Alternative Design Consistency Rating Methods for Two-Lane Rural Highways

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FORWARD

Current procedures for designing rural alignments rely on the selection and application of design speeds. U.S. highway geometric design researchers and practitioners generally recognize the need to supplement current design procedures for two-lane rural highways with reliable, quantitative safety-evaluation methods. To address this need, the Federal Highway Administration is developing the Interactive Highway Safety Design Model (IHSDM) as a framework for an integrated design process that systematically considers both the roadway and the roadside in developing cost-effective highway design alternatives. The focus of IHSDM is on the safety effects of design alternatives. Design consistency is one of several modules built around a commercial computer-aided design package in the current vision of IHSDM. Other modules include: crash prediction, driver/vehicle, intersection diagnostic review, policy review, and traffic analysis.

The research documented in this report investigated alternatives that could be used in the design consistency module of IHSDM. The three methods studied included: alignment indices, spot speed variability measures, and driver workload. Based upon the findings, alignment indices and speed variability measures were not recommended for use in the design consistency module. Driver workload, however, has a good potential as a design consistency rating measure.

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NOTICE

1. Report No. FHWA-RD-99-172	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle ALTERNATIVE DESIGN CONSISTENCY RATING METHODS FOR TWO-LANE RURAL HIGHWAYS		5. Report Date
		6. Performing Organization Code
7. Author(s) Kay Fitzpatrick, Mark D. Wooldridge, Omer Tsimhoni, Jon M. Collins, Paul Green, Karin M. Bauer, Kelly D. Parma, Rodger Koppa, Douglas W. Harwood, Ingrid Anderson, Raymond A. Krammes, and Brian Poggioli		8. Performing Organization Report No.
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DTFH61-95-R-00084
12. Sponsoring Agency Name and Address Office of Safety and Traffic Operations R&D Federal Highway Administration U.S. Department of Transportation 6300 Georgetown Pike McLean, VA 22101-2296		13. Type of Report and Period Covered Final Report September 1995 - January 1999
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract
Design consistency refers to the conformance of a highway's geometry with driver expectancy. Drivers make fewer errors in the vicinity of geometric features that conform with their expectations. Techniques to evaluate the consistency of a design documented within this report include alignment indices, speed distribution measures, and driver workload. Alignment indices are quantitative measures of the general character of a roadway segment's alignment. Potential indicators of geometric inconsistency include a large increase in the magnitude of the alignment indices for a successive roadway segment or feature or a high rate of change occuring over some length of road. Speed distribution measures—including variance, standard deviation, coefficient of variation, and coefficient of skewness—were investigated as potential candidates for a consistency rating method. The results indicated that speed variance is inappropriate as a design consistency measure for horizontal curvature. Driver workload is a measure of the information processing demands imposed by roadway geometry on a driver. The efforts for this study used both objective and subjective measures to model geometric features and combinations of features in terms of the difficulty that they pose to drivers. Vision occlusion, subjective difficulty ratings, a driving simulator, and an eye-mark system were used during the research.

17. Key Words Rural two-lane highway, design consistency measures, alignment indices, speed distribution, driver workload, visual demand.	18. Distribution Statement This document is available to the public via internet access at www.tfhrc.gov/safety/ihsdm.ihsdm.htm		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 162	22. Price

Form DOT F 1700.7 (8-72)

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1. INTRODUCTION

BACKGROUND

The goal of transportation is generally stated as the safe and efficient movement of people and goods. To achieve this goal, designers use many tools and techniques. One technique used to improve safety on roadways is to examine the consistency of the design. Design consistency refers to a highway geometry's conformance with driver expectancy. Generally, drivers make fewer errors at geometric features that conform with their expectations than at features that violate their *a priori* and/or *ad hoc* expectancies.[1]

In the United States, design consistency on rural two-lane highways has been assumed to be provided through the selection and application of a design speed. Design speed is defined by the American Association of State Highway and Transportation Officials (AASHTO) as "the maximum safe speed that can be maintained over a specified section of highway when conditions are so favorable that the design features of the highway govern."[2] If a road is consistent in design, then the road should not violate the expectations of motorists or inhibit the ability of motorists to control their vehicle safely.[3] Consistent roadway design should ensure that "most drivers would be able to operate safely at their desired speed along the entire alinement."[4]

One weakness of the design-speed concept is that it uses the design speed of the most restrictive geometric element within the section, usually a horizontal or vertical curve, as the design speed of the road. Consequently, the design-speed concept currently used in the United States does not explicitly consider the speeds that motorists travel on tangents. Other weaknesses in the design-speed concept have generated discussions and additional research into other methods for evaluating design consistency along two-lane rural highways. Both speed-based and non-speed-based highway geometric design consistency evaluation methods have been considered. These methods have taken several forms, and can generally be placed into the following areas: vehicle operations-based consistency (including speed), roadway geometrics-based consistency, driver workload, and consistency checklists.

Some of these methods may be incorporated into the Interactive Highway Safety Design Model (IHSDM). IHSDM is being developed by the Federal Highway Administration (FHWA) as a framework for "an integrated design process that systematically considers both the roadway and the roadside in developing cost-effective highway design alternatives."[5] The focus of IHSDM is on the safety effects of design alternatives. Design consistency is one of several modules built around a commercial computer-aided design package in the current version of IHSDM.[6] Other modules include: crash prediction, driver/vehicle, intersection diagnostic review, policy review, and traffic analysis.

OBJECTIVES

An earlier FHWA study developed a design consistency evaluation procedure that used a speed-profile model based on horizontal alinement.[7] The objective of this study, "Design Consistency Evaluation Module for the Interactive Highway Safety Design Model (IHSDM)," was to expand the research conducted under the previous FHWA study into two directions. These directions were to (1) expand the speed profile model and (2) investigate three promising design consistency rating methods. The expansion of the speed profile model is documented elsewhere.[8] While operating speed is the more common method for evaluating the consistency of a roadway, other methods have been discussed and explored. The three methods selected for additional investigation in this study and documented in this report include:

- Alignment Indices
- Speed Distribution Measures
- Driver Workload/Visual Demand

ORGANIZATION OF THE REPORT

The report is organized into eight chapters:

Chapter 1. Introduction describes the background of the research project and the research objective.

Chapter 2. Methods for Rating Design Consistency provides a review of different design consistency methods and identifies the methods selected for this research project.

Chapter 3. Alignment Indices presents background information on different methods and the analysis methodology and results from this research.

Chapter 4. Speed Distribution Measures presents the analysis methodology and results from this research.

Chapter 5. Driver Workload— Field presents information from previous research projects and the methodology and results from this research.

Chapter 6. Driver Workload / Eye Fixation—Simulation presents the driving simulator and eye fixation methodology and results from this research.

Chapter 7. Comparison of Workload Values presents results from comparisons made between similar aspects of the field and driving simulator workload efforts.

Chapter 8. Summary, Findings, Conclusions, and Recommendations summarizes the study effort and findings and provides conclusions and recommendations.

2. METHODS FOR RATING DESIGN CONSISTENCY

DESIGN CONSISTENCY CONCEPT

Design consistency implies that the design or geometry of a road does not violate either the expectation of the motorist or the ability of the motorist to guide and control a vehicle in a safe manner.[3] Keeping a roadway consistent in design is important because it is believed that motorists make fewer errors at geometric features that conform with their expectations than at features that violate their expectancies.[9] An inconsistency in design can be defined as "a geometric feature or combination of adjacent features that have such unexpectedly high driver workload that motorists may be surprised and possibly drive in an unsafe manner."[10]

A consistent alignment is important because the relationship that exists between consistency and safety. The inconsistencies that exist on a roadway can produce a sudden change in the characteristic of the roadway, which can surprise motorists and lead to speed errors.[4] These speed errors result in critical driving maneuvers for motorists and an unfavorable level of accident risks.[11] These design inconsistencies arise when the general character of alignment changes between segments of the roadway. A consistent alignment would ensure that "most drivers would be able to operate safely at their desired speed along the entire alignment."[4]

Design consistency refers to the conformance of the highway geometry to driver expectancy. Expectancy, in general, can be thought of as a set of possible probabilities regarding a given situation.[12] Those probabilities are subjective and are based upon learned and experienced events. An operational definition of expectancy with regard to transportation has been given by Ellis:

> "Driver expectancy relates to the observable, measurable features of the driving environment which: (1) increase a driver's <u>readiness</u> to perform a driving task in a particular manner, and (2) cause the driver to <u>continue</u> in the task until it is completed or interrupted."[13]

A similar definition was provided by Alexander and Lunenfeld:

> "Expectancy relates to a driver's readiness to respond to situations, events, and information in predictable and successful ways."[1]

Attempts to learn about and to provide information to the designer regarding design consistency and driver expectancy have been the subject of several major research projects and reports. In general, they can be grouped into the following areas: vehicle operations-based consistency, roadway geometrics-based consistency, driver workload, and consistency checklists. The most common vehicle operations-based consistency measure is operating speed, although other methods such as conflicts and accidents have been suggested. A method for using

operating speed as a consistency check is to predict speed using a speed profile model. Roadway geometrics-based consistency focuses on evaluating the consistency of the design using only information that would be typically available from a set of roadway plans. Driver workload assumes that there is a relationship between the effort required to perform a task and the roadway geometrics presented during that performance. Checklists largely consist of reminders to designers to examine design features for possible expectancy violations. Following is a brief summary of these different types of design consistency approaches.

SPEED - PROFILE MODELS FOR RATING DESIGN CONSISTENCY

Since the 1930s, the design-speed concept has been the principal quantitative mechanism for ensuring consistency of safe operating speeds along rural highway alignments. The concept arose from safety concerns about differentials between the speeds at which drivers could safely operate their vehicles on tangents and the lower speeds at which they could safely operate on horizontal curves. The solution implemented by the design-speed concept was that all alignment features should be designed to accommodate the desired speeds of most drivers using the roadway or, in other words, that an appropriate design speed should be uniformly applied to all alignment elements of the roadway.

Unfortunately, speed inconsistencies continue to be observed on rural two-lane highways.[7,14,15] Observed speed inconsistencies led Australia and several European countries to revise their design policies to strengthen consistency considerations. In the United States, speed-profile models for consistency evaluation have been developed but not incorporated into design policy and, therefore, are not widely used.[16,17,18]

In the early 1970s, Switzerland incorporated into its design policy a method for estimating speed profiles as a means of identifying features that would require undesirably large speed reductions.[19] At about the same time, Germany implemented a procedure that evaluated the angular change in direction per unit of distance (i.e., curvature change rate), correlated curvature change rate with operating speeds, and limited the difference in rates (speeds) between successive roadway segments.[20] In the late 1970s, Australian research found 85th percentile speeds faster than design speeds on curves with design speeds less than 90 km/h; these findings prompted revisions in alignment design procedures that added iterations to estimate 85th percentile speeds along an alignment, check for speed consistency, and adjust designs to limit the change in speeds between successive features.[16,21] In all three countries, consistency procedures consider only horizontal alignment.

Leisch and Leisch in the 1970s, Lamm et al. in the 1980s, and Krammes et al. in the 1990s developed speed-based consistency evaluation procedures for U.S. use.[7,17,18] None of the methods have been widely used. The Leisch procedure is unique in three primary ways: (1) it considers both passenger vehicle and truck speeds, whereas other procedures consider only passenger vehicles; (2) it considers the combined effects of horizontal and vertical alignment,

whereas other procedures consider only horizontal alignment; and (3) it varies deceleration rates approaching and acceleration rates departing curves as a function of approach tangent, curve, and departure tangent parameters, whereas other procedures assume equal and constant acceleration and deceleration rates.[17] The principal weakness of the procedure is that it is based upon speed information contained in 1965 and 1973 AASHTO design policies that are now updated. The Lamm model for estimating 85th percentile speeds along horizontal alignments is similar to the Swiss procedure.[18] The procedure was calibrated using data from more than 200 curves in New York State.

