Board, Washington, D.C.

Decina, L.E. and Staplin, L. (1993). "Retrospective Evaluation of Alternative Vision Screening Criteria for Older and Younger Drivers." *Accident Analysis and Prevention*, 25(3), pp. 267-275.

Department of Health and Human Services. (1994). *Vital and Human Statistics*. Washington, D.C.

Dewar, R. (1992). "Driver and Pedestrian Characteristics." In: James L. Pline (Ed.), *Traffic Engineering Handbook*. Prentice Hall, Englewood Cliffs, NJ.

Dewar, R., Ells, J., and Cooper, P. (1977). "Evaluation of Roadway Guide Signs at a Large Airport." *Transportation Engineering*, 47(6), pp.19-23.

Donaldson, G.A. (1986). "Safety of Large Trucks and the Geometric Design of Two-Lane, Two-Way Roads." *Transportation Research Record*, 1052, pp. 10-14. Transportation Research Board: Washington, D.C.

Dudek, C.L. (1991). *Guidelines on the Use of Changeable Message Signs*. Publication No. FHWA-TS90-043. Federal Highway Administration, Washington, D.C.

Dudek, C.L. and Huchingson, R.D. (1986). *Manual on Real Time Motorist Information Displays*. Publication No. FHWA-IP-86-16. Federal Highway Administration, Washington, D.C.

Dudek, C.L., Huchingson, R.D., Creasey, F., and Pendleton, O. (1988). "Field Studies of Temporary Pavement Markings at Overlay Project Zones on Two-Lane, Two-Way Rural Highways." *Transportation Research Record*, 1160, pp. 22-34. Transportation Research Board: Washington, D.C.

Dudek, C.L., Huchingson, R.D., Williams, R.D., and Koppa, R.J. (1981). *Human Factors Design of Dynamic Visual and Auditory Displays for Metropolitan Traffic Management, Vol 2: Dynamic Displays*. Publication No. FHWA-RD-81-040. Federal Highway Administration, Washington, D.C.

Dudek, C.L., Huchingson, R.D., and Woods, D. (1986). "Evaluation of Temporary Marking Patterns for Work Zones." *Transportation Research Record*, 1086, pp. 12-20. Transportation Research Board: Washington, D.C.

Dudek, C.L., Richards, S.H., and Faulkner, M.J.S. (1981). *Feasibility of Changeable Message Signs and Highway Advisory Radio for Freeway Maintenance*. Research Report 228-9-263-2. Texas Transportation Institute. Texas State Department of Highways and Public Transportation and the Federal Highway Administration.

Dudek, CL; Schrock, SD; Ullman, GL; Chrysler, ST. ( 2006). "Flashing Message Features on Changeable Message Signs." *Transportation Research Record* 1959, *Freeway Operations And High Occupancy Vehicle Systems*: 122-129.

Durkop, B.R., and Dudek, C.L. (2001). "Texas Driver Understanding of Abbreviations for Changeable Message Signs." *Transportation Research Record*, 1748, 87-95Earnhart, G. and Simon, L. (1987). *Accessibility for Elderly and Handicapped Pedestrians—A Manual for Cities*. Publication No. 88-113170/AS. Federal Highway Administration, Washington, D.C.

Eccles. K., Tao, R., and Mangum, B. (2003). *Evaluation of Pedestrian Countdown Signals in Montgomery County, Maryland*

Eck, R.W. and Shanmugam, T. (1987). "Physical and Operational Characteristics of Rail-Highway Grade Crossings on Low-Volume Roads." *Transportation Research Record*, 1106, pp. 246-255. Transportation Research Board: Washington, D.C.

Eck, R.W. and Winn, G. (2002) "Older-Driver Perception of Problems at Unsignalized Intersections on Divided Highways", Transportation Research Record 1818, pp. 70-77.

Eckhardt, P.K. and Flanagan, J.C. (1956). "Role of Roadway Elements in Pennsylvania Turnpike Accidents." *Highway Research Board Bulletin*, 120, pp. 1-5.

Eisdorfer, C. (1975). "Verbal Learning and Response Time in the Aged." *Journal of Genetic Psychology*, 109, pp. 15-22.

Eldritch, M. (1989). "Bad Turns." *Traffic Safety*, 89(6), pp. 8-11.

Eriksen, C.W., Hamlin, R.M., and Daye, C. (1973). "Aging Adults and Rate of Memory Scan." *Bulletin of the Psychonomics Society,* (1).

Faulkner, M.J.S. and Dudek, C.L. (1982). "Flashing Arrowboards in Advance of Freeway Work Zones." *Transportation Research Record*, 864, pp. 5-7. Transportation Research Board: Washington, D.C.

Fambro, D.B. (1999). *Recommended Devices and Applications for Use at Rail-Highway Grade Crossings*. Working Paper No 5, Prepared under U.S.DOT/FHWA Contract No. DTFH61-96-R-00089: Improved Traffic Control Devices at Rail-Highway Grade Crossings.

Fambro, D.B., Beitler, M.M, and Hubbard, S.M. (1994). *Enhancements to Passive Warning Devices at Railroad-Highway Grade Crossings*. Publication No. FHWA/TX-94/1271-3. Texas Department of Transportation and the Federal Highway Administration.

Fambro, D.B., Fitzpatrick, K., and Koppa, R.J. (1997). *Determination of Stopping Sight Distances*. Publication No. 400. National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C.

Fambro, D.B., Heathington, K.W., and Richards, S.H. (1989). "Evaluation of Two Active Traffic Control Devices for Use at Railroad Highway Grade Crossings." *Transportation Research Record*, 1244, pp. 52-62. Transportation Research Board: Washington, D.C.

Fambro, D.B., Koppa, R.J., Picha, D.L., and Fitzpatrick, K. (1998). "Driver Perception-Brake Response in Stopping Sight Distance Situations." *Transportation Research Record*, 1628, pp. 1-7. Transportation Research Board: Washington, D.C.

Fambro, D.B., Schull, L.A., Noyce, D.A., and Rahman, K.M.A. (1997). *Enhanced Traffic Control Devices and Railroad Operations for Highway-Railroad Grade Crossings: Second Year Activities*. Publication No. FHWA/TX-98/1469-2. Texas Department of Transportation and the Federal Highway Administration.

Fambro, D.B. and Woods, D.L. (1981). "Safety Benefits of Left-Turn Signal Phasing Alternatives." *Institute of Transportation Engineers Journal*. Institute of Transportation Engineers: Washington, D.C.

Fancher, P.S. (1986). "Sight Distance Problems Related to Large Trucks." *Transportation Research Record*, 1052, pp. 29-35. Transportation Research Board: Washington, D.C.

Farber, E. (1982). "Driver Eye-Height Trends and Sight Distance on Vertical Curves." *Transportation Research Record*, 855, pp. 27-33. Transportation Research Board: Washington, D.C.

Farr, E.H. and Hitz, J.S. (1985). *Effectiveness of Motorist Warning Devices at Rail-Highway Crossings*. Publication No. FHWA-RD-85-015. Federal Highway Administration, Washington, D.C.

FARS (2013). "Traffic Safety Facts: 2011 Data". Report No. DOT HS 811 745. *NHTSA National Center for Statistics and Analysis*. National Highway Traffic Safety Administration, Washington, D.C.

Faulkner, M.J. and Dudek, C.L. (1981). *Field Evaluation of Flashing Arrowboards at Freeway Work Zones*. Report No. 288-5, Texas Transportation Institute.

Federal Highway Administration. (1979). *Standard Highway Signs as Specified in the Manual on Uniform Traffic Control Devices*. Washington, D.C.

Federal Highway Administration. (1983). *Roadway Lighting Handbook, Addendum to Chapter Six: Designing the Lighting System Using Pavement Luminance*. Addendum to Implementation Package 78-15. Washington, D.C.

Federal Highway Administration. (1993). *Part VI of the Manual on Uniform Traffic Control Devices for Streets and Highways: Standards and Guides for Traffic Controls for Street and Highway Construction, Maintenance, Utility, and Incident Management Operations*. Washington, D.C.

Federal Highway Administration. (1996). *The 1996 Annual Report on Highway Safety Improvement Programs*. Publication No. FHWA-SA-96-040. Washington, D.C.

Federal Highway Administration. (1997). *FHWA Study Tour for Road Safety Audits*. Washington, D.C.

Federal Highway Administration. (2000). *Roundabouts: An Informational Guide*. Publication No. FHWA-RD-00-067. Washington, D.C.

Federal Highway Administration. (2007). *Railroad-Highway Grade Crossing Handbook*. Revised Second Edition. Publication No. FHWA-SA-07-010. Washington, D.C.

Federal Highway Administration. (2007). *Manual on Uniform Traffic Control Devices for Streets and Highways,* 2003 Edition with Revisions Number 1 and 2 Incorporated. Washington, D.C.

Federal Highway Administration. (2009). *Manual on Uniform Traffic Control Devices for Streets and Highways,* 2009 Edition. Washington, D.C.

Federal Highway Administration. (2004). *Standard Highway Signs*. Available at http://mutcd.fhwa.dot.gov/ser-shs_millennium_eng.htm

Federal Highway Administration. (2012). *EDC High Friction Surface Treatment*. Avaliable at http://www.fhwa.dot.gov/everydaycounts/edctwo/2012/friction.cfm.

Federal Highway Administration. (2012). *FHWA Lighting Handbook*. Washington, D.C. Available at http://safety.fhwa.dot.gov/roadway_dept/night_visib/lighting_handbook/

Federal Railroad Administration. (2014). Office of Safety Analysis Web Site. Washington, D.C. Available at http://safetydata.fra.dot.gov/officeofsafety/default.aspx. Accessed on April 17, 2014.

Firestine, M., Hughes, W., and Natelson, N. (1989). *Operating Larger Trucks on Roads with Restrictive Geometry: Summary Report*. Publication No. FHWA-IP-89-025, NCP 3A9d-0063. Washington, D.C.

Fisher, A. (1969). *A Photometric Specification for Vehicular Traffic Signal Lanterns, Part 1: Luminous Intensity Necessary for the Detection of Signals on the Line of Sight*. Research Project 207, New South Wales, Department of Motor Transport.

Fisher, A. (1969). *A Photometric Specification for Vehicular Traffic Signal Lanterns, Part 2: Luminous Intensity Necessary for the Detection of Signals Eccentric to the Line of Sight*. Research Project 207, New South Wales, Department of Motor Transport.

Fisher, A. and Christie, A. (1965). "A Note On Disability Glare." *Vision Research*, 5, pp. 565-571.

Fisher, A. and Cole, B. (1974). "The Photometric Requirements of Vehicular Traffic Signal Lanterns." Paper No. A46, *Australian Road Research Board Proceedings*, 7(5), pp. 246-265.

Fisher, R.L. (1961). "Accident and Operating Experience at Interchanges." *Highway Research Board Bulletin*, 291, pp. 124-138.

Fisk, A.D., McGee, N.D., and Giambra, L.M. (1988). "The Influences of Age on Consistent and Varied Semantic-Category Search Performance." *Psychology and Aging*, 3, pp. 323-333.

Fitzpatrick, K., Chrysler, S.T., Iragavarapu, V., and Park, E. (2010) Crosswalk Marking Field Visibility Study. Research Report. FHWA-HRT-10-068. Federal Highway Administration, Washington, DC.

Flannery, A. and Datta, T. (1996). "Modern Roundabouts and Traffic Crash Experience in United States." *Transportation Research Record*, 1553, pp. 103-109. Transportation Research Board: Washington, D.C.

Flener, B.R. (1972). "A Study of Traffic Operations and Safety At Exit Gore Areas: Findings and Applications." *American Association of State Highway Officials Proceedings*.

Florida Department of Transportation. (1996). *Florida Roundabout Guide*.

Florida Section of Institute of Transportation Engineers. (1982). "Left-Turn Phase Design in Florida." *Institute of Transportation Engineers Journal*, 52(9), pp. 28-35. Institute of Transportation Engineers: Washington, D.C.

Forbes, T.W. and Holmes, R.S. (1939). "Legibility Distances of Highway Destination Signs in Relation to Letter Height, Width, and Reflectorization." *Highway Research Board*, 19, pp. 321-326.

Forbes, T.W., Moskowitz, K., and Morgan, G. (1950). "A Comparison of Lower Case and Capital Letters for Highway Signs." *Highway Research Board Proceedings*, 30, pp. 355-373.

Foxen, G. (1986). "The Signing and Marking of Trap Lanes." *Institute of Transportation Engineers Journal*, 56(6), pp. 48-49. Institute of Transportation Engineers: Washington, D.C.

Fredericksen, E. and Rotne, N. (1978). *Calculation of Visibility in Road Lighting*. Report 17 of the Danish Illuminating Engineering Laboratory.

Freedman, M., Davit, P.S., Staplin, L., and Breton, M. (1985). *Traffic Signal Brightness: An Examination of Nighttime Dimming*. Publication No. FHWA-RD-85-005. Federal Highway Administration, Washington, D.C.

Freedman, M., Flicker, L., Janoff, M.S., Schwab, R.N., and Staplin, L.K. (1997). *Visibility Performance Requirements for Vehicular Traffic Signals*. Interim Report. NCHRP Project No. 5-15. Westat, Inc: Rockville, MD.

Freedman, M., Janoff, M.S., Koth, B.W., and McCunney, W. (1975). *Fixed Illumination for Pedestrian Protection*. Publication No. FHWA-RD-76-8. Federal Highway Administration, Washington, D.C.

Freedman, M., Staplin, L., Decina, L., and Farber, E. (1984). *Limited Sight Distance Warning for Vertical Curves–Volume II, Final Technical Report*. Publication No. DTFH61-82-C-00062. Federal Highway Administration, Washington, D.C.

Freedman, M.L., Staplin, L., Gilfillan, D., and Brynes, A.M. (1988). *Noticeability Requirements for Delineation on Non-Illuminated Highways*. Publication No. FHWA-RD-88-028. Federal Highway Administration, Washington, D.C.

Friebele, J.D., Messer, C.J., and Dudek, C.L. (1971). *State-of-the-Art of Wrong-Way Driving on Freeways and Expressways*. Report No. 139-7. Texas Transportation Institute and the U.S. Department of Transportation.

Fukutome, I. and Moskowitz, K. (1963). "Traffic Behavior and Off-Ramp Design." *Highway Research Record*, 21, pp. 17-31.

Gabriel, J.D. (1974). "Wrong-Way Driving on California Freeways." *Traffic Quarterly*, pp. 227-240.

Gamble, A. (1996). *Montpelier Roundabout, Main Street/Spring Street*. Vermont Agency of Transportation, Traffic Research Section. Montpelier, Vermont.

Garber, N.J. and Srinivasan, R. (1991) "Characteristics of Accidents Involving Elderly Drivers at Intersections." *Transportation Research Record*, 1325, pp. 8-16. Transportation Research Board: Washington, D.C.

Garber, N.J. and Srinivasan, R. (1991). "Risk Assessment of Elderly Drivers at Intersections: Statistical Modeling." *Transportation Research Record*, 1325, pp. 17-22. Transportation Research Board: Washington, D.C.

Garber, N.J. and Woo, T.H. (1990). *Accident Characteristics at Construction and Maintenance Zones in Urban Areas*. Report No. VTRC90-R12. Virginia Transportation Research Council, Charlottesville, VA.

Garvey, P.M., Gates, M.T., and Pietrucha, M.T. (1997). "Engineering Improvements to Aid Older Drivers and Pedestrians." *Conference Proceedings of the American Society of Civil Engineers*. Traffic Congestion, and Traffic Safety in the 21st Century: Challenges, Innovations, and Opportunities, pp. 222-228. Chicago, IL

Garvey, P.M. and Mace, D.J. (1996). *Changeable Message Sign Visibility*. Publication No. FHWA-RD-94-077. Federal Highway Administration, Washington, D.C.

Garvey, P.M., Meeker, D., and Pietrucha, M.T. (1996). *Development of a New Guide Sign Font*. The Pennsylvania Transportation Institute, The Pennsylvania State University, University Park, PA.

Garvey, P.M., Pietrucha, M.T., and Meeker, D. (1997)."Effects of Font and Capitalization on Legibility of Guide Signs." *Transportation Research Record*, 1605, pp. 73-79. Transportation Research Board: Washington, D.C.

Garvey, P.M., Pietrucha, M.T., and Meeker, D.T. (1998). "Clearer Road Signs Ahead." *Ergonomics in Design*, 6(3), pp. 7-11.

Gattis, J.L. (1996). *Cross Traffic Signing for Stop Signs*. Paper No. 960073, Transportation Research Board 75th Annual Meeting, Washington, D.C.

George, L.E. (1987). "Oregon's Sign Refinishing Project." *Institute of Transportation Engineers Journal*, pp. 45-46. Institute of Transportation Engineers: Washington, D.C.

Gish, K. (1995). *Condition-Responsive Work Zone Traffic Control System: CMS and HAR Human Factors Guidelines*. Paper presented to the User Information Systems Committee at the 74th Annual Meeting of the Transportation Research Board.

Glennon, J.C., Neuman, T.R., and Leisch, J.E. (1985). *Safety and Operational Considerations for Design of Rural Highway Curves*. Publication No. FHWA-RD-86-035. Federal Highway Administration, Washington, D.C.

Glennon, J.C. and Weaver, G.D. (1971). *The Relationship of Vehicle Paths to Highway Curve Design*. Texas Highway Department and the Federal Highway Administration.

Goggin, N.L. and Stelmach, G.E. (1990). "Age-Related Differences in the Kinematic Analysis of Precued Movements." *Canadian Journal of Psychology*, *9*, pp. 371-385.

Goggin, N.L., Stelmach, G.E., and Amrhein, P.C. (1989). "Effects of Age on Motor Preparation and Restructuring." *Bulletin of the Psychonomics Society*, *27*, pp. 199-202.

Goldblatt, R.B. (1977). "Effect of Flashing Beacons on Intersection Performance." *Transportation Research Record*, 644, pp. 91-96. Transportation Research Board: Washington, D.C.

Golembiewski, G. and Katz, B.J. (2008). *Diagrammatic Freeway Guide Sign Design.* Final Report, Traffic Control Devices Pooled Fund Study. Washington, D.C.: Federal Highway Administration.

Good, M.C. (1978). "A Review of Empirical Studies of Driver-Vehicle Behavior on Road Curves." *Road Curve Geometry and Driver Behavior.* Special Report, 15, pp. 75-92.

Good, M.C. and Baxter, G.H. (1986). "Evaluation of Short Range Roadway Delineation." *Human Factors,* 28(6), pp. 645-660. Human Factors and Ergonomics Society: Santa Monica, CA.

Goodwin, D.N. (1975). "Operational Effects of Geometric Design at Freeway Lane Drops." *Transportation Research Record*, 541, pp. 26-30. Transportation Research Board: Washington, D.C.

Gordon, D.A. (1972). "Evaluation of Diagrammatic Guide Signs." *Highway Research Record*, 414, pp. 30-41.

Gordon, D.A. (1981). *Informational Load of Highway Guide Signs*. Publication No. FHWA-RD-80-161, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C.

Gordon, D.A., McGee, H.W., and Hooper, K.G. (1984). "Driver Characteristics Impacting on Highway Design and Operations." *Public Roads*, June, pp. 12-16. Federal Highway Administration, Washington, D.C.

Graham, J.L. (1977). *Accident and Speed Studies in Construction Zones*. Publication No. FHWA-RD-77-080. Federal Highway Administration, Washington, D.C.

Graham, J.L., Migletz, D.J., and Glennon, J.C. (1978). *Guidelines for the Application of Arrow Boards in Work Zones*. Publication No. FHWA-RD-79-58. Federal Highway Administration, Washington, D.C.

Graham, J.L., Paulsen, R.J., and Glennon, J.C. (1977). *Accidents and Speed Studies in Construction Zones*. Publication No. FHWA-RD-77-80. Federal Highway Administration, Washington, D.C.

Graham, J.R., Harrold, J.K., and King, L.E. (1996). "Pavement Marking Retroreflectivity Requirements for Older Drivers." *Transportation Research Record*, 1529, pp. 65-70. Transportation Research Board: Washington, D.C.

Gramza, K., Hall, J.A., and Sampson, W. (1980). *Effectiveness of Freeway Lighting.* Publication No. FHWA-RD-79-77. Federal Highway Administration, Washington, D.C.

Greene, F.A., Koppa, R.J., Rodriguez, K., and Wright, S. (1996). *Positive Guidance and Older Motorists - Guidelines for Maintenance Supervisors*. Southwest Region University Transportation Center, Texas Transportation Institute. Publication No. RF721917-2.

Guichet, B. (1992). "Mini-Roundabouts in France." *Actes du Seminiaire Giratoires 92*, October 14-16, Nantes, France. Research conducted by the Center for Technical Studies of the Western Facilities.

Gutman, G., Milstein, S. (1988). *Focus Group Study of Older Drivers*. Gerontology Research Center, Simon Fraser University, Burnaby, B.C., Canada.

Habib, P.A. (1980). "Pedestrian Safety: The Hazards of Left-Turning Vehicles." *TEH Journal,* 50 (4), pp. 33-37.

Hagenauer, G.F., Upchurch, J., Warren, D., and Rosenbaum, M.J. (1982). "Intersections." In: *Synthesis of Safety Research Related to Traffic Control and Roadway Elements, Chap. 5*. Publication No. FHWA-TS-82-232. Federal Highway Administration, Washington, D.C.

Hall, J.W. (1987). "Evaluation of Wide Edgelines." *Transportation Research Record*, 1114, pp. 21-30. Transportation Research Board: Washington, D.C.

Hall, J.W., Burton, C.J., Coppage, D.G., and Dickinson, L.V. (1976). "Roadside Hazards on Nonfreeway Facilities." *Transportation Research Record*, 601, pp. 56-58. Transportation Research Board: Washington, D.C.

Hallmark, S.L. and Mueller, K. (2004). "Impact of left-turn phasing on older and younger drivers at high-speed signalized intersections", Center for Transportation Research and Education, Iowa State University, Ames, IA,.

Hanna, J.T., Flynn, T.E. and Tyler, W.K. (1976). "Characteristics of Intersection Accidents in Rural Municipalities." *Transportation Research Record*, 601, pp. 79-82. Transportation Research Board: Washington, D.C.

Hans, M. (1993). "High-Mast Lights Beckon Traffic Planners." *Traffic Safety*, *July*, pp. 12-14.

Hanscom, F. (1976). "Evaluation of Signing to Warn of Wet Weather Skidding Hazard." *Transportation Research Record,* 600, pp. 20-27. Transportation Research Board: Washington, D.C.

Hargroves, B. and Martin, M. (1980). *Vehicle Accidents in Highway Work Zones*. Publication No. FHWA-RD-80-063. Federal Highway Administration, Washington, D.C.

Harkey, D.L., F.M. Council, R. Srinivasan, C. Lyon, B. Persaud, K. Eccles, N. Lefler, F. Gross, J. Baek, E. Hauer, and J. Bonneson, (2008). *Accident Modification Factors for Traffic Engineering and ITS Improvements.* NCHRP Report 617, National Cooperative Highway Research Program, Transportation Research Board.

Harkey, D.L. and Carter, D.L. (2006). "Observational Analysis of Pedestrian, Bicyclists, and Motorist Behaviors at Roundabouts in the United States. *Transportation Research Record 1982,* pp. 155-165. Transportation Research Board.

Harkey, D.L. (1995). "Intersection Geometric Design Issues for Older Drivers and Pedestrians." *1995 Compendium of Technical Papers*, Institute of Transportation Engineers 65$^{th}$ Annual Meeting, Denver Colorado, August 5-8, 1995.

Harkey, D.L., Huang, H., and Zegeer, C.V. (1996). *Examination of Older Driver Problems on Freeways Using the Highway Safety Information System*. Submitted to the Transportation Research Board for Presentation and Publication, August 1995.

Harkey, D., Mera, R., and Byington, S. (1992). *Non-Permanent Pavement Markings in Work Zones*. Publication No. FHWA-RD-92-007. Federal Highway Administration, Washington, D.C.

Harrell, A. (1990). "Perception of Risk and Curb Standing at Street Corners by Older Pedestrians." *Perceptual and Motor Skills*, 70 (3, pt 2), pp. 1363-1366.

Harwood, D.W. (1993). *Synthesis of Highway Practice 191: Use of Rumble Strips to Enhance Safety*. National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C.

Harwood, D.W., Mason, J.W., Jr., Brydia, R.E., Pietrucha, M.T., and Gittings, G.L. (1996). *Intersection Sight Distance*. NCHRP Report No. 383. National Cooperative Highway Research Program, Project No. 15-14(1). Transportation Research Board, Washington, D.C.

Harwood, D.W., Mason, J.W., Jr., Pietrucha, M.T., Brydia, R.E., Hostetter, R.S., and Gittings, G.L. (1993). *Intersection Sight Distance*. National Cooperative Highway Research Program, Project No. 15-14(1), Interim Report. Transportation Research Board, Washington, D.C.

Harwood, D.W., Pietrucha, M.T., Wooldridge, M.D., Brydia, R.E., and Fitzpatrick, K. (1995). *Median Intersection Design*. Report No 375. National Cooperative Highway Research Program, Project No. 15-14(2). Transportation Research Board, Washington, D.C.

Harwood, D.W. and Glennon, J.C. (1976). "Framework for Design and Operation of Passing Zones on Two-Lane Highways." *Transportation Research Record,* 601, pp. 45-50. Transportation Research Board: Washington, D.C.

Harwood, D.W., Hoban, C.J., and Warren, D.L. (1988). "Effective Use of Passing Lanes on Two-Lane Highways." *Transportation Research Record*, 1195, pp. 79-91. Transportation Research Board: Washington, D.C.

Hasher, L. and Zacks, R.T. (1988). "Working Memory, Comprehension, and Aging: a Review and a New View." In G.H. Bower (Ed.), *The Psychology of Learning and Motivation*. Academic, San Diego, CA.

Hauer, E. (1988). "The Safety of Older Persons at Intersections." In: *Transportation in an Aging Society, Volumes 1 and 2*. Special Report 218. Transportation Research Board, Washington, D.C.

Hawkins, H.G., Kacir, K.C., and Ogden, M.A. (1992). *Traffic Control Guidelines for Urban Arterial Work Zones, Volume 2*. Publication No. FHWA-TX-91-1161-5. Federal Highway Administration, Washington, D.C.