Krammes et al. reviewed previous research and the state of the practices in the United States as well as Australia, Canada, and Europe, and concluded that: (1) the greatest concerns with rural two-lane highway consistency relate to horizontal alignment, and (2) the model framework developed by the Swiss and adapted by Lamm was sound in concept, appropriate in sophistication, and reasonable in data requirements.[7] The principal concern about the Lamm model was the data with which it was calibrated. Therefore, Krammes et al. adopted the basic model form proposed by Lamm, collected additional speed and geometry data in three regions of the United Stated to recalibrate the model, and implemented a computerized procedure to use the model. Subsequently, a limited validation study (using data from 10 curves in Texas with characteristics similar to those used to calibrate the model) indicated that the Krammes et al. model produces reasonable estimates of speed reductions from an approach tangent to a curve.[22] This current FHWA project also developed a speed profile model that considered both horizontal and vertical alignment. The discussion of the findings from those efforts is contained in another report.[8]

VEHICLE OPERATIONS-BASED CONSISTENCY (OTHER THAN SPEED)

Measures of vehicle operations that may be an appropriate basis for consistency rating methods include speed variance, lateral placement (mean and variance), erratic maneuvers, and traffic conflicts. These measures have been evaluated as surrogate measures of accident experience and measures of effectiveness of delineation treatments.[23-26] In roadway delineation research, speed variance and lateral placement variance have been considered as indicators of the effectiveness of alternative treatments at reducing errors in the guidance level of the driving task. Design inconsistencies also increase guidance-level errors, and it is reasonable to hypothesize that these measures would be correlated with and could complement speed reduction in evaluating design consistency.

In this FHWA study, alternative methods other than speed are also being investigated to examine the design consistency rating of two-lane rural highways. One of the methods evaluated was speed distribution measures. Speed distribution measures—including variance, standard deviation, coefficient of variation, and coefficient of skewness—are logical candidates for a consistency rating method to complement speed reduction estimates from the 85th percentile speed models. The rationale for using spot speed variability measures is that inconsistent

features are expected to cause more driver errors and greater variation in guidance-level decisions (i.e., speed and path choice) than consistent features. Correspondingly, it is hypothesized that inconsistent features will exhibit more spot speed variability than consistent features and that single-vehicle accidents resulting from guidance-level errors will increase with increasing speed variability. Discussion on the findings from the research are contained in chapter 4 of this report.

ROADWAY GEOMETRICS-BASED CONSISTENCY

Some consistency rating methods focus directly on roadway geometry. For example, the curvature change rate used in Germany is a horizontal alignment index that indicates the alignment severity.[20] The British use two indices—one for alignment and one for layout—to check for compatibility between a roadway segment's design speed and likely operating speeds on the roadway.[27] The alignment constraint is an indicator of the extent to which the alignment constrains speeds and is a function of the total angular change in direction per km and the harmonic mean of available sight distance along the alignment. The layout constraint is an indicator of the extent to which roadway type, cross-section width, and access density constrain speed. Polus and Dagan proposed alignment indices based upon: the proportion of a roadway section that is curved, the ratio of the minimum and maximum radii of a roadway section, the ratio of the average radius of curves on a roadway section to the minimum radius for the roadway's design speed, and spectral analysis of the extent to which the alignment exhibits a cyclical or repeating pattern.[28] Their preliminary evaluations suggested that such indices hold promise as measures of consistency.

In this FHWA study, one of the alternative methods for rating the design consistency is alignment indices (see chapter 3). Alignment indices are quantitative measures of the general character of a roadway segment's alignment. Problems with geometric inconsistencies arise when the general character of alignment changes between segments of roadway. A common example is where the terrain transitions from level to rolling or mountainous, and the alignment correspondingly changes from gentle to more severe. Proposed indicators of increasing geometric inconsistency are a large increase in the magnitude of alignment indices for successive roadway segments or a high rate of change in alignment indices over some length of roadway.

DRIVER WORKLOAD

Workload has been defined by Senders as "a measure of the 'effort' expended by a human operator while performing a task, independently of the performance of the task itself."[29] Another definition of workload was given by Knowles as consisting of the answer to two questions: "How much attention is required?" and "How well will the operator be able to perform additional tasks?"[30] The definition presented by Knowles is very appropriate to the driving environment, since that environment consists of many overlapping tasks, each requiring a portion of the driver's attention. A method of examining the workload demands placed on the

driver would appear to be a way of directly arriving at the capabilities of the driver as he or she negotiates a given roadway.

In previous studies by (Texas Transportation Institute) in the general area of roadway design and its impact on driver performance, considerable attention has been given to the concept of mental workload as an approach to measuring or rating the design. The driver is more or less continuously processing visual and kinesthetic information (to say nothing of proprioceptive cues used to actually control the vehicle), making decisions, and carrying out control movements.

Generally, little visual information processing capacity is required of the experienced driver to perform the driving task. It is performed almost at a subconscious level when the road is free of traffic and obstacles, and the driver's visual evaluations are consistent with the tracking requirements. Consistency of the visual evaluation of the road with the actual road requirements is a function of the sight distance and the driver's expectancies regarding the road. A consistent roadway geometry allows a driver to accurately predict the correct path while using minimal visual information processing capacity, thus allowing attention or capacity to be dedicated to obstacle avoidance and navigation.

Several research efforts have been undertaken to measure the effects of design consistency on driver workload. These studies have used various methods and parameters to model or rate geometric features or combinations of features in terms of the difficulty that they might pose to a driver. The logic underlying these efforts is that the more difficult a feature or feature combination, the greater the visual information processing requirement and, in turn, the less desirable the feature.

A major FHWA research study by Messer, Mounce, and Brackett presented a method of evaluating driver workload.[31] A model was formed by gathering empirical evidence regarding driver expectations of roadway features and relating violations of those expectancies to workload. The model is based on the presumption that the roadway itself provides most of the information that the driver uses to control the vehicle; hence, the roadway imposes a workload on the driver. This workload is higher during encounters with complex geometric features and can be dramatically higher when drivers are surprised by encounters with combinations or sequences of severe geometric features (see figure 1).

The driver workload procedure quantifies design consistency by computing a value for driver workload.[31] The technique relies on a set of assigned ratings developed for various roadway elements. Roadway features receiving ratings are (listed in order of severity): bridges, divided highway transitions, lane drops, intersections, railroad grade crossings, shoulder-width changes, alignment, lane-width reductions, and the presence of crossroad overpasses. The ratings, based on the type and severity of design element, are then modified in accordance with their location. Influencing factors include sight distance to the element, similarity to previous elements, workload of previous segments, and percentage of drivers estimated to be familiar users of the facility. The workload along the roadway is estimated using an equation which

defines a subjective level of consistency (LOC) in terms related to driver workload.[31] The results from the design consistency procedure are categorized using A, "no problem expected," to F, "big problem possible."
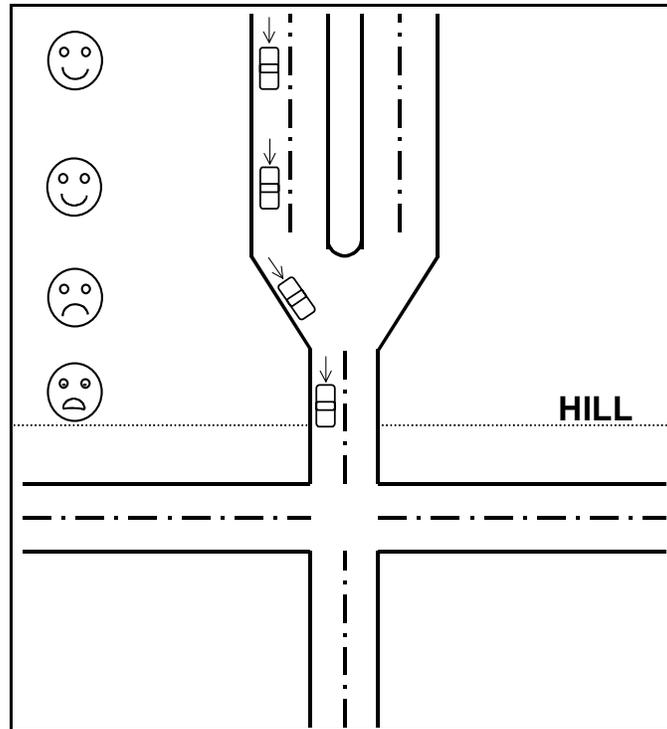
**Figure 1. Example of
Inconsistent Design.**[31]

Although two recent studies have indicated generally acceptable results when relating accident rates and the workload values derived using Messer et al.'s procedure, problems have arisen when attempting to use the procedure in locations with closely spaced features.[14,32] Workload carryover effects may be overstated in those cases, although conclusive evidence has not been published.

In a 1990 study directed primarily at studying motorcycle safety, Hancock, Wulf, Thom, and Fassnacht found increased mental workload during turn sequences when compared with straight driving.[33] Workload was measured through the use of response time to the illumination of a probe light; subjective workload judgments were also measured through use of the NASA *Task Load Index* procedure and the USAF *Subjective Workload Assessment Technique.* No significant difference in workload for left and right turns was found, although the consequences of failing to detect an oncoming vehicle were noted to be quite different for the two maneuvers.

Using an approach initially reported by Senders et al., Krammes et al. examined design consistency for horizontal curves using vision occlusion to determine the effective workload on the driver.[34,7] Drivers wore an occlusion device that provided fixed-length glimpses of the roadway in response to presses of a switch. Recording the frequency and location of requested glimpses provided a measure of the amount of information needed to successfully traverse the roadway. It was found that workload increased linearly as the degree of curvature increased, increasing on the approach to and peaking near the beginning of horizontal curves. No effect was found for deflection angle.

This current FHWA project validated and extended the work begun previously by Krammes et al.[7] Like the previous study, a test-track study to examine driver workload was performed, and companion efforts using on-road and simulator studies were also performed. Curve sequence, separation distance between curves, radius, and deflection angle were examined through the use of vision occlusion and subjective ratings. The vision occlusion procedure (the primary measure of effectiveness) is identical to that previously used. Subjective ratings used a modified Cooper-Harper scale. Efforts to include heart-rate variability as a measure of driver workload were discontinued after collecting initial data. Heart rate data are not suitable for use in a short-term, transient task like traversing a highway curve. Discussions on the findings from the research are contained in chapters 5, 6, and 7 of this report.

DESIGN CONSISTENCY CHECKLISTS

A driver expectancy checklist was prepared in a project sponsored by AASHO.[35] Using a multidiscipline diagnostic team approach, the project encompassed 16 studies in 13 States involving drivers with widely varying backgrounds. Observers accompanying the drivers noted their behavior; in addition, questionnaires and interviews were conducted to obtain additional input from the drivers. One of the primary outcomes of the study was the development of an expectancy checklist.

The expectancy checklist largely consists of reminders to examine various design features.[35] Designers' attention is called to possible expectancy violations and is then tasked to either remedy the problem or to provide mitigating treatments. Typical remedies for rural roads include "Minor roadways join major roadways with T-intersections wherever possible;" mitigating treatments include "Wherever possible, a sight distance greater than the minimum value has been provided to enhance safety during periods of adverse weather." The checklist, while encompassing many aspects of design that could influence design consistency, provides little in the way of discussion of principles or specific measures. In the face of this lack of information, a designer could face problems in applying the recommendations.

In a 1986 report, Alexander and Lunenfeld present one of the most influential views to date of design consistency and the driving task.[1] Reprising their development of three performance levels in the driving task (control, guidance, and navigation), Alexander and Lunenfeld

present the idea that *a priori* (lifetime or long-term) and *ad hoc* (in-transit or short-term) expectancies are present and affect the driver's responses to the current situation.

The premise of examining driver expectancies is again based on the principle that user performance is enhanced and tends to be more rapid and error-free if these expectancies are met.[1] A series of violation examples and potential remedial measures are then provided. The analysis technique used is derived from the *Users' Guide to Positive Guidance*.[9] A detailed expectancy checklist is provided, directed at problems affecting navigation and guidance. A list of factors to be used in the general review is shown in table 1. Navigation checklist items included items directed at finding problems related to route and direction finding; items intended to help detect guidance expectancy problems were largely related to specific geometric features and feature characteristics.

Table 1. Design Consistency Review Factors.[9]

Factors to Consider in the General Review		
Cross-Section Markings	Lighting	Road Surface
Guide Signs & Route Markers	Missing Information Terrain	Sight Distance Signals
Geometry	Traffic	Warning & Regulatory Signs
Land Use	Road Type	Weather
Detailed Analyses		
Navigation Expectancies	Guidance Expectancies	Special Features

SUMMARY

Several techniques have been identified for measuring design consistency. Design consistency implies that the design or geometry of a road does not violate either the expectancy of the motorist or the ability of the motorist to guide and control a vehicle in a safe manner. Because speed inconsistencies have been observed on rural two-lane highways, even when designed using the design-speed concept, speed profile models or speed prediction equations have been proposed for evaluating design consistency. When an unacceptable change in speed is encountered between features, a design inconsistency is present. The findings from additional research into developing a speed profile model is contained in a companion report from this study.[8]

Other design consistency evaluations include vehicle - operations - based consistency (other than speed), roadway - geometrics based consistency, and driver workload. These evaluation techniques were selected for further study. The measures of vehicle operations selected were speed distribution measures, including variance, standard deviation, coefficient of

variation, and coefficient of skewness. Alignment indices were selected as the roadway -
geometrics based design consistency measure. Driver workload was examined in on-road, test
track, and simulator environments.