Hawkins, H.G., Picha, D.L., Wooldridge, M.D., Greene, F.K., and Brinkmeyer, G. (1999). "Performance Comparison of Three Freeway Guide Sign Alphabets." *Transportation Research Record*, 1692, pp. 9-16. Transportation Research Board: Washington, D.C.

Hawkins, H.G., Womak, K.N., and Mounce, J.M. (1993). "Driver Comprehension of Regulatory Signs, Warning Signs, and Pavement Markings." *Transportation Research Record*, 1403, pp. 67-82. Transportation Research Board: Washington, D.C.

Haywood, J.C. (1980). "Highway Alignment and Superelevation: Some Design-Speed Misconceptions." *Transportation Research Record,* 757, pp. 22-25. Transportation Research Board: Washington, D.C.

Heathington, K.W. (1996). "Railroad Grade Crossing Accident Behavior and Countermeasures." *Infrastructure*, 2, pp. 10-16.

Heathington, K.W., Fambro, D.B., and Richards, S.H. (1989). "Field Evaluation of a Four-Quadrant Gate System for Use at Railroad-Highway Grade Crossings." *Transportation Research Record*, 1244, pp. 39-51. Transportation Research Board: Washington, D.C.

Heathington, K.W., Richards, S.H., and Fambro, D.B. (1990)."Guidelines for the Use of Selected Active Traffic Control Devices at Railroad-Highway Grade Crossings." *Transportation Research Record*, 1254, pp. 50-59. Transportation Research Board: Washington, D.C.

Henderson, B.L. and Burg, A. (1973). *The Role of Vision and Audition in Truck and Bus Driving* (Final Report). Publication No. SDC-TM-L-5260. Systems Development Corporation, Santa Monica, CA.

Henderson, B.L. and Burg, A. (1974). *Vision and Audition in Driving*. Publication No. DOT-HS-801-265. Federal Highway Administration, Washington, D.C.

Hills, B.L. (1975). *Some Studies of Movement Perception, Age, and Accidents*. Publication No. SR137. Department of the Environment, Transport and Road Research Laboratory, Crowthorne, Berkshire, England.

Hills, B.L. (1980). "Vision, Visibility and Perception in Driving." *Perception*, 9, pp.183-216.

Hills, B.L. and Johnson, L. (1980). *Speed and Minimum Gap Acceptance Judgements at Two Rural Junctions*. Publication No. SR515. Department of the Environment, Transport and Road Research Laboratory, Crowthorne, Berkshire, England.

Hoffman, M.R. (1969). *Evaluation of Traffic Lane-Use Control Signs*. Publication No. TSD-SS-112-69. Michigan Department of State Highways.

Holahan, C.J. (1977). *Relationship Between Roadside Signs and Traffic Accidents: A Field Investigation*. Texas Department of Transportation Report No. 54. Publication No. HS-025 863. National Highway Traffic Safety Administration, Washington, D.C..

Holowachuk, L., and Leung, S. (1994). "Signal Design to Improve Visibility for Old Age and Colour Vision-Deficient Drivers." *Roads to the 21st Century: A Key to Competitiveness*. Proceedings of the International Road Federation Conference and Exposition, Vol 5, pp. A83-A104. Co-Sponsored by the Transportation Association of Canada. Calgary, Alberta.

Holowachuk, L., Leung, S. and Lakowski, R. (1993). "Color Vision Deficiencies and the Visibility of Various Traffic Signals." *Transportation and National Prosperity*. Proceedings of the 1993 Annual Conference of the Transportation Association of Canada, Vol 3, pp. C29-C54. Ottawa, Ontario.

Holzmann, F.D. and Marek, M.A. (1993). "Interchange Study and Selection Process." *Transportation Research Record*, 1385, pp. 90-99. Transportation Research Board: Washington, D.C.

Hopkins, J. and Holmstrom, F. (1976). "Toward More Effective Grade-Crossing Flashing Lights." *Transportation Research Record*, 562, pp 1-14. Transportation Research Board: Washington, D.C.

Hopkins, J. and White, E. (1977). *Improvement of the Effectiveness of Motorist Warnings at Railroad-Highway Grade Crossings*. Publication No. FRA-ORD-77-07. Federal Railroad Administration.

Hostetter, R.S., McGee, H.W., Crowley, K.W., Seguin, E.L., and Dauber, G.W. (1986). *Improved Perception-Reaction Time Information for Intersection Sight Distance. Final Report*. Publication No. FHWA-RD-87-015. Federal Highway Administration, Washington, D.C.

Hostetter, R.S., Crowley, K.W., Dauber, G.W., and Seguin, E.L. (1989). *Trade-Off Between Delineation and Lighting on Freeway Interchanges*. *Final Report* Publication No. FHWA-RD-88-223. Federal Highway Administration, Washington, D.C.

Hoxie, R.E. and Rubenstein, L.Z. (1994). "Are Older Pedestrians Allowed Enough Time to Cross Intersections Safely?" *Journal of the American Geriatrics Society*, 42(3), pp. 241-244.

Hoyer, W.J. and Familant, M.E. (1987). "Adult Age Differences in the Rate of Processing Expectancy Information." *Cognitive Development*, 2, pp. 59-70.

Huchingson, R., Koppa, R., and Dudek, C. (1978). *Human Factors Requirements for Real-Time Motorist Displays, Vol 13: Human Factors Evaluation of Audio and Mixed Modal Variables*. Publication No. FHWA-RD-78-17. Federal Highway Administration, Washington, D.C.

Hughes, W.E., Joshua, S., and McGee, H.W. (1992). *Study Designs for Passing Sight Distance Requirements*. *Final Report*. Publication No. FHWA-RD-91-078. Federal Highway Administration, Washington, DC

Hughes, W.E., McGee, H.W., Hussain, S., and Keegal, J. (1989). *Field Evaluation of Edgeline Widths*. Publication No. FHWA-RD-89-111. Federal Highway Administration, Washington, D.C.

Hulbert, S., Beers, J., and Fowler, P. (1979). *Motorists' Understanding of Traffic Control Devices, Test I*. American Automobile Association, Foundation for Traffic Safety, Falls Church, VA.

Hulbert, S. and Fowler, P. (1980). *Motorists Understanding of Traffic Control Devices-Test II*. American Automobile Association Foundation for Traffic Safety, Falls Church, VA.

Hulscher, F.R. (1974). "Practical Implementation of Performance Objectives for Traffic Light Signals." *Australian Road Research Board Proceedings*, 7(5).

Hulscher, F.R. (1975). "Photometric Requirements for Long-Range Road Traffic Light Signals." *Journal of the Australian Road Research Board*, 5(7).

Hummer, J.E. (1989). "Supplemental Interchange Signing and Driver Control Behavior." *Transportation Research Record*, 1213, pp. 56-63. Transportation Research Board: Washington, D.C.

Hummer, J.E., Montgomery, R.E., and Sinha, K.C. (1990). "Motorist Understanding of and Preferences for Left-Turn Signals." *Transportation Research Record*, 1281, pp. 136-147. Transportation Research Board: Washington, D.C.

Hummer, J.E., Montgomery, R.E., and Sinha, K.C. (1991). "Guidelines for Use of Leading and Lagging Left-Turn Signal Phasing." *Transportation Research Record*, 1324, pp. 11-20. Transportation Research Board: Washington, D.C.

Hummer, J.E. and Scheffler, C.R. (1999). "Driver Performance Comparison of Fluorescent Orange to Standard Orange Work Zone Traffic Signs." *Transportation Research Record*, 1657, pp. 55-62. Transportation Research Board: Washington, D.C.

Humphreys, J., Maulden, H., and Sullivan, T. (1979). *Identification of Traffic Management Problems In Work Zones*. Publication No. FHWA-RD-79-4. Federal Highway Administration, Washington, D.C.

Hunter-Zaworski, K. (1990). "T-Intersection Simulator Performance of Drivers With Physical Limitations." *Transportation Research Record, 1281*, pp. 11-15. Transportation Research Board: Washington, D.C.

Illinois Division of Highways. (1970). *Rumble Strips Used as a Traffic Control Device: An Engineering Analysis*. Accident Study Report No. 102.

Institute of Transportation Engineers. (undated). *Traffic Control Devices for Elderly and Handicapped Pedestrians*. Institute of Transportation Engineers Committee 4A-6, Institute of Transportation Engineers, Washington, D.C.

Institute of Transportation Engineers. (1980). *Lane-Use Traffic Control Signal Heads*.

Institute of Transportation Engineers. (1982) *Transportation and Traffic Engineering Handbook*. Second Edition. Wolfgang S. Homburger, (Ed.). Institute of Transportation Engineers, Prentice Hall, Englewood Cliffs, NJ.

Institute of Transportation Engineers. (1984). *Recommended Guidelines for Subdivision Streets- A Recommended Practice*.

Institute of Transportation Engineers. (1985a). *Pedestrian Traffic Control Signal Indications*. Standard Number ST-011B.

Institute of Transportation Engineers. (1985b). *Vehicle Control Signal Heads*. Standard Number ST-008B.

Institute of Transportation Engineers. (1986). *Traffic Signal Lamps*. Standard Number ST-010.

Institute of Transportation Engineers. (1992). "Driver Behavior at Right-Turn-On-Red Locations." *Institute of Transportation Engineers Journal*, 62(4), pp. 18-20. Institute of Transportation Engineers: Washington, D.C.

Institute of Transportation Engineers. (1992). *Traffic Engineering Handbook*. Fourth Edition. James L. Pline (Ed.). Institute of Transportation Engineers, Prentice Hall, Englewood Cliffs, NJ.

Institute of Transportation Engineers. (1995). "Road Safety Audit: A New Tool for Accident Prevention." *TEH Journal*, *65(2)*.

Institute of Transportation Engineers. (1999). *Traffic Engineering Handbook,* Fifth Edition, James L. Pline (Ed.). Washington, D.C.

Insurance Institute for Highway Safety (IIHS). (1991). *Elderly*. Arlington, VA.

Insurance Institute for Highway Safety (IIHS). (1993). "Elderly." In: *IIHS Facts*. July, Washington, D.C.

Insurance Institute for Highway Safety (IIHS). (2000). "Elderly." In: *IIHS Fatality Facts*. Washington, D.C.

IIHS. (2007). *Insurance Institute for Highway Safety Fatality Facts 2007.* Available at http://www.iihs.org/research/fatality_facts_2007

Iowa Department of Transportation. (1991). *Iowa Running Stop Signs as a Contributing Circumstance in Fatal Accidents 1986-1990.* Iowa Department of Transportation, Driver Safety and Improvement, Des Moines, IA.

Isler, R.B., Parsonson, B.S., and Hansson, G.J. (1997). "Age Related Effects of Restricted Head Movements on the Useful Field of View of Drivers." *Accident Analysis and Prevention*, Vol. 29(6), pp 793-801.

Jacobs, G.F., Hedblom, T.P., Bradshaw, T.I., Hodson, N.A., and Austin, R.L. (1995). "Detectability of Pavement Markings Under Stationary and Dynamic Conditions as a Function of Retroreflective Brightness. *Transportation Research Record*, 1495, pp. 68-76. Transportation Research Board: Washington, D.C.

Jacquemart, G. (1998). *Synthesis of Highway Practice 264: Synthesis of Roundabout Practice in the United States*. National Cooperative Highway Research Program. Transportation Research Board: Washington, D.C.

Jainski, P. and Schmidt-Clausen, J. (1967). "Uber den Einfluss der Schwellenleuchtdicten auf das Erkennen Farbiger Signallichter (The Effect of Intensity on the Perception of Colored Signal Lights)." *Lichttechnik*, 19(1).

Janke, M. (1994). *Age-Related Disabilities That May Impair Driving and Their Assessment*. Cooperative agreement between U.S. DOT/NHTSA and the California Department of Motor Vehicles, Contract No. DTNH22-93-Y-5330. CA DMV Publication No. RSS-94-156. Sacramento, California.

Janoff, M.S. (1990). *Review of Traffic Signal Intensity Standards. Final Report*. National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, D.C.

Janoff, M., Freedman, M., and Decina, L. (1982). *Partial Lighting of Interchanges*. National Cooperative Highway Research Program, Report 256. Washington, D.C.

Jenkins, S.E. (1991). "Optical and Photometric Standards for Variable Message Signs." *Australian Road Research Board*, 216.

Jennings, B.E. (1984). *Evaluation of Rural Highway Curve Delineation Signs*. (Unpublished M.S. Thesis). School of Engineering, University of Virginia, Charlottesville.

Jenssen, G.D., Moen, T., Brekke, B., Augdal, A., and Sjøhaug, K. (1996). *Visual Performance of Fluorescent Retroreflective Traffic Control Devices. Part I: Human Factors Visibility Study*. SINTEF Transport Engineering Report No. STF22 A96606. Trondheim, Norway.

Job, R.F.S., Haynes, J., Prabhakar, T., Lee, S.H.V., and Quach, J. (1992). *Elderly and Non-Elderly Pedestrian Behavior, Knowledge, and Attitudes*. Report to the Roads and Traffic Authority of New South Wales, Australia, Central Region.

Job, R.F.S., Haynes, J., Quach, J., Lee, S.H.V., and Prabhaker, T. (1994). *Elderly Pedestrian Behaviour and Driver Attitudes and Knowledge Regarding Pedestrians. Vol 1.: Introduction to the Problem and Clearance Phase Change Evaluation*. Roads and Traffic Authority, New South Wales, Australia.

Johansson, G. and Rumar, K. (1971). "Drivers' Brake Reaction Times." *Human Factors*, *13(1)*, pp. 3-27. Human Factors and Ergonomics Society: Santa Monica, CA.

Johnston, I.R. (1983). "The Effects of Roadway Delineation on Curve Negotiation by Both Sober and Drinking Drivers." *Australian Road Research Board,* 128.

Johnston, I.R. (1982). "Modifying Driver Behaviour on Rural Road Curves—A Review of Recent Research." *Proceedings of the Eleventh Australian Road Research Board Conference*. University of Melbourne, Australia.

Jonah, B.A. and Engel, G.R. (1983). "Measuring the Relative Risk of Pedestrian Accidents." *Accident Analysis and Prevention*, 15, pp. 193-206.

Jordan, T.C. and Rabbitt, P.M.A. (1977). "Response Times to Stimuli of Increasing Complexity as a Function of Aging." *British Journal of Psychology*, 68, pp. 189-201.

Joshua, S.C. and Saka, A.A. (1992). "Mitigation of Sight-Distance Problem for Unprotected Left-Turning Traffic at Intersections." *Transportation Research Record*, 1356, pp. 73-79. Transportation Research Board: Washington, D.C.

Juergens, W.R. (1972). *Construction Zone, Detour, and Temporary Connection Accidents*. California Division of Highways and the Federal Highway Administration.

Kahn, H.A., Leibowitz, H.M., Ganley, J.P., Kini, M.M., Colton, T., Nickerson, R.S., and Dawber, T.R. (1977). "The Framingham Eye Study, 1." Outline and Major Prevalence Findings, *American Journal of Epidemiology*, 106, pp. 17-32.

Kahn, M. (1985). *Evaluation of Delineation System for Temporary Traffic Barriers in Work Zones*. Ohio Department of Transportation, Columbus, OH.

Kaub, A.R. (1990). "Passing Operations on a Recreational Two-Lane, Two-Way Highway." *Transportation Research Record*, 1280, pp. 156-162. Transportation Research Board: Washington, D.C.

Keller, J.A. (1993). "Interchange Ramp Geometrics—Alignment and Superelevation Design." *Transportation Research Record*, 1385, pp. 148-154. Transportation Research Board: Washington, D.C.

Kelly, P.D. and Bryden, J.E. (1983). *Evaluation of Louvre Type Glare Screen*. Publication No. HS-036 310. New York State Department of Transportation and the National Highway Traffic Safety Administration.

Kermit, M.L. (1968). "Rumble Strips Revisited." *Traffic Engineering,* February.

Ketvirtis, A., Moonah, S. (1995). *An Effective Use of Composite Photometry in High Mast Lighting Applications*. Paper No. 950051. 74th Annual Meeting of the Transportation Research Board, Washington, D.C.

Khasnabis, S. (1986). "Operational and Safety Problems of Trucks in No-Passing Zones on Two-Lane Highways." *Transportation Research Record*, 1052, pp. 36-44. Transportation Research Board: Washington, D.C.

Khasnabis, S. and Tad, R.R. (1983). "A Reevaluation of Crest Vertical Curve Length Requirements." *Transportation Quarterly*, 37(4), pp. 567-582.

Kihl, M. (2005). "Extending Older Drivers' Access to Freeways with Intelligent Transportation System Technologies. " *Transportation Research Record* No. 1924: Journal of the Transportation Research Board, pp 19-27.

Kihl, M., Bansal, S., Brungart, J., Gannon, A., Johnson, T., & Majumdar, D. (2004). *Its Technologies And Mature Drivers*. Arizona State University, Tempe Arizona Department of Transportation, Federal Highway Administration.

Kihlberg, K.K. and Tharp, K.J. (1968). *Accident Rates as Related to Design Elements of Rural Highways*. National Cooperative Highway Research Program, Report No. 47. Transportation Research Board, Washington, D.C.

King, G.G., Abramson, P., Cohen, J.W., and Wilkinson, M.R. (1978). *Seven Experimental Designs Addressing Problems of Safety and Capacity on Two-Lane Rural Highways: Vol. VIII—Experimental Design and Evaluate Remedial Aids for Intersections with Inadequate Sight Distance*. Publication No. DOT-TSC-FHWA-78-2. Federal Highway Administration, Washington, D.C.

Kinnan, J.P. (1993). "Grade-Crossing Safety: Safety Improvements and Awareness Help Motorists Cross Tracks With Care." *Traffic Safety*, *93(2)*, pp. 10-13.

KLD Associates (1992). *Steady-Burn Warning Lights. Final Report*. No. KLD TR-266A. Prepared for American Traffic Safety Services Association.

Klein, T., Morgan, T., and Weiner, A. (1994). *Rail-Highway Crossing Safety Fatal Crash and Demographic Descriptors*. Publication No. DOT-HS-808-196. National Highway Traffic Safety Administration, Washington, D.C.

Kline, D.W., Kline, T., Fozard, J.L., Kosnik, W., Schieber, F. and Sekuler, R. (1992). "Vision, Aging, and Driving: the Problems of Older Drivers." *Journals of Gerontology: Psychological Sciences*, *47(1)*, pp. 27-34.

Kline, D. and Fuchs, P. (1993) "The Visibility of Symbolic Highway Signs Can Be Increased among Drivers of All Ages." *Human Factors*, *35(1)*, pp. 25-34. Human Factors and Ergonomics Society: Santa Monica, CA.

Kloeppel, E., Peters, R.D., James, C., Fox, J.E., and Alicandri, E. (1995). *Comparison of Older and Younger Driver Responses to Emergency Driving Events*. Publication No. FHWA-RD-95-056. Federal Highway Administration. McLean, VA.

Knoblauch, R., Nitzburg, M., Dewar, R., Templer, A. and Pietrucha, M. (1995). *Older Pedestrian Characteristics for Use in Highway Design*. Publication No. FHWA-RD-93-177. Federal Highway Administration, Washington, D.C.

Knoblauch, R., Nitzburg, M., Reinfurt, D., Council, F., Zegeer, C., and Popkin, C. (1995). *Traffic Operations Control for Older Drivers*. Publication No. FHWA-RD-94-119. Federal Highway Administration, Washington, D.C.

Knoblauch, R., Nitzburg, M., and Seifert, R. (1997). *An Investigation of Older Driver Freeway Needs and Capabilities*. Publication No. FHWA-RD-95-194. Federal Highway Administration, Washington, D.C.

Koepke, F.J. (1993). "Ramp Exit/Entrance Design-Taper Versus Parallel and Critical Dimensions." *Transportation Research Record*, 1385, pp 126-132. Transportation Research Board: Washington, D.C.

Kostyniuk, L.P. and Cleveland, D.E. (1986). "Sight Distance, Signing, and Safety on Vertical Curves." *Institute of Transportation Engineers Journal*, 56(5), pp. 25-28. Institute of Transportation Engineers: Washington, D.C.

Krebs, H.G. and Kloeckner, J.H. (1977). "Investigation of the Effects of Highway and Traffic Conditions Outside Built-Up Areas on Accident Rates." *Forschung Strassenbau und Strassenverkehrstechnik*, 223.

Kuemmel, D. (1992). "Maximizing Legibility of Traffic Signs in Construction Work Zones." *Transportation Research Record,* 1352, pp. 25-34. Transportation Research Board: Washington, D.C.

Kyte, M. (1995). *Capacity Analysis of Unsignalized Intersections*. Draft Final Report of National Cooperative Highway Research Program, Project 3-46. Transportation Research Board, Washington, D.C.

Langlois, J.A., Keyl, P.M., Guralnik, J.M., Foley, D.J., Marottoli, R.A., and Wallace, R.B. (1997). "Characteristics of Older Pedestrians Who Have Difficulty Crossing the Street." *American Journal of Public Health*, Vol. 87(3), pp. 393-397.

Lanman, M., Lum, H., and Lyles, R. (1979). "Evaluation of Techniques for Warning of Slow-Moving Vehicles Ahead." *Transportation Research Record,* 739, pp. 45-50. Transportation Research Board: Washington, D.C.

Lee, D.N. (1976). "A Theory of Visual Control of Braking Based on Information About Time-to-Collision." *Perception*, 5, pp. 437-459.

Leibowitz, H.W. (1985). "Grade Crossing Crashes and Human Factors Engineering." *American Scientist*, 73, pp. 558-562.

Lerner, N.D., Benel, D.C., Huey, R.C., and Steinberg, G.V. (1997). *Delineation of Hazards for Older Drivers - Volume 1*. Publication No. FHWA-RD-96-161. Federal Highway Administration, Washington, D.C.

Lerner, N.D., Huey, R.W., McGee, H.W., and Sullivan, A. (1995). *Older Driver Perception-Reaction Time for Intersection Sight Distance and Object Detection. Volume I, Final Report*. Publication No. FHWA-RD-93-168. Federal Highway Administration, Washington, D.C.

Lerner, N.D. and Ratté, D.J. (1991). "Problems in Freeway Use as Seen by Older Drivers." *Transportation Research Record*, 1325, pp. 3-7. Transportation Research Board: Washington, D.C.

Lerner, N., Ratté, D., and Walker, J. (1990). *Driver Behavior at Railway-Highway Crossings*. U.S.DOT/FHWA Publication No. FHWA/SA-90/008. Federal Highway Administration, Washington, D.C.

Lerner, N.D. and Sedney, C.A. (1988). "Some Observations on Older Driver Behavior." Paper presented at the January 1988 Annual Meeting, Transportation Research Board, Washington, D.C.

Lew, A. (1971). *Wrong Way Driving, Phase III. Driver Characteristics, Effectiveness of Remedial Measures, and Effect of Ramp Type*. State of California Division of Highways, Traffic Department, Sacramento, CA.

Lewis, R. (1985). *Safer Work Zone Devices: The Next Generation. American Transportation Builder*, 62(4), pp. 10.

Ligon, C.M., Carter, E.C., and McGee, H.W. (1985). "Multiway Stop Sign Removal Procedures." *Transportation Research Record*, 1010, pp. 45-53. Transportation Research Board: Washington, D.C.

Lisle, F.N. (1978). "Evaluation of Timber Barricades and Precast Concrete Traffic Barriers for Use in Highway Construction Areas." *Transportation Research Record*, 693, pp. 18-25. Transportation Research Board: Washington, D.C.

Livneh, M., Polus, A., and Factor, J. (1988). "Vehicle Behavior on Deceleration Lanes." *Journal of Transportation Engineering*, 114, pp. 706-717.

Lord, D., Van Schalwyk, L., Staplin, L., and Chrysler, S. (2005). *Reducing Older Driver Injuries at Intersections Using More Accommodating Roundabout Design Practices.* TTI Report CTS-05-01. Texas Transportation Institute, College Station, TX. Available at http://ceprofs.tamu.edu/dlord/Papers/.

Lord, D., Van Schalwyk, L., Chrysler, S., and Staplin, L. (2007). "A Strategy to Reduce Older Driver Injuries at Intersections Using More Accommodating Roundabout Design Practices." *Accident Analysis and Prevention*., 39(3), pp 427-432.

Lum, H.S. and Hughes, W.E. (1990). Edgeline Widths and Traffic Accidents. *Public Roads*, 54(1), pp. 153-159. Federal Highway Administration, Washington, D.C.

Lundy, R.A. (1967). "The Effect of Ramp Type and Geometry on Accidents." *Highway Research Record*, 163, pp. 80-117.

Lunenfeld, H. (1977). "A Human Factors Assessment of Decreased Traffic Signal Brightness." *Public Roads*, 41(3), pp. 119-125. Federal Highway Administration, Washington, D.C.

Lunenfeld, H. (1993). "Human Factors Associated With Interchange Design Features." *Transportation Research Record*, 1385, pp. 84-89. Transportation Research Board: Washington, D.C.

Lyles, R. (1980). "Evaluation of Signs for Hazardous Rural Intersections." *Transportation Research Record,* 782, pp, 22-30. Transportation Research Board: Washington, D.C.

Lyles, R.W. (1981). "Alternative Sign Sequences for Work Zones on Rural Highways." *Transportation Research Record*, 833, pp. 13-17. Transportation Research Board: Washington, D.C.

Lyles, R.W., Kane, M.R., Vanosdall, F., and McKelvey, F.X. (1997). *Improved Traffic Control Device Design and Placement to Aid the Older Driver*. National Cooperative Highway Research Program, Project No. 3-44. Transportation Research Board, Washington, D.C.

Mace, D.J. (1988). "Sign Legibility and Conspicuity." In: *Transportation in an Aging Society*. Special Report 218, pp. 270-290. Transportation Research Board, Washington, D.C.

Mace, D., Finkle, M., and Pennak, S. (1996). *Advanced Warning Arrow Panel Visibility*. Final Report. Prepared by The Last Resource, Bellefonte, PA, for the National Academy of Sciences, Washington, D.C.

Mace, D., Finkle, M., and Pennak, S. (1996). "Photometric Requirements for Arrow Panel Visibility." *Transportation Research Record*, 1553, pp. 66-72. Transportation Research Board: Washington, D.C.

Mace, D.J., Garvey, P.M., and Heckard, R.F. (1994). *Relative Visibility of Increased Legend Size Vs. Brighter Materials for Traffic Signs*. Publication No. FHWA-RD-94-035. Federal Highway Administration, Washington, D.C.