3. ALINEMENT INDICES

Alinement indices are quantitative measures of the general character of a roadway segment's alinement that appear to have several conceptual advantages for use in design consistency evaluations. If logically formulated, they should be easy for designers to use, understand, and explain. They would be a function of the dimensions of horizontal and/or vertical alinement elements. Therefore, they would provide a mechanism for quantitative assessment of successive elements from a system-wide perspective, which is a fundamental motivation of design consistency research.

Alinement indices should also attempt to quantify the interaction between the horizontal and vertical alinements that is missing from current design policy. Under AASHTO design guidelines, horizontal and vertical alinements are usually designed separately to meet certain criteria and are then brought together. Although it is assumed that design consistency will be maintained, this assumption is not always valid.

USING ALINEMENT INDICES

The alinement indices were developed for use in this study as either a possible measure of design consistency or as possible predictors of 85th percentile speeds on rural two-lane highways. The research into the use of alinement indices as predictors of 85th percentile speeds is documented in another report.[(8)] Alinement indices did not explain the variation in measured speeds on long tangents. The research concluded that the observed mean of 85th percentile speeds is the best estimate of the desired speed of motorists on long tangents for posted speeds of 88.5 km/h (55 mph).

While a poor predictor of speeds on long tangents, alinement indices may be able to provide an indication of the consistency of a rural, two-lane highway. Proposed indicators of geometric inconsistency include:

- A large increase/decrease in the values of alinement indices for successive roadway segments
- A high rate of change in alinement indices over some length of roadway
- A large difference between the individual feature and the average value of the alinement index

For each of these indicators, a determination must be made of the amount of change in the alinement index value that would indicate a significant change in alinement consistency. Using the average of the geometry parameters along a roadway segment can indicate the general character of the road. An individual feature that has a value dissimilar to that of the average of

the roadway can possibly indicate that there is some inconsistency between that feature and the general alinement of the roadway.

ALINEMENT INDICES

The initial step in determining alinement indices consisted of identifying all possible indices that could be useful for this research. Therefore, some of the alinement indices that had been used in other countries or proposed for use were included. Additionally, other indices thought to have some potential were developed. Table 2 lists the alinement indices considered for the speed prediction work.[8] These indices were then examined for their applicability for use in design consistency.

Table 2. Alinement Indices Selected for Speed Prediction Evaluation.

Horizontal Alinement Indices

• Curvature Change Rate - CCR (deg/km)

$$\frac{\sum \Delta_i}{\sum L_i}$$

where:
Δ = deflection angle (deg)
L = length of section (km)

• Degree of Curvature - DC (deg/km)

$$\frac{\sum (DC)_i}{\sum L_i}$$

where:
DC = degree of curvature (deg)
L = length of section (km)

• Curve Length: Roadway Length - CL:RL

$$\frac{\sum (CL)_i}{\sum L_i}$$

where:
CL = curve length (m)
L = length of section (m)

• Average Radius - AVG R (m)

$$\frac{\sum R_i}{n}$$

where:
R = radius of curve (m)
n = number of curves within section

• Average Tangent - AVG T (m)

$$\frac{\sum (TL)_i}{n}$$

where:
TL = tangent length (m)
n = number of tangents within section

Vertical Alinement Indices

• Vertical CCR - V CCR (deg/km)

$$\frac{\sum A_i}{\sum L_i}$$

where:
A = absolute difference in grades (deg)
L = length of section (km)

• Average Rate of Vertical Curvature - V AVG K (km/percent)

$$\frac{\sum \frac{L}{|A|}}{n}$$

where:
L = length of section (km)
A = algebraic difference in grades (%)
n = number of vertical curves

• Average Gradient - V AVG G (m/km)

$$\frac{\sum |\Delta E_i|}{\sum L_i}$$

where:
ΔE = change in elevation between VPI_{i-1} and VPI_i (m)
L = length of section (km)

Composite Alinement Indices

• Combination CCR - COMBO (deg/km)

$$\frac{\sum \Delta_i}{\sum L_i} + \frac{\sum A_i}{\sum L_i}$$

where:
Δ = deflection angle (deg)
A = absolute difference in grades (deg)
L = length of section (km)

EVALUATION OF ALINEMENT INDICES

The use of a composite alinement index was investigated in predicting 85th percentile speeds on long tangents of rural two-lane highways. However, its use as a measure of design consistency was not considered. It was determined that design inconsistencies in the horizontal alinement can best be identified using horizontal alinement indices and inconsistencies in the vertical alinement can best be identified using vertical alinement indices. Therefore, a composite alinement index would not be expected to provide information necessary in determining the design consistency of individual features along a roadway.

Indices that involved sight distance were not considered because an automated method of calculating the actual sight distance available to the motorists from roadway design plans was not available. In addition, the amount of sight distance available to motorists is based on varying parameters such as driver eye height and object height. The intent of this research was to use alinement indices that were roadway geometry-based.

The use of statistical measures as alinement indices was not considered because these indices provided more information on the character of a section of roadway rather than on the individual features themselves. In addition, the variation in the alinement indices can be better interpreted by comparing the individual alinement feature with the average feature of a roadway, rather than statistical measures such as standard deviation, coefficient of variation, and weighted averages.

One alinement index (ratio of curve length to roadway length) provides only an indication of the general character of the roadway. It was not expected to provide information on individual features of the roadway in attempting to determine those features that may be inconsistent; therefore, it was not considered further.

Length-based alinement indices using both the horizontal and vertical alinement provide more information related to the consistency of a section of roadway than as an individual measure. In addition, these length-based indices were hypothesized for use in predicting the speeds of motorists on long tangents rather than as design consistency measures. However, they were not determined to be significant predictors of operating speeds.

The relationship that exists between the deflection angle, degree of curve, and radius of a roadway is shown in the equations that follow:

$$\Delta = \frac{L \times DC}{100} \quad (1) \qquad\qquad R = \frac{5729.58}{DC} \quad (2)$$

where:

Δ = deflection angle (deg)
L = length of curve (ft)
DC = degree of curve (deg)
R = radius (ft)

Because of these relationships, it was determined that only one of the three alinement indices that use these parameters should be used in measuring the design consistency of a roadway.

RECOMMENDED ALINEMENT INDICES

Table 3 presents the alinement indices that are recommended to be investigated as possible measures of rating the design consistency of rural two-lane highways. Discussion of these indices will be included in the following paragraphs.

Table 3. Recommended Alinement Indices as Measures of Design Consistency.

Horizontal Alinement Indices
1. Radii Measures
   - Average Radius
   - Maximum Radius / Minimum Radius
2. Tangent Length
   - Average Tangent Length

Vertical Alinement Indices
1. Angular Change in Direction
   - Average Rate of Vertical Curvature

Horizontal Alinement Indices

The horizontal alinement indices recommended are indicators of the amount of curvature of the road and how winding it is. The curvature of a roadway is important because of the relationship that exists among curves, speeds, and accident rates. These relationships are exemplified by the following statements:

- A review of accident spot maps normally shows that accidents tend to cluster on curves, particularly on very sharp curves.[11]
- Accident studies indicate horizontal curves experience a higher accident rate than tangents, with rates from 1.5 to 4 times greater than on tangent sections.[36,37,38]
- Greater speed reductions for approaching vehicles are associated with sharper curves.[37]

Additionally, roads with long tangents or little angular change are not conducive to controlling maximum speeds, which can lead to drastic speed reductions when curves are encountered.

Radii Measures

Radii measures alinement indices are based upon the radii for the curves on the road and provide an indication of the sharpness of the curves along the roadway. These indices were recommended because they appeared to relate well to both speed and accident values. The speed of motorists on two-lane roads is constrained by the curves that motorists encounter. As stated previously, the majority of accidents tend to occur on the curves of two-lane rural roadways as opposed to the tangents. Additionally, "sharper curves are associated with higher accident rates than milder curves."[37-40]

Using the radii of individual curves, they can be compared with the average radius in determining which curve appears to be in conflict with the general character of the horizontal curves of the alinement. Figure 2 provides an example of the difference between the individual curves and the average radii for a sample roadway. This figure provides a good visual indication of where differences in radii exist among the individual curves.

The range of the radii along a roadway can be determined by computing the ratio of the maximum to minimum radius. This ratio can represent "the consistency of the design in terms of the use of similar horizontal radii along the road. As this value approaches one (i.e., as the consistency of the chosen design radii is increased), a reduced accident rate may be expected."[41]

While this comparison of radii appears to be useful, there are some concerns with these measures. If the maximum radius is much different than all other radii, the curve with the maximum radius may be the inconsistency. However, if the ratio of the individual radii to the maximum radius is similar for all radii, this can indicate that there is consistency among the curves along the roadway. Additionally, ratios have different implications for different situations. A value of two for this index may be the ratio between either a 1,746-m (1-deg) and 873-m (2-deg) curve or a 350 m (5-deg) and 174.6 m (10-deg) curve. It is hypothesized that motorists would react differently to each situation, therefore making it difficult to determine inconsistencies. A possible solution to this problem is to state that the impacts of the different values of this ratio are dependent on the minimum radius of the roadway.
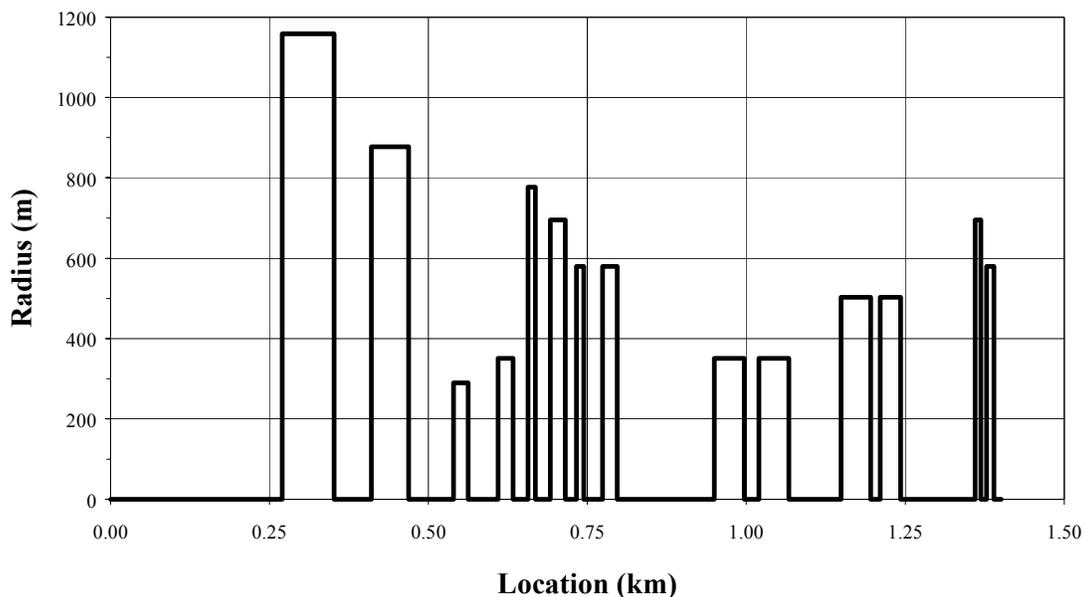
Figure 2. Horizontal Curve Radii of a Sample Roadway Plotted as a Function of Location.

It is recommended that a better representation of the variation of radii along a roadway may be gained by using the average radius as an alinement index rather than the maximum radius to minimum radius. The use of the ratio of maximum to minimum radius should be investigated for possible use though, as it does appear to have some promise.

Tangent Length

The tangent plays an important role in determining the necessary speed reduction of motorists as they enter a horizontal curve. The length of tangent determines the speed motorists will reach on that tangent. If a tangent is long enough, then motorists will drive at their desired speed, which is defined as "the speed at which drivers choose to travel under free-flow conditions when they are not constrained by alinement features."[42] Therefore, if motorists are driving at a high speed on the tangent and a large reduction in speed is required at the following curve, they may not be able to decrease their speed as needed.