Mace, D.J., Hostetter, R.S., and Seguin, E.L. (1967). *Information Requirements for Exiting at Interchanges*. HRB-Singer, Inc., Pennsylvania State University, Pennsylvania Department of Highways, Bureau of Public Roads.

Mace, D.J. and Pollack, L. (1983). "Visual Complexity and Sign Brightness in Detection and Recognition of Traffic Signs." *Transportation Research Record*, 904, pp. 33-41. Transportation Research Board: Washington, D.C.

Malfetti, J.L. and Winter, D.J. (1987). *Safe and Unsafe Performance of Older Drivers: A Descriptive Study*. American Automobile Association Foundation for Traffic Safety, Falls Church, VA.

Markowitz. (2006). "Pedestrian Countdown Signals: Experience with an Extensive Pilot Installation," *TEH Journal*, Institute of Transportation Engineers, Washington, DC.

Maryland Department of Transportation, State Highway Administration. (1995). *Roundabout Design Guidelines*.

Maryland State Highway Administration (MSHA). (1993). *Left-Turn Yield on Green*. Memorandum to Richard I. Kahl, Office of Traffic and Safety, from Ronald D. Lipps, Chief, Traffic Safety Division.

Massie, D., and Campbell, K. (1993). *Analysis of Accident Rates by Age, Gender, and Time of Day Based on the 1990 Nationwide Personal Transportation Survey*. Report No. UMTRI-93-7. University of Michigan Transportation Research Institute.

Mast, T.H. and Ballas, J. (1976). "Diversionary Signing Content and Driver Behavior." *Transportation Research Record,* 600, pp. 14-19. Transportation Research Board: Washington, D.C.

Mast, T.H., Chernisky, J.B., and Hooper, F.A. (1972). *Diagrammatic Guide Signs for Use on Controlled Access Highways: Vol II: Laboratory, Instrumented Vehicle, and State Traffic Studies of Diagrammatic Guide Signs*. Publication No. FHWA-RD-73-22. Federal Highway Administration, Washington, D.C.

Mather, R.A. (1991). "Seven Years of Illumination at Railroad-Highway Crossings." *Transportation Research Record*, 1316, pp. 54-57. Transportation Research Board: Washington, D.C.

Mathey, F.J. (1983). "Attitudes and Behavior of Elderly Pedestrians." *International Journal of Aging and Human Development*, 17, pp. 25-28.

Matle, C. and Bhise, V. (1984). *User's Manual for the Visibility Distance and Glare Prediction Model (DETECT)*. Ford Motor Company, Automotive Safety Office.

Matthais, J.S. and Upchurch, J.E. (1985). *Left-Turn Warrants for Arizona*. Prepared for Arizona Department of Transportation.

Maurer, D.A. (1984). *Paddle-Type Glare Screen: Final Evaluation Report*. Publication No. FHWA-PA-84-006, Pennsylvania Department of Transportation and the Federal Highway Administration, Washington, D.C.

May, J. (1992). "Guidelines for the Design and Placement of Street Signs in the Denver Region." *In: 1992 Compendium of Technical Papers*. Institute of Traffic Engineers Annual Meeting August 9, 1992–August 12, 1992.

McCoy, P.T., Navarro, U.R., and Witt, W.E. (1992). "Guidelines for Offsetting Opposing Left-Turn Lanes on Four-Lane Divided Roadways." *Transportation Research Record*, 1356, pp. 28-36. Transportation Research Board: Washington, D.C.

McDonald, L.B. and Ellis, N.C. (1975). "Driver Work Load for Various Turn Radii and Speeds." *Transportation Research Record*, 530, pp. 8-30. Transportation Research Board: Washington, D.C.

McFarland, R.A., Domey, R.C., Warren, A.B., and Ward, D.C. (1960). "Dark Adaptation as a Function of Age: A Statistical Analysis." *Journals of Gerontology*, *15*, pp. 149-154.

McFarland, W.F., Griffin, L.I., Rollins, J.B., Stockton, W.R., Phillips, D.T., and Dudek, C.L., (1979). *Assessment of Techniques for Cost-Effectiveness of Highway Accident Countermeasures.* Publication No. FHWA-RD-79-53. Federal Highway Administration, Washington, D.C.

McGee, H.W. (1991). *Freeway Guide Sign Replacement: Policies and Criteria*. National Cooperative Highway Research Program, Synthesis of Highway Practice, Report No. 155. Transportation Research Board, National Research Council, Washington, D.C.

McGee, H.W. (1995). *The Effect of Highway Standards on Safety*. National Cooperative Highway Research Program, Report No. 374. Transportation Research Board, National Research Council, Washington, D.C.

McGee, H.W. and Blankenship, M.R. (1989). *Guidelines for Converting Stop to Yield Control at Intersections*. National Cooperative Highway Research Program, Report No. 320. Transportation Research Board, National Research Council, Washington, D.C.

McGee, H.W. and Hooper, K.G. (1983). *Highway Design and Operations Affected by Driver Characteristics. Final Report*. Publication No. FHWA-RD-83-015. Federal Highway Administration, Washington, D.C.

McGee, H.W. and Knapp, B.G. (1979). "Visibility Requirements for Traffic Control Devices in Work Zones." *Transportation Research Record*, 703, pp. 6-19. Transportation Research Board: Washington, D.C.

McGee, H.W., Moore, W., Knapp,,B.G., and Sanders, J.H. (1978). *Decision Sight Distance for Highway Design and Traffic Control Requirements*. Publication No. FHWA-RD-78/78. Federal Highway Administration, Washington, D.C.

McKnight, A.J. and Adams, B.B. (1970a). *Driver Education Task Analysis, Volume 1: Task Descriptions*. Human Resources Research Organization, Alexandria, VA.

McKnight, A.J. and Adams, B.B. (1970b). *Driver Education Task Analysis, Volume 2: Task Analysis Methods*. Human Resources Research Organization, Alexandria, VA.

McKnight, A.J., Simone, G.A., and Weidman, J.R. (1982). *Elderly Driver Retraining*. Publication No. DOT HS-806 336. National Highway Traffic Safety Administration, Washington, D.C.

McKnight, A.J. and Stewart, M.A. (1990). *Development of a Competency-Based Driver's License Testing System*. National Public Services Research Institute and the California Department of Motor Vehicles.

McKnight, A.J. and Urquijo, J.I. (1993). "Sign of Deficiency Among Elderly Drivers." *Transportation Research Record*, 1405, pp. 81-86. Transportation Research Board: Washington, D.C.

McNees, R. and Messer, C. (1977). *Evaluating Urban Freeway Guide Signing—Laboratory Studies*. Report No. TTI-2-18-77-220-3, Texas Transportation Institute.

Mercier, C.R., Goodspeed, C., Simmons, C.J., and Paniati, J.F. (1995). "Evaluation of Proposed Minimum Retroreflectivity Requirements for Traffic Signs." *Transportation Research Record*, 1495, pp. 57-67. Transportation Research Board: Washington, D.C.

Messer, C.J., Mounce, J.M., and Brackett, R.Q. (1981). *Highway Geometric Design Consistency Related to Driver Expectancy*. Publication No. FHWA-RD-81-035. Federal Highway Administration, Washington, D.C.

Messer, C., Stockton, W., and Mounce, J. (1978). *Human Factors Requirements for Real-Time Motorist Information Displays, Vol 9: A Study of Physical Design Requirements for Motorist Information Matrix Signs*. Report No. FHWA-RD-78-13. Federal Highway Administration, Washington, D.C.

Michaels, R.M. and Fazio, J. (1989). "Driver Behavior Model of Merging." *Transportation Research Record*, 1213, pp. 4-10. Transportation Research Board: Washington, D.C.

Micsky, R.J. (1993). *Intersection Sight Distance Requirements for Vehicles Turning Left Off Major Highways*. M.S. Thesis, Pennsylvania State University.

Migletz, J., Fish, J.K., and Graham, J.L. (1994). *Roadway Delineation Practices Handbook*. Publication No. FHWA-SA-93-001. Federal Highway Administration, Washington, D.C.

Mihal, W.L. and Barrett, G.V. (1976). "Individual Differences in Perceptual Information Processing and Their Relation to Automobile Accident Involvement." *Journal of Applied Psychology*, 61, pp. 229-233.

Minnesota Department of Transportation. (1982). *Elderly, Pedestrian Walking Speeds—Preliminary Report*. Minnesota Department of Transportation, Office of Traffic Engineering.

Mitchell, M. (1972). "Identifying and Improving High Accident Locations." *Public Works*,3(12), pp. 75-76.

Molino, J.A., Inman, V.W., Katz, B.J., and Emo, A. (2007). *Lane Restriction Signing and Marking for Double-Lane Roundabouts*. Science Applications International Corporation and Federal Highway Administration Turner-Fairbank Highway Research Center. McLean, VA.

Morrall, J.F. and Hoban, C.J. *(1985). "Design Guidelines for Overtaking Lanes." Traffic Engineering and Control*, 26(10), pp. 476-484.

Mullins, B. and Keese, C. (1961). "Freeway Traffic Accident Analysis and Safety Study." *Highway Research Board Bulletin*, 291.

Mullowney, W. (1978). *Center Barrier Visibility Study*. Publication No. FHWA-NJ-80-002. New Jersey Department of Transportation and the Federal Highway Administration.

National Highway Traffic Safety Administration. (1987). *Fatal Accident Reporting System, 1985.* Publication No. DOT-HS-807-071. National Highway Traffic Safety Administration, Washington, D.C.

National Transportation Safety Board. (1992). *Safety Study: Highway Work Zone Safety*. Publication No. NTSA-SS-92-02, Notation 5734. Washington, D.C.

National Transportation Safety Board. (1998). *Safety Study: Safety at Passive Grade Crossings, Volume 1: Analysis*. Publication No. NTSB/SS-98/02; PB98-917004, Notation 7036. Washington, D.C.

National Transportation Safety Board. (2013). *Highway Special Investigation Report: Wrong-Way Driving*. Publication No. NTSB/SIR-12/01; PB12- 917003, Notation 8453. Washington, D.C.

Naylor, D.W. and Graham, J.R. (1997). "Intersection Design and Decision-Reaction Time for Older Drivers." *Transportation Research Record*, 1573, pp. 68-71. Transportation Research Board: Washington, D.C.

Niederhauser, M.E., Collins, B.A., and Myers, E.J. (1997). "The Use of Roundabouts: Comparisons with Alternate Design Solutions." *Compendium of Technical Papers*, 67th Annual Meeting, Institute of Transportation Engineers, Boston, MA.

Nemeth, Z.A. and Migletz, D. (1978). "Accident Characteristics Before, During, and After Safety Upgrading Projects on Ohio's Rural Interstate System." *Transportation Research Record*, 672, pp. 19-24. Transportation Research Board: Washington, D.C.

Nemeth, Z.A. and Rathi, A. (1983). "Freeway Work Zone Accident Characteristics." *Transportation Quarterly*, 37(1). pp. 145-159.

Nemeth, Z.A., Rockwell, T.H. and Smith, G.L. (1985). *Recommended Delineation Treatments at Selected Situations on Rural State Highways, Part 2: Effects of Delineation Treatment on Curve Detection Distances Under Simulated Rural Nighttime Driving Conditions*. Publication No. FHWA-OH-85-002. Ohio State University and the Federal Highway Administration.

Neuman, T.R. (1985). *Intersection Channelization Design Guide*. Report No. 279. Transportation Research Board, National Cooperative Highway Research Program, Washington, D.C.

Neuman, T.R. (1989). "New Approach to Design for Stopping Sight Distance." *Transportation Research Record*, *1208*, pp. 14-22. Transportation Research Board: Washington, D.C.

Neuman, T.R. (1992). "Chapter 6: Roadway Geometric Design." In: *Traffic Engineering Handbook,* Fourth Edition, Pline, J.L. (Ed.). Institute of Transportation Engineers, Prentice Hall, Englewood Cliffs, New Jersey.

Niessner, C.W. (1978). *Construction Zone Delineation (Raised Pavement Markers)*. Publication No. FHWA-TS-78-222. Federal Highway Administration, Washington, D.C.

Niessner, C.W. (1984). *Raised Pavement Markers at Hazardous Locations*. Publication No. FHWA-TS-84-215. Federal Highway Administration, Washington, D.C.

Noel, E.C., Gerbig, J. and Lakew, M. (1982). *Evaluation of the Left Turn Red Arrow*. Publication No. FHWA-RD-82-51. Federal Highway Administration, Washington, D.C.

Noyce, D.A. and Kacir, K. C. (2002). "Driver Understanding of Simultaneous Traffic Signal Indications in Protected Left Turns", *Transportation Research Record* 1801, pp. 18-26, 2002.

Normann, O.K. (1953). *Braking Distances of Vehicles from High Speeds*. Proceedings of the Highway Research Board, Washington, D.C.

Office of Inspector General. (2004). Audit of the Highway-Rail Grade Crossing Safety Program. Report No. MH-2004-065. U.S. Department of Transportation, Washington, D.C.

Ogwoaba, D. (1986). "An Evaluation of Portable Concrete Barrier Delineators." In: *1986 Compendium of Technical Papers*, Institute of Transportation Engineers, pp. 274-278.

Ohene, F.A. and Ardekani, S.A. (1988). "Minimum Passing Sight Distance for Completing or Aborting the Passing Maneuver." *Institute of Traffic Engineers Journal*, 58(7), pp. 29-33.

Older, S.J., and Grayson, G.B. (1972). *Perception and Decision in the Pedestrian Task*. Transportation and Road Research Laboratory, Crowthorne, England.

Olson, P.L. (1988). "Problems of Nighttime Visibility and Glare for Older Drivers." In: *Effects of Aging on Driver Performance,* SP-76, pp. 53-60. Society of Automotive Engineers.

Olson, P.L. and Bernstein, A. (1979). "The Nighttime Legibility of Highway Signs as a Function of Their Luminance Characteristics." *Human Factors*, 21, pp. 145-160. Human Factors and Ergonomics Society: Santa Monica, CA.

Olson, P.L., Sivak, M., and Egan, J.C. (1983). *Variables Influencing the Nighttime Legibility of Highway Signs*. Publication No. UMTRI-83-36. University of Michigan Transportation Research Institute, pp. 1-149.

Opiela, K.S. and Knoblauch, R.L. (1990). *Work Zone Traffic Control Delineation for Channelization*. Publication No. FHWA-RD-90-089. Federal Highway Administration, Washington, D.C.

Oppenlander, J.C. and Dawson, R.F. (1970). "Interchange." In: *Traffic Control and Roadway Elements—Their Relationship to Highway Safety—Revised*. Highway Users Federation for Safety and Mobility, Washington, D.C.

Ostrow, A.C., Shaffron, P., and McPherson, K. (1992). "The Effects of a Joint Range-of-Motion Physical Fitness Training Program on the Automobile Driving Skills of Older Adults." *Journal of Safety Research, 23*, pp. 207-219.

Ourston, L. and Bared, J. (1995). "Roundabouts: A Direct Way to Safer Highways." *Public Roads*, 59(2), Autumn 1995, pp. 41-49. Federal Highway Administration, Washington, D.C.

Ourston, L. and Doctors, P. (1995). *Roundabout Design Guidelines*. Santa Barbara, California.

Owens, R.D. (1967). "Effect of Rumble Strips at Rural Stop Locations on Traffic Operation." *Highway Research Record*, 170, pp. 35-55.

Owolabi, B. and Noel, E.C. (1985). "The Right Turn Red Arrow." *Institute of Transportation Engineers Journal*, *55(2)*, pp. 45-48. Institute of Transportation Engineers: Washington, D.C.

Owsley, C. (1987) *Aging and Night Vision. Night Vision: Current Research and Future Directions*. Technical Report, Office of Naval Research, Arlington, VA.

Owsley, C., Ball, K., Sloane, M., Roenker, D., and Bruni, J.R. (1991). "Visual/Cognitive Correlates of Vehicle Accidents in Older Drivers." *Psychology and Aging*, 6(3), pp. 403-415.

Owsley, C., Sekuler, R., and Siemsen, D. (1983). "Contrast Sensitivity Throughout Adulthood." *Vision Research*, 23(7), pp. 689-699.

Oxley, J., Fildes, B. Corben, B., Langford, J. (2006) "Intersection Design for Older Drivers." *Transportation Research, Part F*, Vol. 9, pp. 335-346.

Pain, R.F., McGee, H.W., and Knapp, B.G. (1981). *Evaluation of Traffic Controls for Highway Work Zones*. National Cooperative Highway Research Program, Publication No. 236. Transportation Research Board, Washington, D.C.

Pang, L.M. (1979). *Evaluation of Centerline Treatment Used for Two-Way, Two-Lane, No-Passing Operations on Normally Divided Rural Freeways*. M.S. Thesis, Department of Civil Engineering, University of Nebraska, Lincoln.

Pang, L.M., and Yu, J.C. (1981). "Concrete Barriers at Transition Zones Adjacent to Two-Way Traffic Operation on Normally Divided Highways." *Transportation Research Record*, 833, pp. 10-13. Transportation Research Board: Washington, D.C.

Paniati, J.F. and Mace, D.J. (1993). *Minimum Retroreflectivity Requirements for Traffic Signs*. Publication No. FHWA-RD-93-077. Federal Highway Administration, Washington, D.C.

Pant, P.D., Huang, X.H., and Krishnamurthy, S.A. (1992). "Steady Burn Lights in Highway Work Zones: Further Results of Study in Ohio." *Transportation Research Record*, 1352, pp. 56-59. Transportation Research Board: Washington, D.C.

Parsonson, P.S. (1992). *Signal Timing Improvement Practices*. National Cooperative Highway Research Program, Synthesis of Highway Practice 172. Transportation Research Board, Washington, D.C.

Parsonson, P.S. and Marks, J.R. (1979). *Wrong-Way Traffic Movements on Freeway Ramps*. Publication No. FHWA-GA-79-001. Research Project No. 7703, Georgia Department of Transportation and the Federal Highway Administration, Washington, D.C.

Parsonson, P.S. and Rinalducci, E.J. (1982). "Positive-Guidance Demonstration Project at a Railroad-Highway Grade Crossing." *Transportation Research Record*, 844, pp. 29-34. Transportation Research Board: Washington, D.C.

Paulsen, R.J., Harwood, D.W., and Glennon, J.C. (1978). "Status of Traffic Safety in Highway Construction Zones." *Transportation Research Record*, 693, pp. 6-12. Transportation Research Board: Washington, D.C.

Pegrum, B.V. (1972). *The Application of Certain Traffic Management Techniques and Their Effect on Road Safety*. National Road Safety Symposium.

Perry, J. (1992). *Gait Analysis*. New York: McGraw Hill.

Persuad, B.N., Retting, R.A., Garder, P.E., and Lore, D. (2000). *Crash Reductions Following Installation of Roundabouts in the United States*. Insurance Institute for Highway Safety. Arlington, VA.

Picha, D.L., Hawkins, H.G., and Womack, K.N. (1995). *Motorist Understanding of Alternative Designs for Traffic Signs*. Texas Transportation Institute Research Report No. 1261-5F. College-Station, TX.

Picha, D.L., Schuckel, C.E., Parham, J.A., and Mai, C.T. (1996). *Traffic Control Devices at Two-Way Stop-Controlled Intersections*. Texas Transportation Institute Report No. 1374-1F. Research performed by TTI in cooperation with TXDOT, and the U.S.DOT/FHWA.

Pietrucha, M., Hostetter, R., Staplin, L., and Obermeyer, M. (1996). *Pavement Markings and Delineation for Older Drivers*. Publication No. FHWA-RD-94-145. Federal Highway Administration, Washington, D.C.

Pigman, J.G. and Agent, K.R. (1990). "Highway Accidents in Construction and Maintenance Zones." *Transportation Research Record*, 1270, pp. 12-21. Transportation Research Board: Washington, D.C.

Pitts, D.G. (1982). "The Effects of Aging on Selected Visual Functions: Dark Adaptation, Visual Acuity, Stereopsis, and Brightness Contrast." In: *Aging and Human Visual Function*, Sekuler, R., Kline, D., and Dismukes, K. (Eds.). Liss, New York.

Pivnik, S.I. (1994). "Traffic Engineering Considerations for the Older Driver/Pedestrian." *Proceedings of the Third International Conference on Safety and the Environment in the 21st Century: Lessons Learned form the Past, Shaping the Future*, pp. 329-340. November 7-10. Tel Aviv, Israel.

Planek, T.W. and Fowler, R.C. (1971). "Traffic Accident Problems and Exposure Characteristics of the Aging Driver." *Journal of Gerontology*, 26(2), pp. 224-230.

Planek, T.W. and Overend, R.B. (1973). "Profile of the Aging Driver." *Traffic Safety*, 3(1), pp. 9.

Pline, J.L. (1996). Personal Communication to L. Staplin, August 19, 1996.

Plude, D.J. and Hoyer, W.J. (1985). "Attention and Performance: Identifying and Localizing Age Deficits." In: *Aging and Human Performance*, Charness, N. (Ed.), pp. 47-99. John Wiley and Sons, Ltd, Chichester, England.

Polus, A. and Katz, A. (1978). "An Analysis of Nighttime Pedestrian Accidents at Specially Illuminated Crosswalks." *Accident Analysis and Prevention*, *10(3)*.

Ponds, R.W., Brouwer, W.H., and Van Wolffelaar, P.C. (1988). "Age Differences in Divided Attention in a Simulated Driving Task." *Journal of Gerontology: Psychological Science*, 43, pp. 151-156.

Potts, I. Stutts, J., Pfefer, R., Neuman, T., Slack, K., and Hardy, K. (2004). *Guidance for the Implementation of the AASTHO Strategic Highway Safety Plan – Volume 9: A Guide for Reducing Collisions Involving Older Drivers.* NCHRP Report 500. Transportation Research Board.

Potts, I., Harwood, D,, and Pietrucha, M. (2001). A Supplemental Guideline on Highway Design to Accommodate Older Drivers and Pedestrians. NCHRP Project 20-7, Task 118.

Preusser, D.F., Leaf, W.A., DeBartolo, K.B., and Levy, M.M. (1982). "The Effect of Right-Turn-On-Red On Pedestrian and Bicyclist Accidents." *Journal of Safety Research*, 13(2), pp. 45-55.

Pulling, N.H., Wolf, E.S., Sturgis, S.P., Vaillancourt, D.R., and Dolliver, J.J. (1980). "Headlight Glare Resistance and Driver Age." *Human Factors*, 22(1), pp. 103-112. Human Factors and Ergonomics Society: Santa Monica, CA.

Puvanachandran, V.M. (1995). "Effect of Road Curvature on Accident Frequency: Determining Design Speeds to Improve Local Curves." *Road and Transport Research*, 4, pp. 76-83.

Rabbitt, P.M.A. (1968). "Age and the Use of Structure in Transmitted Information." In: G.A. Talland (Ed.), *Human Aging and Behavior*. New York, Academic.

Rabbitt, P.M.A. (1979). "How Old and Young Subjects Monitor and Control Responses for Accuracy and Speed." *British Journal of Psychology*, 70, pp. 305-311.

Rackoff, N.J. and Mourant, R.R. (1979). "Driving Performance of the Elderly." *Accident Analysis and Prevention*, 11(4), pp. 247-253.

Rahaman, M. (1995). "Design Criteria for Roundabouts." *1995 Compendium of Technical Papers*, Institute of Transportation Engineers 65th Annual Meeting. Denver, CO.

Raslear, T.G. (1995). "Driver Behavior at Rail-Highway Grade Crossings: A Signal Detection Theory Analysis," In: *Safety of Highway-Railroad Grade Crossings, Research Needs Workshop, Volume II— Appendices,* Caroll, A.A. and Helser, J.L. (Eds.). Report No. DOT/FRA/ORD/14.2, DOT-VNTSC-FRA-95-12.2, pp. F9-F56. U.S. Department of Transportation, Washington, D.C.

Redington, T. (1997). "Emergence of the Modern Roundabout as a Reality in Vermont and its Relation to Vermont Urban Design and Development." Paper Presented at the 32nd Annual Conference of the Canadian Transportation Research Forum, May 25-28. Toronto, Canada

Redington, T. (1997). *Montpelier's Modern Roundabout at Keck Circle*, Neighborhood Opinion Survey.

Reilly, W.R., Pfefer, R.C., Michaels, R.M., Polus, A., and Schoen, J.M. (1989). *Speed Change Lanes—Final Publication*. National Cooperative Highway Research Program, Project No. 3-35. Transportation Research Board, Washington, D.C.

Reinfurt, D., Council, F., Zegeer, C. and Popkin, C. (1992). *Summary of Literature Review, Accident Analysis, and Focus Group Study with Identification of Possible Countermeasures-Task D Working Paper*. UNC Highway Safety Research Center, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C.

Retting, R.A. and Farmer, C.M. (1998). "Use of Pavement Markings to Reduce Excessive Traffic Speeds on Hazardous Curves." *TEH Journal*, 68(9), pp. 30-36.

Richards, O.W. (1972). "Some Seeing Problems: Spectacles, Color Driving and Decline From Age and Poor Lighting." *American Journal of Optometry, Archives of the American Academy of Optometry,* 49.

Richards, S.H., Heathington, K.W., and Fambro, D.B. (1990). "Evaluation of Constant Warning Times Using Train Predictors at a Grade Crossing with Flashing Light Signals." *Transportation Research Record*, 1254, pp. 60-71. Transportation Research Board: Washington, D.C.

Riedel, C.E. (1986). "Safer Work Zone Channelization with Plastic Drums." *Institute of Transportation Engineers Journal*, *56(9)*, pp. 35-38. Institute of Transportation Engineers: Washington, D.C.

Rinalducci, E., and Beare, A. (1974). *Visibility Losses Caused by Transient Adaptation at Low Luminance Levels*. Transportation Research Board, Special Report No. 156, pp. 11-22.

Rinde, E.A. (1978). *Off-Ramp Surveillance: Wrong Way Driving*. California Department of Transportation, Office of Traffic, Sacramento, CA.

*Rural and Urban Roads*. (1973). "Phoenix Street Signs Big, Legible." Vol. 11 (5), pp. 40-41.

Roberts, A.W. (1972). Diagrammatic Sign Study. *Highway Research Record*, 414, pp. 42-49.

Roberts, A.W., Reilly, E.F., and Jagannath, M.V. (1974). *Freeway Style Diagrammatic Signs in New Jersey*. Publication No. FHWA-HPR-T-0133. New Jersey Department of Transportation, Bureau of Operations Research, Trenton, NJ and the Federal Highway Administration, Washington, D.C..