The tangent length alinement index was used to calculate values for a sample roadway. An average tangent length of 601 m was used. Table 4 shows the ratio of the tangent length to the average length for each tangent. A comparison of individual tangent lengths to the average tangent length appears to be very valuable in rating the design consistency of the roadway. It shows the amount of variation for each individual tangent and can possibly be used in determining locations where motorists may expect the tangents to be longer than they are.

Table 4. Tangent Length Alinement Index for Sample Roadway.

Location (km)	Curve	Length (m)	Radius (m)	Delta (deg)	DC (deg)	Preceding Tangent (m)	Ratio of Tangent Length to Average Tangent Length
		Horizontal Alinement Data					Ratio of Tangent Length to Average Tangent Length
0.00	START						
2.65	PC*	818	1164	40.2	1.5	2650	4.4
3.47	PT						
4.03	PC	633	873	41.5	2	559	0.9
4.66	PT						
5.32	PC	310	291	60.9	6	657	1.1
5.63	PT						
6.11	PC	234	349	38.3	5	481	0.8
6.34	PT						
6.60	PC	142	776	10.5	2.3	255	0.4
6.74	PT						
6.98	PC	306	699	25.1	2.5	242	0.4
7.29	PT						
7.44	PC	187	582	18.4	3	154	0.3
7.63	PT						
7.87	PC	258	582	25.4	3	241	0.4
8.13	PT						
9.59	PC	366	349	60	5	1465	2.4
9.96	PT						
10.10	PC	361	349	59.2	5	144	0.2
10.46	PT						
11.21	PC	408	499	46.8	3.5	751	1.2
11.62	PT						
11.72	PC	365	499	41.9	3.5	130	0.2
12.12	PT						
13.20	PC	85	699	7.0	2.5	1082	1.8
13.28	PT						
13.39	PC	138	582	13.6	3	103	0.2
13.52	PT						
13.62	END					101	-

*PC = point of curvature; PT = point of tangent

Vertical Alinement Indices

The average rate of vertical curvature alinement index can provide an indication of the amount of changes in the vertical alinement for a roadway. The amount of hilliness on an alinement can have an effect on the speed and accident data, as well as on the available passing or overtaking sight distance. These alinement indices can be used as a primary indication of the vertical alinement of the roadway, which can especially be important depending on the types of vehicles using the facility.

RELATIONSHIP OF ALINEMENT INDICE MEASURES TO SAFETY

The geometric design consistency measures based on alinement indices are conceptually attractive. Before a design consistency methodology is recommended to geometric designers, however, it would be valuable to demonstrate that the proposed design consistency measures are, in fact, related to safety. Such a demonstration was performed and the details of the analyses are presented in Fitzpatrick et al.[8] Following is a summary of the evaluation.

Database

A database was developed to test the relationship to safety of the roadway alinement indices. To assemble this database, data were obtained from the FHWA Highway Safety Information System (HSIS) for State-maintained rural two-lane highways in the State of Washington. Criteria used in establishing study segments included: a minimum section length of 6.4 km, a maximum section length of 32 km, minimum posted speed limit of 88.5 km/h or more, and elimination of portions of roadway with features that might interfere with the analysis. These criteria resulted in 291 highway sections available for analysis. The analysis considered only non-intersection accidents between 1993 and 1995 that involved: (1) a single-vehicle running off the road; (2) a multiple-vehicle collision between vehicles traveling in opposite directions; or (3) a multiple-vehicle collision between vehicles traveling in the same direction. All accidents involving parking, turning, or passing maneuvers, animals in the roadway, or bicycles or motorcycles were excluded.

Models

The alinement indices selected for evaluation as potential design consistency measures included:

- Average radius of curvature for a roadway section
- Ratio of maximum radius of curvature to minimum radius of curvature for a roadway section
- Average tangent length for a roadway section
- Average rate of vertical curvature for a roadway section

- Ratio of an individual curve radius to the average radius for the roadway sections as a whole
- Ratio of an individual tangent length to the average tangent length for the roadway section as a whole

Regression models between each alinement index and safety were developed to test its appropriateness as a design consistency measure. In addition, the relationship between safety and predicted speed reduction from one geometric feature to another determined in accordance with procedures developed by Fitzpatrick et al.[8] was also investigated. The statistical models developed were not intended for use as accident predictive models but, rather, were intended to illustrate the nature of the relationship of candidate design consistency measures to safety. Accident frequencies were modeled as a function of exposure [average annual daily traffic (AADT) and section length, both on the logarithmic scale] and each of the alinement indices taken one at a time. Sensitivity analyses were also conducted to examine the sensitivity of predicted accident experience to the alinement index.

Findings

Of the candidate design consistency measures, three have relationships to accident frequency, that are statistically significant and appear to be sensitive enough that they may be potentially useful in a design consistency methodology. These three candidate design consistency measures are:

- Ratio of an individual curve radius to the average radius for the roadway section as a whole
- Average rate of vertical curvature for a roadway section
- Average radius of curvature for a roadway section

Thus, these measures appear promising for assessing the design consistency of roadway alinements.

However, while these alinement indices are promising as design consistency measures, none of them has as strong a relationship to safety as the speed reduction measure developed by Fitzpatrick et al.[8] (i.e., the speed reduction of a horizontal curve relative to the preceding curve or tangent). Accident frequency is not as sensitive to the alinement indices reviewed as it is to the speed reduction for individual horizontal curves. In addition, the evaluation has shown that the speed reduction on a horizontal curve is a better predictor of accident frequency than the radius of that curve. This makes a strong case that a design consistency methodology based on speed reduction provides a better method for anticipating and improving the potential safety performance of a proposed alinement alternative than a review of horizontal curve radii alone. Alinement indices may have a role as supplementary measures of design consistency to the primary measure based on speed reduction.

4. SPEED DISTRIBUTION MEASURES

BACKGROUND

Drivers have a desired operating speed, i.e., the speed at which they would operate if unimpeded by other traffic. Desired speeds depend on roadway condition, weather, environment, and roadway geometry; thus, they cannot be measured directly. As a result, a common assumption is that desired speeds are directly related to free-flow speeds and can be approximated using a sample of free-flow vehicle speeds. The similarities between desired and free-flow speeds suggest that free-flow speeds could depend on the driver's perception of the roadway conditions, environment, and geometry. Thus, free-flow speeds and the statistical measures associated with them may identify alinement deficiencies.

Statistical measures from sample speed populations are considered an alternative form of design consistency that can be used to identify potential problems of individual features on specific roadways. Alinement features exhibiting higher values of speed variability have been identified as potential locations for driver error. Significant changes in speed distributions may suggest that design inconsistencies are present at that alinement feature. The basis for using descriptive speed statistics originates from the idea that speed variance is the issue, not speed magnitude.[43]

Statistical Measures of Speed Distributions

A common hypothesis in traffic flow theory and traffic engineering studies is that speeds, particularly of free-flowing vehicles, are normally distributed. Figure 3 is an example of the normal distribution measures being considered within this approach. Continuous distributions have interval scales with certain properties defined in terms of actual units of measurements.[44] It is believed that vehicle speeds on a roadway follow this type of continuous distribution, and that these units could identify geometric deficiencies. To provide a clear understanding of the scope of this research, the following definitions are provided:

- *Mean Speed-* the arithmetic average spot speed of a sample population, measured in km/h.
- *Variance-* a measure of the variability among the speeds about the mean speed. Variance is not directly related to skewness and kurtosis, but generally variance increases as skewness increases and decreases as kurtosis increases. The units for speed variance are given in $(km/h)^2$.
- *Standard Deviation-* the square root of the variance. This quantity is typically used to estimate the proportion of speeds that fall within a range about the mean. An estimated 68 percent of speeds lie within one standard deviation on either side of the mean. The unit is km/h.

- *Coefficient of Variation-* the standard deviation divided by the sample mean. This descriptive parameter is used to 'normalize' two different samples with different means and standard deviations. While as a coefficient it is unitless, it is often modified to a percent form (standard deviation divided by mean multiplied by 100).
- *Skewness-* the third moment of the distribution, it characterizes asymmetry of a distribution around its mean. This parameter is a non-dimensional number that characterizes the shape of the distribution. A positive value of skewness signifies a distribution with more values lower than the mean; a negative value signifies a distribution with more values above the mean.[45] The normal distribution has a skewness of zero because it is symmetric about the mean.
- *Kurtosis-* the fourth moment of the distribution. It is a non-dimensional parameter that measures the "peakedness" or flatness of a distribution, relative to a normal distribution. A distribution with a kurtosis above three is termed *leptokurtic*; a distribution with kurtosis below three is termed *platykurtic*.[45] The normal peak distribution has a kurtosis of three.
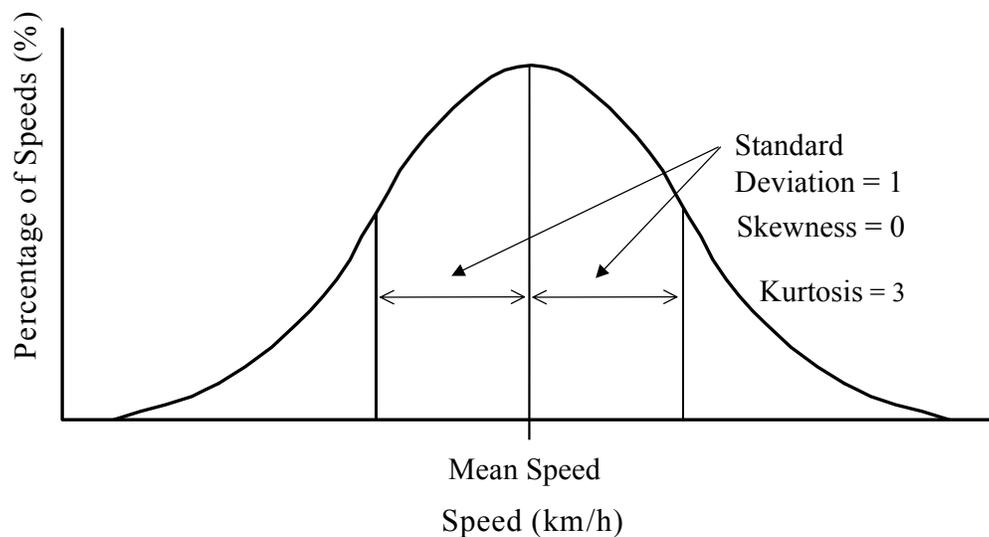
Figure 3. Continuous Normal Distribution.

Statistical Measures and Accident Potential

Previous research has made general observations regarding the variability of speed distributions with a focus on the relationship between statistical measures and accident potential. An understanding of these statistical measures and how they relate to the design of roadways will provide valuable insight for future design and reconstruction of existing roadways in order to minimize accident potential.

Traditionally, higher speed variability suggests a higher accident potential. Several research reports support this statement and relate speed variance to accident rates. "The weight of evidence would lead to the conclusion that speed variance and accident frequency are directly related. The greater the absolute deviation from mean traffic speed, the higher the accident rate."[46] A recent review of the safety effects of the 55 mph (88.5 km/h) National Maximum Speed Limit reached a similar conclusion: "The wider variability in speeds increases the actual probability of accident occurrence."[47]

Taylor analyzed the relationship between the measured speed distributions and accident frequencies on 22 sections of a highway.[48] Skewness and kurtosis were evaluated to determine their relationship to accident rates. The results showed that "a significantly greater number of accidents occur on sections of highways that have a skewed distribution than on sections with a non-skewed distribution," but that "there is no significant difference in the number of accidents when kurtosis is used as a measure of non-normality."[48] The results did not suggest that these parameters can effectively predict accident rates. The aforementioned general relationship between statistical measures suggests variance increases as skewness increases and variance decreases as kurtosis increases. Taylor's results did not support this statement.

A 1989 study by Garber and Gadiraju related speed variance and accident experience.[49] The study examined 36 roadway segments in Virginia, including urban and rural interstates, urban and rural arterials, and rural major collectors. The analysis used accident data from 1983 through 1986 and compared the results with four different speed measures: design speed, posted speed, and the mean and variance of operating speeds. The mean and variance of operating speeds were computed from individual vehicle speeds measured using automatic traffic data recorders for continuous 24-hour weekday periods. Their results compared the effects of traffic and geometry on vehicle speeds, indicating that the measured speeds were not free flow. Conclusions from their research were:[49]

- Accident rates increase with increasing speed variance for all classes of roads.
- Speed variance on a highway segment tends to be a minimum when the difference between the design speed and the posted speed limit is between 8 and 16 km/h (5 and 10 mph).
- For average speeds between 40 and 112.5 km/h (25 and 70 mph), speed variance decreases with increasing average speed.
- The difference between the design speed and the posted speed limit has a significant effect on the speed variance.
- The increasing trend of average speed with respect to the design speed suggests that, as the roadway geometric characteristics improve, drivers tend to drive at increasing speeds irrespective of the posted speed limit.
- The accident rate on a highway does not necessarily increase with an increase in average speed.