Roberts, W.N. and Roberts, P.C. (1993). "Evaluation of the Elderly Driver with Arthritis." *Clinics in Geriatric Medicine*, 9(2), pp. 311-322.

Robertson, H.D., Berger, W.G., and Pain, R.F. (1977) *Urban Intersection Improvements for Pedestrian Safety—Volume 2—Identification of Safety and Operational Problems at Intersections*. Publication No. FHWA-RD-77-143. Federal Highway Administration, Washington, D.C.

Rockwell, T.H., Hungerford, J.C., and Balasubramanian, K.N. (1976). "Evaluation of Illumination Designs for Accident Reduction at High Nighttime Accident Sites." Proceedings of the American Association for Automotive Medicine, 20.

Rodegerdts, L., Bansen, J., Tiesler, C., Knudsen, J., Myers, E., Johnson, M., Moule, M., Persaud, B., Lyon, C., Hallmark, S., Isebrands, H., Crown, R.B., Guichet, B., and O'Brien, A. (2010) *Roundabouts: An Informational Guide*. NCHRP Report 672. Transportation Research Board: Washington, D.C.

Rousseau, G. and Davis, G. (2003). *A Comparison of Countdown Pedestrian Signal Display Strategies-Draft Report*, FHWA, Federal Highway Administration, Washington, D.C.

Rowan, N.J. (1963). *Marking the Approach Ends of Channelization*. Bulletin No. 25. Texas Transportation Institute, Texas A&M University.

Ruddock, K. (1965) "The Effect of Age Upon Color Vision—II. Changes with Age in Light Transmission of the Ocular Media." *Vision Research*, 5, pp. 47-58.

Russell, E.R. and Burnham, A. (1999). "A Review of Past and Present Research, Guidelines, and Practice for the Proper Use of Stop Signs at Rail-Highway Grade Crossings." *Proceedings of the TEH International Conference: Enhancing Transportation Safety in the 21st Century*. Institute of Transportation Engineers: Washington, D.C.

Russell, E.R. and Kent, W. (1993). *Highway-Rail Crossing Safety Demonstrations*. Final Report, Contract No. DTFR53-90-C-00034. Federal Railroad Administration, Washington, D.C.

Russell, E.R. and Konz, S. (1980) "Night Visibility of Trains at Railroad-Highway Grade Crossings (Abridgment)." *Transportation Research Record*, 773, pp. 7-11. Transportation Research Board: Washington, D.C.

Russell, E.R., and Rys, M. (1994). Unpublished Field Data, Kansas State University, Manhattan, KS.

Rutley, K.S., Christie, A.W., and Fisher, A. (1965). *Photometric Requirements for Traffic Signals: Vol 1, Peak Intensities*. Road Research Laboratory, Crowthorne, England.

Saito, M. (1984). "Evaluation of the Adequacy of the MUTCD Minimum Passing Sight Distance Requirement for Aborting the Passing Maneuver." *Institute of Transportation Engineers Journal*, *January*. Institute of Transportation Engineers: Washington, D.C.

Salthouse, T.A. (1979). "Adult Age and the Speed-Accuracy Trade-Off." *Ergonomics*, 22, pp. 811-821.

Salthouse, T.A. (1991). "Mediation of Adult Age Differences In Cognition by Reductions in Working Memory and Speed of Processing." *Psychological Science*, 2, pp. 179-183.

Salthouse, T.A. and Babcock, R.L. (1991). "Decomposing Adult Age Differences in Working Memory." *Developmental Psychology*, 27, pp. 763-776.

Salthouse, T.A. and Somberg, B.L. (1982). "Isolating the Age Deficit in Speeded Performance." *Journal of Gerontology*, 37, pp. 59-63.

Sanders, J.H. (1972). *Speed Profiles and Time Delay at Rail-Highway Grade Crossings*. Publication No. FHWA-RD-72-22. Federal Highway Administration, Washington, D.C.

Sanders, J.H., McGee, H.W., and Yoo, C.S. (1978). *Safety Features of Stop Signs at Rail-Highway Grade Crossings, Volume II*. Publication No. FHWA-RD-78-41. Federal Highway Administration, Washington, D.C.

Sarkar, S., Burden, D., and Wallwork, M. (1999). "Are Drivers Well Informed About Non-Conventional Traffic Controls at Intersections?" Paper presented at the 78th Annual Meeting of the Transportation Research Board, January 10-14, 1999: Washington, D.C.

Sayed, T., Abdelwahab, W., and Nepomuceno, J. (1998). "Safety Evaluation of Alternative Signal Head Design." *Transportation Research Record*, 1635, pp. 140-146.

Scenic North Carolina News. (1998). *Circular Logic: Modern Roundabouts Offer Safety Improvements, Shorter Delays, Visual Enhancement*. Fall, 1998, pp. 4-5. Raleigh, NC.

Schwab, R.N. and Capelle, D.G. (1979). "Is Delineation Needed?" *Public Roads*, 43(3), pp. 89-96. Federal Highway Administration, Washington, D.C.

Scialfa, C.T., Guzy, L.T., Leibowitz, H.W., Garvey, P.M., and Tyrrell, R.A. (1991). "Age Differences in Estimating Vehicle Velocity." *Psychology and Aging*, 6(1), pp. 60-66.

Scifres, P.N. and Loutzenheiser, R.C. (1975). *Wrong-Way Movements on Divided Highways*. Purdue and Indiana State Highway Commission JHRP, Publication No. JHRP-13-75, HS-017 293, Civil Engineering Building, Purdue University, West Lafayette, IN.

Sekuler, R., Kline, D., and Dismukes, K. (1982). *Aging and Human Visual Function*. Liss, New York, NY.

Shechtman, O., Classen, S., Stephens, B., Bendixen, R., Belchior, P., Sandhu, M., McCarthy, D., and Mann, W. (2007). "The Impact of Intersection Design on Simulated Driving Performance of Young and Senior Adults." *Traffic Injury Prevention*, 8, pp 78-86.

Schnell, T. and Zwahlen, H.T. (1996). "Visibility of New, Dashed Yellow and White Center Stripes as a Function of Material Retroreflectivity." *Transportation Research Record*, 1553, pp. 73-80. Transportation Research Board: Washington, D.C.

Schroeder, B., Hughes, R., Rouphail, N., Salamati, K., Long, R., Guth, D.,Emerson, R.W., Kim, D., Barlow, J., Bentzen, B.L., Rodegerdts, L., and Myers, E.(2011) *Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities*. NCHRP Report 674. Transportation Research Board: Washington, D.C.

Shah, S. and Ray, G. (1976). *Advance Traffic Control Warning Systems for Maintenance Operations*. Publication No. 105. Louisiana Department of Highways Research and Development Section.

Shepard, F. (1989). *Improving Work-Zone Delineation on Limited Access Highways*. Publication No. VTRC-89-R16, FHWA-VA-89-16. Virginia Department of Transportation and the Federal Highway Administration.

Sheppard, D. and Pattinson, M. (1986). *Interviews with Elderly Pedestrians Involved in Road Accidents*. Transportation and Road Research Laboratory, Publication No. 98. Crowthorne, United Kingdom.

Shinar, D. and Eberhard, J.W. (1976). *Driver Visual Requirements: Increasing Safety Through Revised Visual Screening Tests*. American Association for Auto Medicine Conference Proceedings 20.

Simon, J.R. and Pouraghabagher, A.R. (1978). "The Effect of Aging on the Stages of Processing in a Choice Reaction Time Task." *Journal of Gerontology*, 33, pp. 553-561.

Simon, M. and Rutz, H. (1988). Sicherheit von Verkehrskreiseln Innerorts. Emch + Berger AG, Aarau, Switzerland. In Jacquemart, 1998, *Synthesis of Highway Practice 264: Synthesis of Roundabout Practice in the United States*. National Cooperative Highway Research Program. Transportation Research Board: Washington, D.C.

Sivak, M., Olson, P.L., and Pastalan, L. (1981). "Effect of Driver's Age on Nighttime Legibility of Highway Signs." *Human Factors*, 23(1), pp. 59-64. Human Factors and Ergonomics Society: Santa Monica, CA.

Sjostedt, L. (1967). "Fotgangare vid Overgangsstallen." Special Report 57, Cited In: T.W. Forbes (Ed.), *Human Factors in Highway Traffic Safety Research*. John Wiley and Sons, Inc., New York, 1972.

Skinner, R.E. (1971). "Investigate Uses and Types of Rumble Strips and their Adaptability for Approaches to Highway-Rail Grade Crossings." *American Railway Engineering Association Bulletin*, 73(635), pp. 198-199.

Sleight, R.B. (1972). "The Pedestrian." In: T.W. Forbes, (Ed.), *Human Factors in Highway Traffic Safety Research*. Wiley, New York, pp. 224-253,

Sloane, M.E., Owsley, C., and Alvarez, S. (1988). "Aging, Senile Miosis, and Spatial Contrast Sensitivity at Low Luminance." *Vision Research*, *28*, pp. 1235-1246.

Sloane, M.E., Owsley, C., and Jackson, C. (1988). "Aging and Luminance Adaptation Effects in Spatial Contrast Sensitivity." *Journal of the Optical Society of America*.

Sloane, M.E., Owsley, C., Nash, R., and Helms, H. (1987). "Acuity and Contour Interaction in Older Adults." *The Gerontologist*, 27, pp. 132A.

Smith, B.H. and Sethi, P.K. (1975). "Aging and the Nervous System." *Geriatrics*, 30, pp. 109-115.

Spencer, L.J. (1978). *Construction Zone Delineation (Raised Pavement Markers).* Publication No. DOT-FH-11-8899. Arkansas State Highway and Transportation Department and the Federal Highway Administration, Washington, D.C.

Stamatiadis, N., Taylor, W.C., and McKelvey, F.X. (1991). "Elderly Drivers and Intersection Accidents." *Transportation Quarterly*, 45(3), pp. 377-390.

Staplin, L. and Fisk, A. (1991). "A Cognitive Engineering Approach to Improving Signalized Left-Turn Intersections." *Human Factors,* 33(5), pp. 559-571. Human Factors and Ergonomics Society: Santa Monica, CA.

Staplin, L., Harkey, D., Lococo, K., and Tarawneh, M. (1997). *Intersection Geometric Design and Operational Guidelines for Older Drivers and Pedestrians, Volume I: Final Report*. Publication No. FHWA-RD-96-132. Federal Highway Administration, Washington, D.C.

Staplin, L., Lococo, K., McKnight, A.J., McKnight, A.S., and Odenheimer, G. (1994). *Task 2 Letter Report: Intersection Negotiation Problems of Older Drivers*. Publication No. DTNH22-93-C-05237. National Highway Traffic Safety Administration, Washington, D.C.

Staplin, L., Lococo, K., and Sim, J. (1990). *Traffic Control Design Elements for Accommodating Drivers With Diminished Capacity*. Publication No. FHWA-RD-90-055. Federal Highway Administration, Washington, D.C.

Staplin, L., Lococo, K., and Sim, J. (1993). *Traffic Maneuver Problems of Older Drivers*. Publication No. FHWA-RD-92-092. Federal Highway Administration, Washington, D.C.

Staplin, L., Lococo, K., Sim, J., and Gish, K. (1996). *Visibility from Vehicles Research Volume II: Indirect Visibility Study of Alternate Mirror Systems for Passenger Vehicles*. Publication No. DTNH22-91-C-07000. National Highway Traffic Safety Administration, Washington, D.C.

Staplin, L. and Lyles, R.W. (1991). "Age Differences in Motion Perception and Specific Traffic Maneuver Problems." *Transportation Research Record,* 1325, pp. 23-33. Transportation Research Board: Washington, D.C.

Stelmach, G.E., Goggin, N.L., and Amrhein, P.C. (1988). "Aging and Reprogramming: The Restructuring of Planned Movements." *Psychology and Aging*, 3, pp. 151-157.

Stelmach, G.E., Goggin, N.L. and Garcia-Colera, A. (1987). "Movement Specification Time with Age." *Experimental Aging Research*, 13, pp. 39-46.

Strate, H.H. (1980). "Making Highways Safe: A Realistic Approach." *Institute of Transportation Engineers Journal*, pp. 21-30. Institute of Transportation Engineers: Washington, D.C.

Summala, H., and Mikkola, T. (1994). "Fatal Accidents Among Car and Truck Drivers: Effects of Fatigue, Age, and Alcohol Consumption." *Human Factors*, 36(2), pp. 315-326. Human Factors and Ergonomics Society: Santa Monica, CA.

Swanson, H. Allen, Dewar, Robert E., and Kline, Donald W. (1994). *Design of Traffic Sign Symbols*. Paper prepared for presentation at the 1994 International Road Federation Conference, Calgary, Alberta, Canada.

Szlyk, J.P., Severing, K., and Fishman, G.A. (1991). *Peripheral Visual Field Loss and Driving Performance*. AAA Foundation for Traffic Safety, Washington, D.C.

Taekratok, T. (1998). *Modern Roundabouts for Oregon*. Publication No. OR-RD-98-17. Oregon Department of Transportation, Salem, Oregon.

Tamburri, T.N. (1969). "Wrong-Way Driving Accidents are Reduced." *Highway Research Record*, 292, pp. 24-50.