The study results implied, but did not explicitly define, a relationship between speed variance and roadway geometry. For example, if given the opportunity, drivers may travel at a

different speed when other vehicles are not present in the traffic stream. Conversely, drivers may travel at a higher speed on a given roadway if other vehicles are traveling at that higher speed in belief that only the lead vehicle will be stopped by enforcement officers.

The study defined a relationship for variance and average speed as follows:[49]

$$s^2 = -16.7 + 204803/V_M^2 \qquad\qquad (3)$$

where:

s^2 = speed variance in (mph)^2
V_M = mean speed, 25 < V_M < 70 mph

The results of the analysis also suggested that a relationship exists between speed variance and design speed. The analysis included a model that related speed variance and design and posted speeds as follows:[49]

$$s^2 = 57 + 0.05(V_D - V_P - 10)^2 \qquad\qquad (4)$$

where:

V_D = design speed in mph
V_P = posted speed limit in mph

The model suggests that a minimum speed variance will occur when the difference between the design and posted speed is 16 km/h (10 mph). It is important to note that each of these models accounts for both traffic and geometry; however, the influences of each are not separated.

Solomon and Cirillo used accident-involved vehicles on two- and four-lane rural highways and interstates as their unit of analyses.[50,51] Their studies estimated the deviation from the mean speed of the accident-involved vehicle's speed. Incremental groupings of the deviation from the mean speed were analyzed as to accident involvement rates. Both studies found that the lowest accident involvement rate occurred within a speed range 15 to 20 percent higher than the mean speed. As the deviation increased above this range, accident involvement rates increased for both vehicles traveling higher and lower than the mean speed. Neither study clearly defined whether drivers were traveling at the desired speed or if they were influenced by other vehicles within the traffic stream.

Munden observed drivers directly on roadway features and compared their speeds with their accident histories.[52] He then grouped these speeds in increments around the mean speed and compared accident rates using a method similar to that of Solomon and Cirillo.[52] The results corresponded to those of Solomon and Cirillo: accident rates were lowest for drivers

whose observed speeds were closest to the mean speed. As the observed speed deviation increased, accident rates increased.

Lindeman and Ranft analyzed the effect of geometry on the speed distribution measures at the midpoint of a horizontal curve.[53] Their research focused on the standard deviation, skewness, and kurtosis for speed distributions on horizontal curves with radii ranging from 32.5 to 1000 m. The results are presented in table 5. Their findings suggest that standard deviation of speed increases as the radius of the horizontal curve increases for small radius curves, and then remains constant for larger radius curves. Conclusions from the research were that standard deviation becomes greater with increasing radius, and thus with increasing speed. The following equation was developed to predict the relationship between standard deviation and mean speed:[53]

where:

$$s = 0.14 \times V_M \tag{5}$$

s = standard deviation (km/h)

V_M = mean speed, 30 < V_M < 95 km/h

Although Lindeman and Ranft documented skewness and kurtosis, no evidence was found relating these measures of the distribution to the geometry of the roadway or to accident potential at a horizontal curve. Table 5. Standard Deviation, Skewness, and Kurtosis Relationship to Radius.[53]

Radius (m)	Mean Speed (km/h)	Standard Deviation (km/h)	Skewness	Kurtosis
32.5	43	5.5	-0.04	0.81
35	52	8.7	0.30	1.11
45	44	5.1	-0.21	-0.25
120	64	10.4	0.10	0.07
160	73	12.6	0.47	-0.14
200	79	11.2	0.74	0.30
240	79	11.9	0.04	-0.37
300	88	11.2	-0.09	-0.43
500	91	12.8	-0.08	-0.20
1000	87	11.8	0.12	0.33

RESEARCH HYPOTHESES

The objective of this task was to explore relationships between speed distribution measures under free-flow conditions and roadway alinement. It is hypothesized that high speed variance identifies inconsistent design features whereas features in harmony with driver expectancy have low speed variance (see figure 4). If a relationship exists, a model could be developed to predict the speed distribution measures of passenger vehicles on the basis of roadway geometry. The model could serve as an alternative design consistency method.

The literature review suggests several alternatives toward the application of speed variance as it relates to accident potential, but it does not address methods for modeling speed variance. Speed distribution skewness and kurtosis have been used to identify locations where accidents may occur, but these measures have not been predicted with any degree of certainty. The following hypotheses are considered within this study:

1. Roadway geometry can be used to predict speed distribution measures.
2. Design and/or posted speed can be used to predict speed distribution measures.
3. The relationship between successive features can be used to predict speed variance measures.
4. Increased speed variance can be used as an indicator of the presence of a design inconsistency.

The first hypothesis assumes that the design features of horizontal and vertical alinements can predict distribution measures of the sample speeds recorded at these features.

The second hypothesis suggests that distribution measures vary with drivers' desired speeds. Since desired speeds cannot be measured, comparisons will be made between statistical distribution measures and the design and/or posted speed. The inclusion of the design and posted speed hypothesis was considered based on previous research. Garber and Gadiraju's findings suggested that posted speed directly affects the operating speeds of drivers, and design speed is directly related to the design consistency of an individual alinement feature with respect to the overall road section.[49] Therefore, design speed and posted speed could quantify the human perception of the roadway and the behavior within the roadway environment.

The third hypothesis states that the speed distribution measures are associated with the driver's perception of changes in the roadway. Speed distributions are constantly changing from feature to feature, with the relationship being dependent upon the change from feature to feature.

The fourth hypothesis suggests that speed variance can be used to identify locations where design inconsistencies exist. High values of speed variance have been associated with high accident potential. This relationship may be related to the geometry of the roadway.
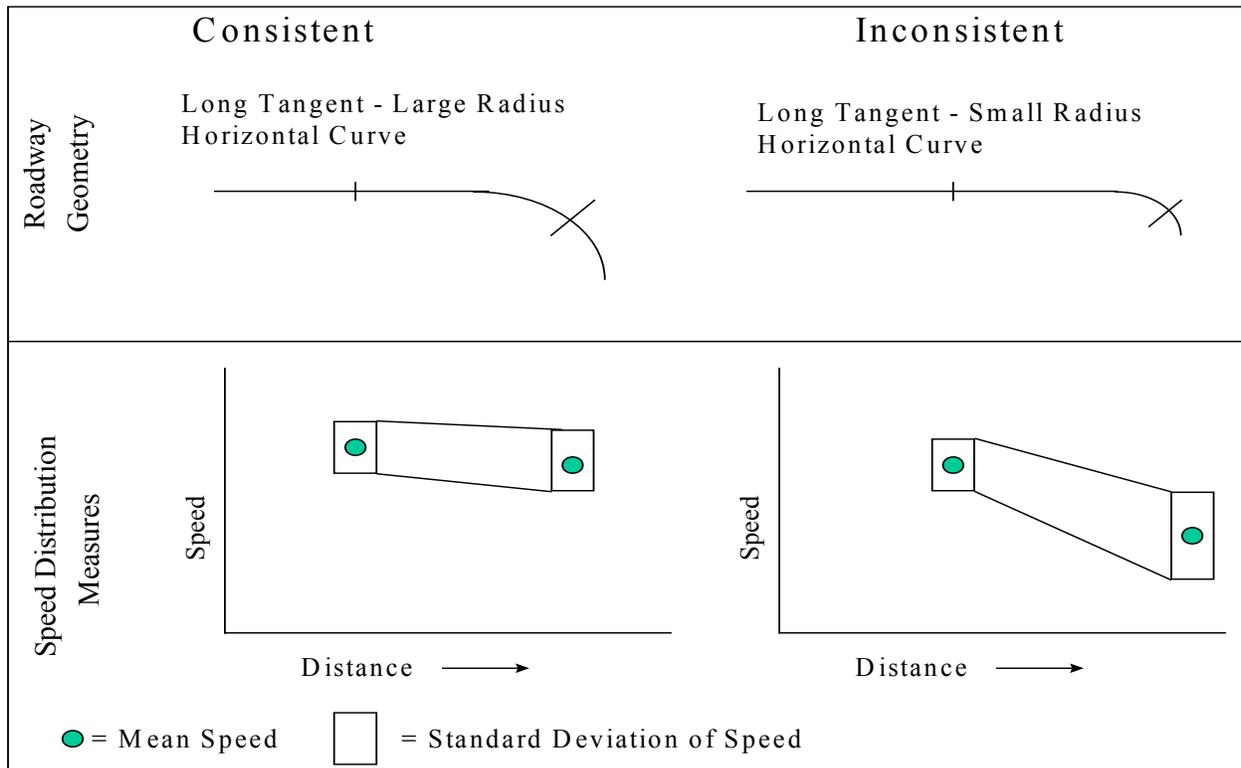
**Figure 4. Hypothesized Relationship of Roadway Geometry
and Standard Deviation of Speed.**

SPEED DATA

One goal of this research was to develop a model that is applicable to the range of
alinements, cross-sections, and conditions found on rural two-lane highways in the United States.
Speed data were collected for a minimum of 100 free-flow vehicles using radar devices or on-
pavement piezoelectric sensors. The 159 study locations were distributed across four regions:
Washington and Oregon in the west, Texas in the south, Pennsylvania and New York in the east,
and Minnesota in the midwest.

Mean speed, standard deviation, skewness, kurtosis, and coefficient of variation for each
study location were recorded with the corresponding geometric information for the site. General
observations were made as to the extreme values found within the statistical measures. The
mean, maximum, and minimum values observed for the tangent, horizontal curve, and limited
sight distance (LSD) vertical curve locations are presented in table 6.

Table 6. Speed Measures by Roadway Feature.

Speed Distribution Measure	Number of Sites	Mean	Median	Minimum	Maximum
Tangent					
Mean Speed (km/h)	159	82	81	55	113
Tangent Standard Deviation (km/h)	159	9.2	8.8	6.0	17.4
Tangent Skewness	159	-0.3	-0.2	-2.7	1.0
Tangent Kurtosis	159	1.7	1.0	-0.9	12.6
Tangent Coefficient of Variation	159	0.1	0.1	0.1	0.2
Horizontal Curve					
Mean Speed (km/h)	155	80	80	49	110
Horizontal Standard Deviation (km/h)	155	8.9	8.8	5.4	16.2
Horizontal Skewness	155	-0.4	-0.2	-3.8	0.8
Horizontal Kurtosis	155	1.9	0.9	-1.0	27.9
Horizontal Coefficient of Variation	155	0.1	0.1	0.1	0.2
Vertical Curve					
Mean Speed (km/h)	22	81	81	52	111
Vertical Standard Deviation (km/h)	22	9.3	9.0	7.2	15.0
Vertical Skewness	22	-0.4	-0.3	-3.1	0.8
Vertical Kurtosis	22	2.3	1.3	-0.4	24.1
Vertical Coefficient of Variation	22	0.1	0.1	0.1	0.2

HYPOTHESIS ONE: EFFECT OF ROADWAY GEOMETRY

The mean speed values for tangent, horizontal curves, and vertical curves were compared. The hypothesis that alinement affects the statistical measures could be validated if the means were significantly different between the midpoints of the tangent and the speeds measured on the horizontal curves, or the vertical curves. The TUKEY method was used to find significant differences in the behavior of the driving sample distribution, controlling for the Type II Error. No significant differences existed in mean speed or standard deviation values between the tangent, horizontal curve, and vertical curve spot speed locations. Similar findings existed for the skewness, kurtosis, and coefficient of variation at the speed locations. Thus, preliminary statistical analysis does not suggest that roadway geometry can be used to predict speed distribution measures. A more powerful statistical method for testing differences in standard deviations of speed is discussed in the Hypothesis Four section.

Basic Relationships

The search for relationships and interactions between variables was made using correlation matrices and graphical plots. SAS® was used to calculate Pearson correlation coefficients between all pairs of variables. Correlation coefficients were used to show potential relationships between roadway alinement and the statistical dispersion measures. The standard deviation, skewness, kurtosis, and coefficient of variation (dependent variables) were correlated with the independent geometric variables using the PROC CORR statement within SAS®. The correlation matrices were also checked to identify relationships assumed to exist among the independent variables, for example the relationship between horizontal curve length and deflection angle.

The standard deviation of most sites varied between 5 and 14 km/h (see figure 5). Outliers within the data set were at the extremes of 17 km/h. The original speed data from those study locations were inspected to ensure the accuracy of the data. No inconsistencies were found in the speed data. Figure 5 illustrates that, as mean speed increased, more variation within standard deviations of the spot speed measurements occurred.
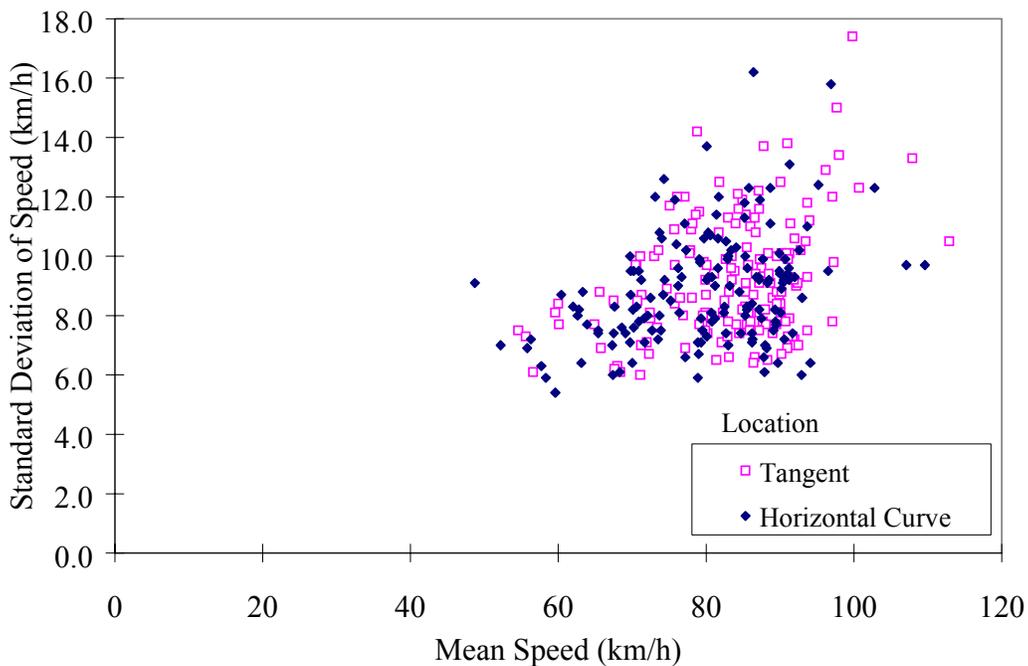
Figure 5. Standard Deviation of Speed versus Mean Speed on Tangents and Horizontal Curves.

Low correlation existed between the geometric alinement features and the speed variance. No correlation existed for skewness, kurtosis, coefficient of variation, horizontal curve radius, deflection angle, and horizontal curve length. Based on these findings and the weak relationships found in the plots of the three speed distribution measures versus the roadway independent geometric parameters, the skewness, kurtosis, and coefficient of variation were not considered useful in modeling the consistency of roadway features.

Graphical Relationships

In evaluating the first hypothesis, plots were created to display the relationship of the statistical speed measures with respect to the geometric elements of the roadway. Horizontal alinement elements considered included tangent length, curve radius, curve length, deflection angle, superelevation, and lane/pavement width. Vertical alinement elements included rate of curvature, vertical curve length, approach grade, and departure grade.

Horizontal Curves

The standard deviation measured at each horizontal curve site is shown in figure 6. The data are separated by curve radius and grade of the horizontal curve. No difference in standard deviation was found with respect to grade, but the figure shows that for small radii (i.e., less than 100 m), the standard deviation was low which could be a result of the lower speeds observed at the lower radii values (i.e., lower mean speeds lead to lower standard deviations). The geometry of the sharper curves influenced the range of speeds comfortable to drivers.

The other statistical measures evaluated with standard deviation included the skewness, kurtosis, and coefficient of variance. General observations that can be made for these measures were as

Figure 6. Horizontal Curve Speed Standard Deviation versus Radius.
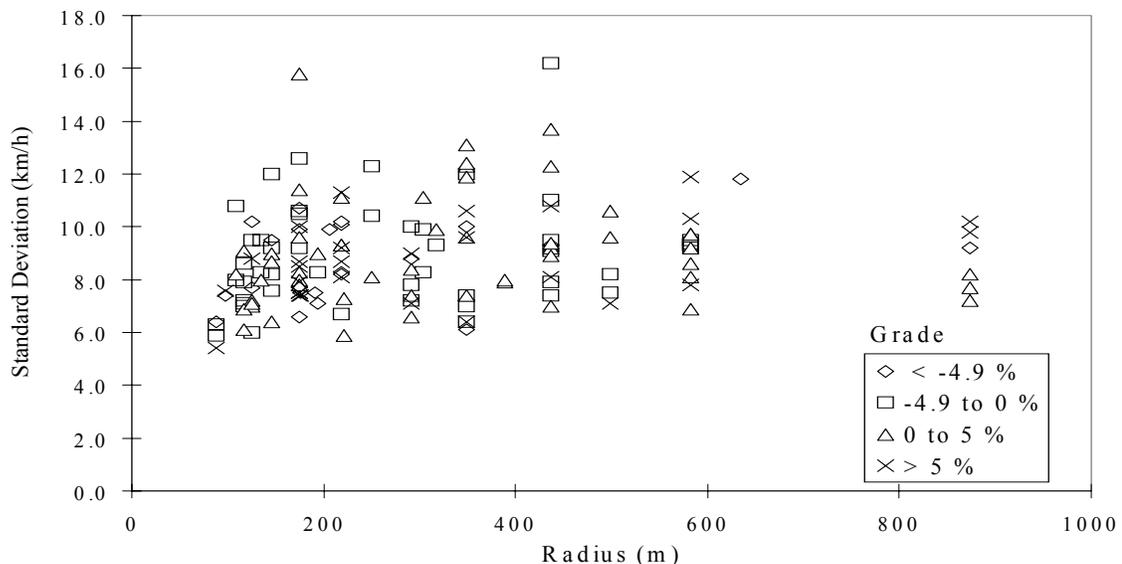
follows:

- The skewness of the data was consistently between -1 and 1 for the sample of horizontal curves. Most of the sample distributions seemed to follow the normality assumption with respect to skewness. Most of the distributions had a negative skewness near zero, indicating the distributions had more values above the mean.
- A kurtosis of three would indicate that the distributions followed a normal distribution. Most sample sites had a kurtosis slightly lower than three, showing that the sample distributions were flatter than normal.
- To "normalize" the data to account for the differences associated with mean speeds at each site, the coefficient of variation was also plotted against the horizontal alinement features. No geometric feature could accurately describe the coefficient of variation differences between sites.

Transformations of the Independent Variables

The poor relationships found through the correlation analysis and plots of features and speed measures suggested that transformations of independent variables might be more appropriate. The correlation was strongest between standard deviation and radius. Based on the correlation results and the non-linear shape of the data in figure 6, the radius was transformed. The transformations included: the inverse of the radius (1/R), the square root of the radius ($R^{1/2}$), the log of radius (LogR), and radius squared (R^2). Other transformations of independent variables, such as horizontal curve length and grade, were conducted with no significant findings.

Figure 7 shows standard deviation with respect to the inverse of the radius. Generally, as 1/R increases (i.e., the radius decreases), the range of the standard deviation decreases. This observation may only be valid for this data set because of the small number of sites with 1/R above 0.008. Two outliers were observed at 0.002 and 0.006. Aside from these two points, the standard deviation was consistently between 5 and 14 km/h.

This relationship implies that the radius of the horizontal curve controls the variation of speeds when the radius is below 100 m. It appears that, for horizontal curves with radii smaller than 100 m, higher-speed drivers entering the curve reduce their speeds more than lower-speed drivers. For the six study locations with curve radii less than 100 m, this greater reduction in speed by higher-speed drivers resulted in a decrease in the standard deviation of speed. The effect of the presence of a horizontal curve on the standard deviation of speed was not as great for horizontal curves with radii greater than 100 m (1/R below 0.01).
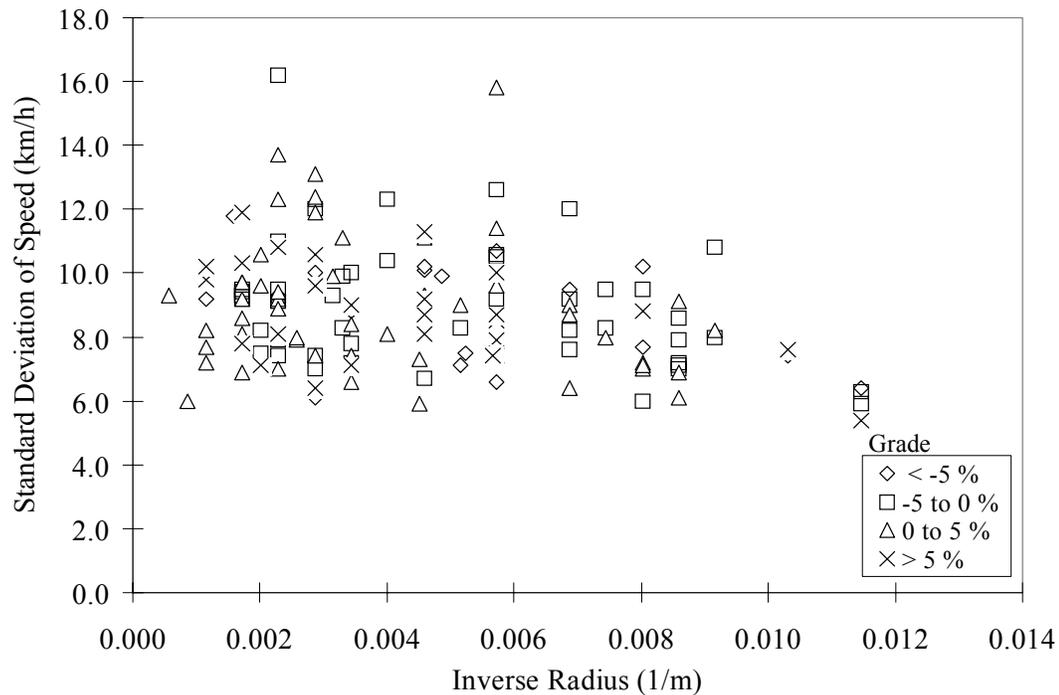
Figure 7. Horizontal Standard Deviation Versus Inverse Radius.

Vertical Curves

The rates of curvature (K), vertical curve length, approach grade, and departure grade of vertical curves were considered as possible independent variables for both sag and crest vertical curves. The rate of curvature was plotted against the standard deviation, skewness, and kurtosis. Figure 8 illustrates the plot of standard deviation by rate of curvature for crest vertical curves. No significant findings were apparent in figure 8 or in any of the other vertical curve-related plots.