Tamburri, T.N. and Theobald, D.J. (1965). *Wrong-Way Driving (Phase II)*. California Division of Highways, Department of Public Works, Traffic Department.

Taoka, G.T. (1991). "Distribution of Driver Spare Glance Durations." *Transportation Research Record*, 1318, pp. 142-146. Transportation Research Board: Washington, D.C.

Tarawneh, M.S. (1991). *Elderly Driver's Perception-Reaction Time in Response to Traffic Signals*. Department of Civil Engineering, University of Nebraska, Lincoln, NE.

Taylor, J.I. and McGee, H.W. (1973). *Improving Traffic Operations and Safety at Exit Gore Areas*. Publication No. 145. National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C.

Tobey, H.N., Shungman, E.M., and Knoblauch, R.L. (1983). *Pedestrian Trip Making Characteristics and Exposure Measures.* U.S. Department of Transportation, Federal Highway Administration, Washington, D.C.

Tranchida, D., Arthur, E., and Stackhouse, S. (1996). *Retroreflective Sheeting Materials on Highway Signs*. Publication No. MN/RC-96/07. Minnesota Department of Transportation.

TranSafety. (1987). "ATSSA Opposes Metal Drums in Work Zones." *TranSafety Reporter, 5(12)*, p. 6.

Transportation Research Board. (1981). *Effectiveness of Changeable Message Displays in Advance of High-Speed Freeway Lane Closures.* National Cooperative Highway Research Program. Washington, D.C.

Transportation Research Board. (1988). *Transportation in an Aging Society, Special Report 218, Volumes 1 and 2*, Washington, D.C.

Transportation Research Board. (1999). *Highway Capacity Manual*. Special Report 209. National Research Council, Washington, D.C.

Transportation Research Board. (1991) "Research Problem Statements Impact of Aging Driver Population on Geometric Design." *Transportation Research Circular, 382*.

Treat, J.R., Tumbas, N.S., McDonald, S.T., Shinar, D., Hume, R.D., Mayer, R.E., Stansifer, R.L., and Castellan, N.J. (1977). *Tri-Level Study of the Causes of Traffic Accidents*. Indiana University, Bloomington, IN.

Tutt, P.R. and Nixon, J.F. (1969). *Driver Communication Through Roadway Delineation*. Research Report No. SS 12.1. Texas Highway Department, Austin, TX.

Ullman, G.L., and Dudek, C.L. (1988). "Delineation of Concrete Safety Shaped Barriers." *Transportation Research Record*, 1160, pp. 97-104. Transportation Research Board: Washington, D.C.

Ullman, G.L., Parma, K.D., Peoples, M.D., Trout, N.D., and Tallamraju, S.S. (1996). *Visibility, Spacing, and Operation of Freeway Lane Control Signals*. Publication No. FHWA/TX-97/1498-3F. Texas Department of Transportation and the Federal Highway Administration.

Upchurch, J. (1991). "Comparison of Left-Turn Accident Rates for Different Types of Left-Turn Phasing." *Transportation Research Record*, 1324, pp. 33-40. Transportation Research Board: Washington, D.C.

Upchurch, J., Baaj, H., Armstrong, J., Thomas, G. (1991). *Evaluation of Variable Message Signs*. Prepared for Kimley-Horn and Associates and the Arizona Department of Transportation.

U.S. Bureau of the Census. (1996). *Current Population Reports*. Special Studies. P23-190, 65+ in the United States, p. 2-1. U.S. Government Printing Office, Washington, D.C.

Van Houten, R., Retting, R.A., Farmer, C.M., and Van Houten, J. (1997). *Field Evaluation of a Leading Pedestrian Interval Signal Phase at Three Urban Intersections*. Insurance Institute for Highway Safety. Arlington, VA.

Van Mauren, P.A. (1977). *Correlation of Design and Control Characteristics with Accidents at Rural Multi-Lane Highway Intersections in Indiana*. Publication No. FHWA-IN-77-20. Federal Highway Administration, Washington, D.C.

Van Nes, F., Koenderink, J., Nas, H., and Bouman, M. (1967). "Spatiotemporal Modulation Transfer Function of the Human Eye." *Journal of the Optical Society of America*, 57(9), pp. 1082-1088.

Van Wolffelaar, P.C., Brouwer, W., and Rothengatter, T. (1990). *Divided Attention in RTI-Tasks for Elderly Drivers*. Traffic Research Center, University of Groningen, Groningen, The Netherlands.

Vaswani, N.K. (1974). "Case Studies of Wrong-Way Entries at Highway Interchanges in Virginia." *Transportation Research Record*, 514, pp. 16-28. Transportation Research Board: Washington, D.C.

Vaswani, N.K. (1977). "Virginia's Crash Program to Reduce Wrong-Way Driving." *Transportation Research Record*, 644, pp. 84-90. Transportation Research Board: Washington, D.C.

Virginia Department of Highways and Transportation. (1981a). *An Evaluation of the Effectiveness of Rumble Strips*. Traffic and Safety Division Evaluation No. 81-5.

Virginia Department of Highways and Transportation (1981b). *Typical Regulatory Signing for Exit Ramp Terminals*. Traffic and Safety Division Memorandum No. T&S 166, Superseding T&S No. 165.

Waller, P.F., House, E.G., and Stewart, J.R. (1977). *An Analysis of Accidents by Age*. Paper presented at the Annual Meeting of the Transportation Research Board, Washington, D.C.

Wallwork, M. (1993). Roundabouts in the USA.

Wallwork, M. (1999) Personal communication, 7/30/99.

Walsh, D., Till, R., and Williams, M. (1978). "Age Differences in Peripheral Perceptual Processing: A Monoptic Backward Masking Investigation." *Journal of Experimental Psychology: Human Perception and Performance,* 4.

Ward, A. (1988). "Discussant: Field Studies of Temporary Pavement Markings at Overlay Project Zones on Two-Lane, Two-Way Rural Highways." *Transportation Research Record*, 1160, pp. 22-34. Transportation Research Board: Washington, D.C.

Warren, D.L. (1985). "Accident Analysis of Left-Turn Phasing." *Public Roads*, 48(4), pp. 121-127. Federal Highway Administration: Washington, D.C.

Waugh, N.C., Thomas, J.C., and Fozard, J.L. (1978). "Retrieval Time from Different Memory Stores." *Journal of Gerontology*, 33.

Weaver, G.D. and Glennon, J.C. (1972). "Design and Striping for Safe Passing Operations." *Highway Research Record,* 390, pp. 36-39.

Weaver, G., Richards, S., Hatcher, D., and Dudek, C. (1978). *Human Factors Requirements for Real-Time Motorist Information Displays, Vol 14: Point Diversion for Special Events Field Studies*. Publication No. FHWA-RD-78-18. Federal Highway Administration, Washington, D.C.

Weiner, E.L. (1968). "The Elderly Pedestrian: Response to an Enforcement Campaign." *Traffic Safety Research Review*, 12(4), pp. 100-110.

Weymouth, F.W. (1960). "Effects of Age on Visual Acuity." In: *Vision of the Aging Patient,* Hirsch, M.I. and Wick, R.E. (Eds.). Chilton, Philadelphia.

Williams, C., Ardekani, S., and Asante, S. (1992). "Motorist Understanding of Left-Turn Signal Indications and Auxiliary Signs." *Transportation Research Record*, 1376, pp. 57-63. Transportation Research Board: Washington, D.C.

Wilshire, R.L. (1992). "Chapter 9: Traffic Signals." In: Pline, J.L (Ed.) *Traffic Engineering Handbook*, *Fourth Edition*. Institute of Transportation Engineers. Prentice Hall: New Jersey.

Wilson, D.G. and Grayson, G.B. (1980). *Age-Related Differences in the Road Crossing Behavior of Adult Pedestrians*. Publication No. TRRL-L-933. Transport and Road Research Laboratory: Crowthorne, England.

Winter, D. (1985). "Learning and Motivational Characteristics of Older People Pertaining to Traffic Safety." In: *Proceedings of the Older Driver Colloquium*. Washington, DC, pp. 77-86.

Wolf, E. (1960). "Glare and Age." *Archives of Ophthalmology*, 64, pp. 502-514.

Wood, J.A. and Troutbeck, R.J. (1994). "Effect of Age and Visual Impairment on Driving and Vision Performance." *Transportation Research Record*, 1438, pp. 84-90. Transportation Research Board: Washington, D.C.

Woods, D.L., Rowan, N.J., and Johnson, J.H. (1970). *Significant Points from the Diagnostic Field Studies—Summary Report*. Research Publication No. 606-4. Texas Transportation Institute, Texas A&M University.

Wooten, B., and Geri, G. (1987). "Psychophysical Determination of Intraocular Light Scatter as a Function of Wavelength." *Vision Research*, 27(8), pp. 1291-1298.

Wright, P.H. (1983). "Low Cost Countermeasures for Ameliorating Run-Off-The-Road Crashes." *Transportation Research Record,* 926, pp. 1-7. Transportation Research Board: Washington, D.C.

Wright, P.H. and Robertson, L.S. (1979). "Amelioration of Roadside Obstacle Crashes." *Journal of Transportation Engineering*, 105(6), pp. 609-622.

Yee, D. (1985). *A Survey of the Traffic Safety Needs and Problems of Drivers Age 55 and Over. Needs and Problems of Older Drivers: Survey Results and Recommendations*. American Automobile Association, Foundation for Traffic Safety; Falls Church, VA.

Zador, P.L. (1984). "Right-Turn-On-Red Laws and Motor Vehicle Crashes: A Review of the Literature." *Accident Analysis and Prevention*, 16(4), pp. 241-245.

Zador, P., Stein, H., Wright, P. and Hall, J. (1986). *Effects of Chevrons, Post-Mounted Delineators, and Raised Pavement Markers on Driver Behavior at Roadway Curves*. Insurance Institute for Highway Safety, Washington, D.C.

Zajkowski, M.M. and Nees, M. (1976). "Diagrammatic Highway Signs." *Transportation Research Record*, 600, pp. 7-13. Transportation Research Board: Washington, D.C.

Zegeer, C.V. (1975). *The Effectiveness of School Signs With Flashing Beacons in Reducing Vehicle Speeds*. Publication No. 429. Division of Research, Kentucky Bureau of Highways.

Zegeer, C.V. (1991). *Synthesis of Safety Research: Pedestrians*. Publication No. FHWA-SA-91-034. Federal Highway Administration, Washington, D.C.

Zegeer, C.V. and Cynecki, M.J. (1986). "Evaluation of Countermeasures Related to RTOR Accidents that Involve Pedestrians." *Transportation Research Record*, 1059, pp. 24-34. Transportation Research Board: Washington, D.C.

Zegeer, C.V., Opiela, K.S., and Cynecki, M.J. (1982). "Effect of Pedestrian Signals and Signal Timing on Pedestrian Accidents." *Transportation Research Record*, 847, pp. 62-72. Transportation Research Board: Washington, D.C.

Zegeer, C.V., Opiela, K.S., and Cynecki, M.J. (1983). *Pedestrian Signalization Alternatives*, Publication No. FHWA-RD-83-102. Federal Highway Administration, Washington, D.C.

Zegeer, C.V., Stewart, R., Reinfurt, D., Council, F.M., et al. (1990). *Cost-Effective Geometric Improvements for Safety Upgrading of Horizontal Curves*. Publication No. FHWA-RD-90-021. Federal Highway Administration, Washington, D.C.

Zegeer, C.V. and Zegeer, S. (1988). *Pedestrians and Traffic Control Measures, Synthesis of Highway Practices*. Publication No. 139, Transportation Research Board, Washington, D.C.

Ziskind, D., Mace, D., Staplin, L., Sim, J., and Lococo, K. (1991). *Minimum Visibility Requirements for Traffic Control Devices*. Publication No. FHWA-RD-91-074. Federal Highway Administration, Washington, D.C.

Zwahlen, H.T. (1978). "Driver Lateral Control Performance and Delineation." *Transportation Research Record,* 1149, pp. 56-65. Transportation Research Board: Washington, D.C.

Zwahlen, H.T. (1989). "Conspicuity of Suprathreshold Reflective Targets in a Driver's Peripheral Visual Field at Night." *Transportation Research Record*, 1213, pp. 35-46. Transportation Research Board: Washington, D.C.

Zwahlen, H.T., Miller, M.E., Khan, M., and Dunn, R. (1988). "Optimization of Post Delineator Placement From a Visibility Point of View." *Transportation Research Record*, 1172, pp. 78-87. Transportation Research Board: Washington, D.C.

Zwahlen, H.T. and Schnell, T. (1998). *Pavement Marking Visibility Research and Proposed Values for Minimum Required Pavement Marking Retroreflectivity*. Final Report Draft. Prepared for Federal Highway Administration, under Grant No. DTFH61-95-X-00034.

Zwahlen, H. and Schnell, T. (2000). *Evaluation of the Buckeye Crossbuck at Public, Passive Railroad/Highway Grade Crossings in Ohio*. Ohio University Human Factors and Ergonomics Laboratory, Ohio Research Institute for Transportation and the Environment. Athens, Ohio.

Zwahlen, H.T., Russ, A., Roth, J.M., and Schnell, T. (2003) "Evaluation of the Effectiveness of Ground Mounted Diagrammatic Advance Guide Signs For Freeway Entrance Ramps", Paper No. 03-3315, presented at the 82nd Annual Transportation Research Board Meeting, National Academy of Sciences, Washington, DC.