Discussion of Results

The analyses conducted found no differences in a variety of speed measures between tangents, horizontal curves, and vertical curves. In particular, there was low correlation between geometric alinement features and speed variance. Similar findings were obtained for other speed measures including skewness, kurtosis, and coefficient of variation. Thus, the hypothesis that roadway geometry can be used to predict speed distribution measures is not supported.
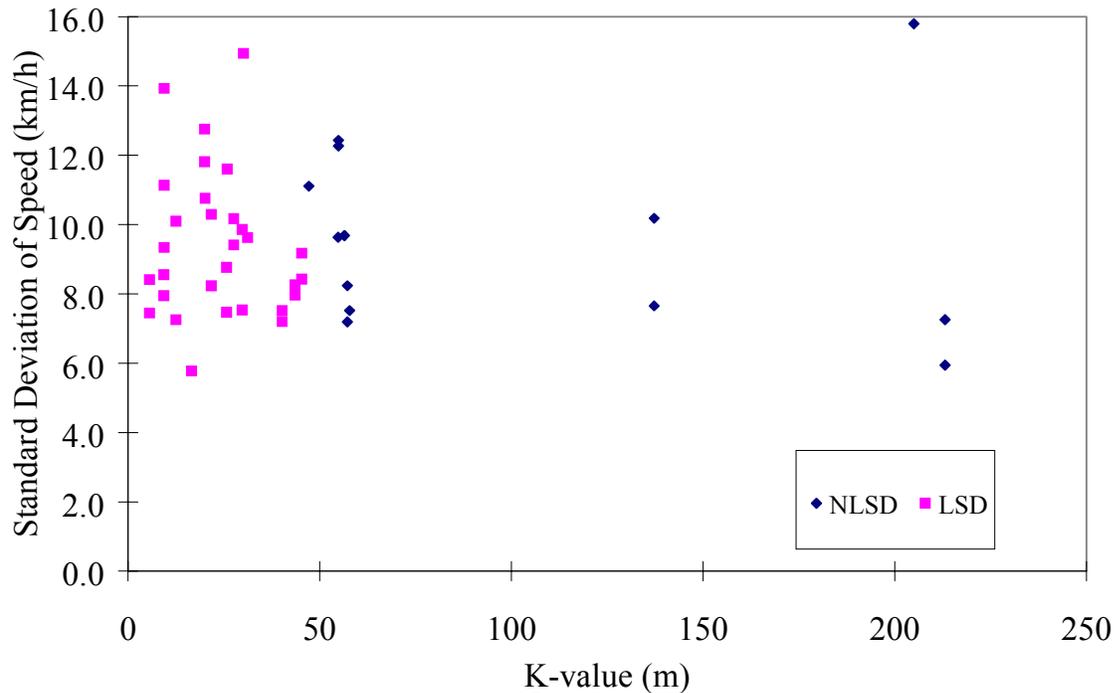
Figure 8. Standard Deviation of Speed Versus Rate of Curvature for Crest Vertical Curves.

HYPOTHESIS TWO: EFFECT OF DESIGN SPEED AND/OR POSTED SPEED

In the preliminary analyses several methods were used to identify possible relationships between the independent geometric variables and the statistical speed parameters. Results suggested no relationships between geometric elements and speed distribution measures with one exception—radii smaller than 100 m result in smaller standard deviations compared with larger radii curves.

Garber and Gadiraju found that speed variance is at a minimum when the difference between design speed and posted speed is between 8 and 16 km/h.[49] Thus, the relationship between these speed components and speed distribution measures was evaluated. The inferred design speed for the data set used in this study was calculated from the known superelevation rate and radius. The posted speeds were recorded on the data collection sheets for each site. Advisory speed limits were not considered since previous research shows they do not affect the operating speed of drivers.[54]

Design Speed

The inferred design speed was compared against standard deviation, skewness, and kurtosis with no clear trends in the data set. Figure 9 shows the plot for design speed versus standard deviation. As the figure shows, there is a large variation in speed standard deviation for design speeds greater than 70 km/h. The smaller range of speed standard deviations for the lower design speeds may be a function of the design speeds but the results are inconclusive for the low number of data points.

Posted Speed

Comparisons made between posted speed limits and speed distribution measures suggested that higher posted speed limits typically have higher standard deviations and mean speeds (see figures 10 and 11). This finding corresponded to the results of Lindeman and Ranft.[53] The skewness of the speed distribution was negative for higher posted speeds. Generally, as posted speed decreased, skewness increased and was positive for the 80.5 km/h locations. Kurtosis was higher for the higher posted speed locations.
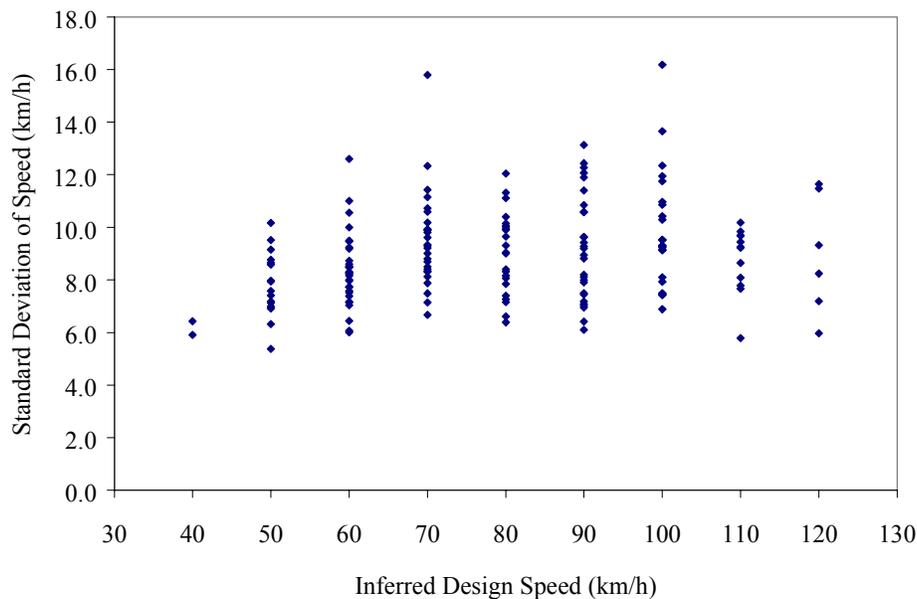
**Figure 9. Standard Deviation of Speed Versus Inferred Design Speed
for Horizontal Curve Sites.**
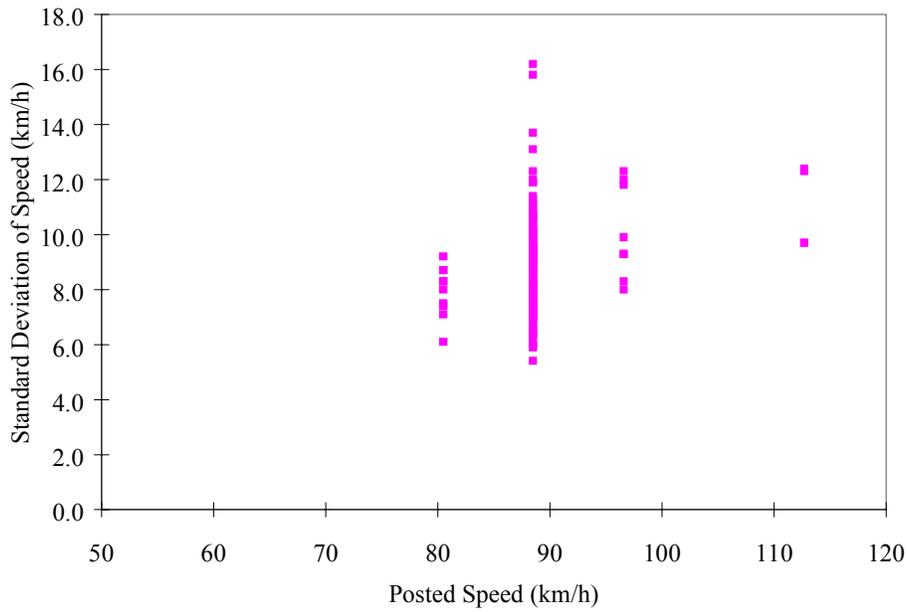
**Figure 10. Standard Deviation Versus Posted Speed Limit
for All Sites.**
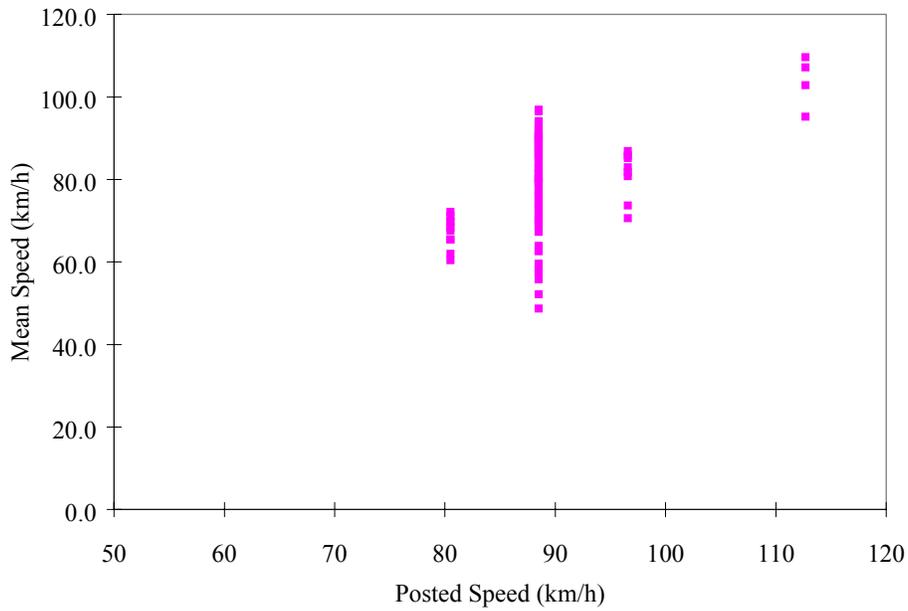
Figure 11. Mean Speed Versus Posted Speed Limit for All Sites.

Design and Posted Speed Differential

The difference between the design speed and the posted speed was determined. Garber and Gadiraju suggest that the difference between these two speeds showed a quadratic relationship against the speed variance.[49] Initial plots of the data did not support this result (see figure 12). Garber and Gadiraju's results, however, were inclusive of all facility types and include all vehicles (i.e., not only free-flow vehicles). It was hypothesized, based on findings from Garber and Gadiraju, that if the difference between the inferred design speed and the posted speed was high, design inconsistencies would be present. Initial analysis suggested that no relationship could be found.
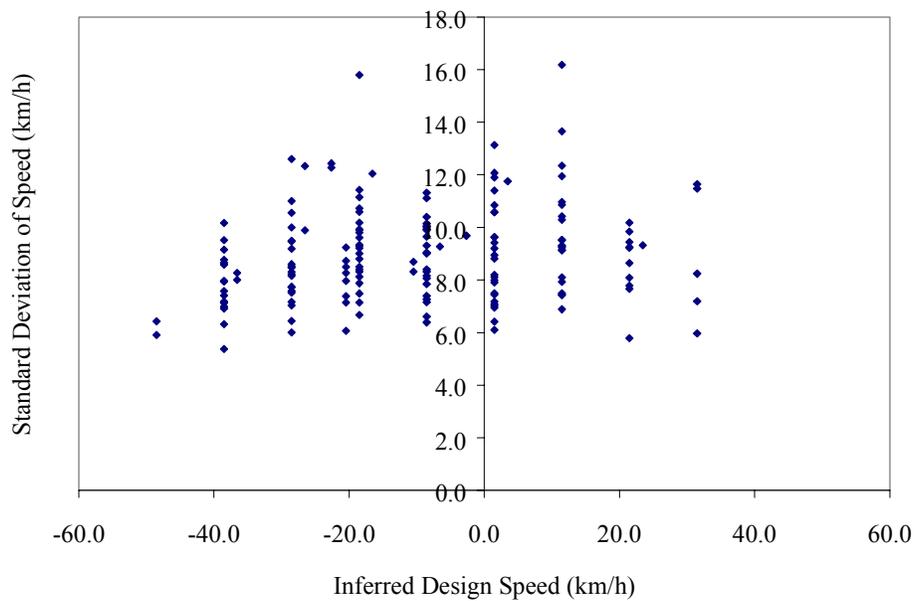
**Figure 12. Standard Deviation of Speed Versus Difference Between
Inferred Design Speed and Posted Speed.**

Revision to this approach involved determination of differences that were less than zero, i.e., the posted speed was higher than the inferred design speed. Radius and pavement width were significantly related to standard deviation for the reduced data set. Figure 13 shows the relationship. This approach accounted for those sites where drivers operated at speeds higher than those assumed by AASHTO design policies. This approach resulted in a model as follows:

$$s = 14.5 - \frac{433.2}{R} - 0.4 \times (PW) \tag{6}$$

where:

s = standard deviation (km/h)
R = radius (m)
PW = pavement width (m)
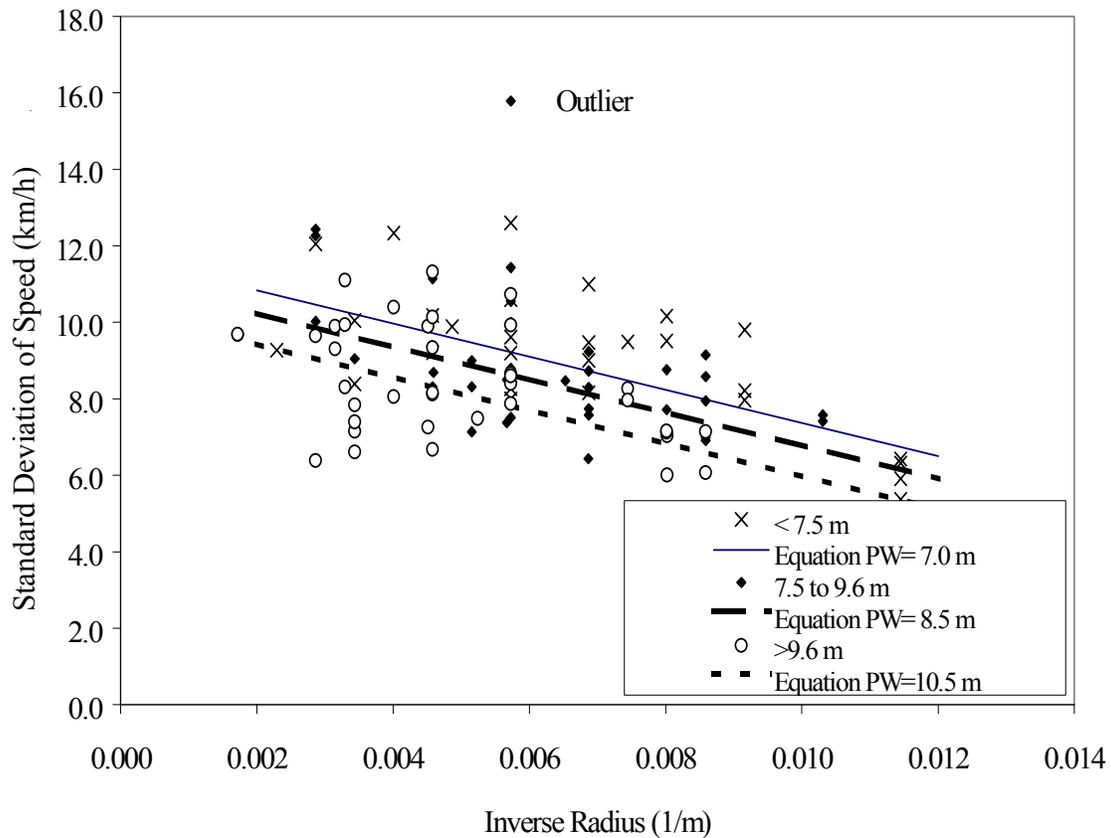
Figure 13. Standard Deviation of Speed Versus Inverse Radius for Sites With Inferred Design Speed Less Than Posted Speed.

The coefficient of determination (R^2) for the model containing radius and pavement width was 0.43, and Mallow's C_p was 4.6. The coefficients for inverse radius and pavement width were found significant at the 0.0001 level for 103 horizontal curves where posted speed exceeded design speed. Thus, if there is a negative difference in the two speed components, this model will predict the amount of speed variance present in the speed distribution at the horizontal curve.

Discussion of Results

The analyses conducted to examine the relationship between speed measures and design, or posted speed, did not find any significant relationships. Expected trends in the data were found that related speed measures to these two speed components, but the variation of the data suggested that design and posted speeds were not accurate predictors of speed measures. For conditions where the design speed is less than the posted speed, a relationship between standard deviation, radius, and pavement width was found. Standard deviation of speed decreased as radius and pavement width decreased. This finding is unique to those conditions where the posted speed exceeds the recommended design speed, or arguably where design inconsistencies exist.

HYPOTHESIS THREE: EFFECT OF PREVIOUS FEATURES

Difference Between Successive Features

The tangent and the horizontal curve spot speed distribution measures were found to be related. The distributions changed from feature to feature, but the change was linear for mean speed, standard deviation, skewness, kurtosis, and coefficient of variation. The tangent mean speed and standard deviation were highly correlated with the mean speed and standard deviation of the curve, respectively. The behavior of the speed distributions at the curve followed the speed distribution measures at the tangent. Thus, if there was high variability in the sample population speeds at the midpoint of the tangent, then there was high variability at the midpoint of the following curve. Figure 14 shows that high standard deviations and mean speeds observed at the tangent resulted in high standard deviations and mean speed at the horizontal curve. The coefficient of variation of both locations was plotted to show the relationship. The figure illustrates a linear relationship, however, not an exact one-to-one ratio. This relationship is not unexpected since the same population of drivers was measured at the tangent and the curve locations.

A similar linear relationship is shown in figure 15 for the relationship of the skewness of the speed distributions collected at the tangent and horizontal curve. Generally, if the skewness is negative along the tangent section (i.e., speed distribution is shifted to the right), the skewness of the horizontal curve will also be shifted to the right.
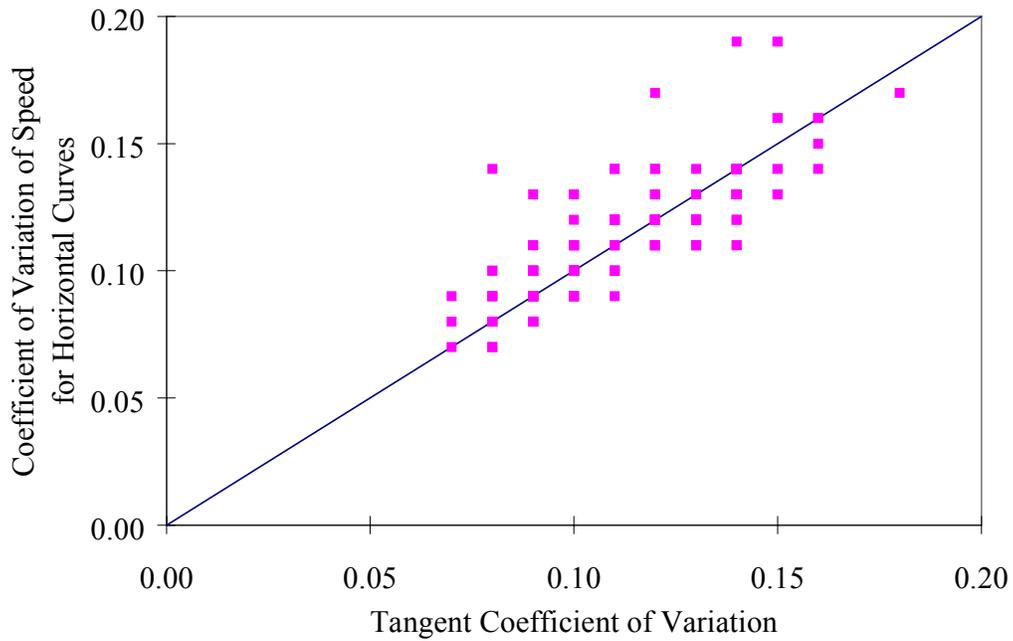
**Figure 14. Coefficient of Variation of Speed for Horizontal Curves Versus
Coefficient of Variation of Speed for Tangents.**
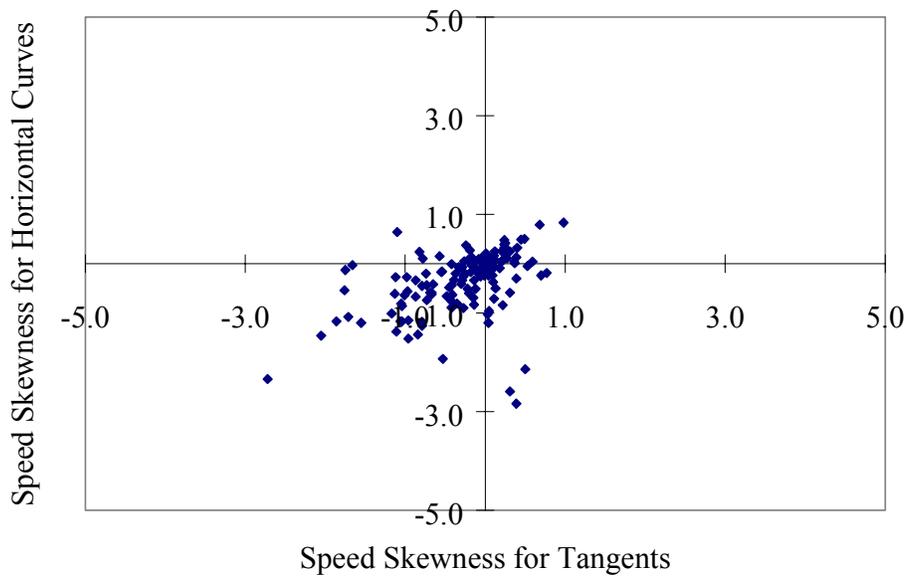
**Figure 15. Speed Skewness for Horizontal Curves Versus
Speed Skewness for Tangents.**

The kurtosis relationship is shown in figure 16. Generally, the kurtosis along the horizontal curve was lower than the kurtosis along the tangent. This relationship stated that the distribution of speeds along the horizontal curve was "flatter" than the distribution along the previous tangent.

The linear relationships for coefficient of variation, skewness, and kurtosis in figures 14 through 16 show some locations where the horizontal distribution measures did not fit a linear trend. These locations need to be further analyzed with accident data to determine whether these locations experience a high accident rate.   Without accident data, no inferences can be made regarding effects of the speed inconsistency at these locations.

Alternative Analysis

This section describes other alternative geometric measures used to relate the statistical variance measures to the geometry of the roadway. Specifically, the change in alinement for a given section of previous roadway and the effect that the previous curve has on the speed variance measures were evaluated.
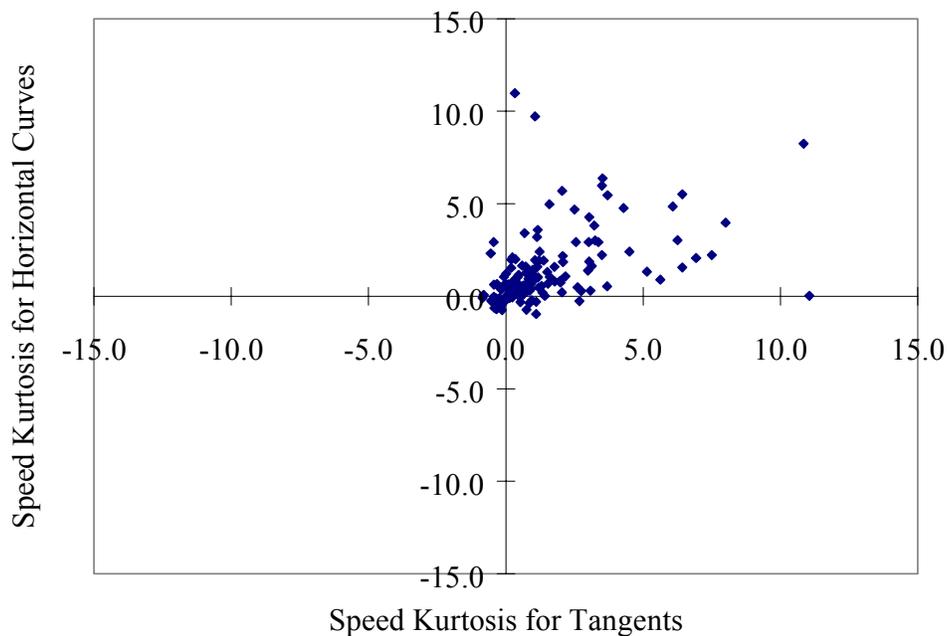
**Figure 16. Speed Kurtosis for Horizontal Curves Versus
Speed Kurtosis for Tangents.**

Relationship Between Speeds and Alinement Indices

An initial analysis using alinement indices proved inconclusive when modeling operating speeds on long tangents. Although the hypothesis did not specifically address alinement indices, the roadway indices developed were evaluated to account for previous roadway environment within this study. Plots and correlation analyses were used to detect potential relationships. No significant findings were apparent.

Relationship Between Preceding Horizontal Curve and Speed Measures

Within Messer et al.'s workload study, an evaluation of the relationship between the preceding horizontal curve and the study curve was examined to account for the differences in radius.[31] It was hypothesized that a large difference in radius between successive curves would show a design inconsistency. This approach seemed reasonable and worked with the database created for the alinement indices analysis. A differential in radius between the preceding horizontal curve and the study curve radius was evaluated. No significant findings were apparent within the statistical speed distribution measures.

Discussion of Results

Data analysis suggests there is a correlation between the coefficient of variation, skewness, and kurtosis of speed on a horizontal curve and on its preceding tangent. Alinement indices and driver workload do not appear useful in relating the speed on a tangent section to the geometric alinement of the upstream roadway. Further analysis, presented in the next section, is needed to determine whether the difference between successive features can, indeed, be used to predict speed variance increases.

HYPOTHESIS FOUR: USE OF STANDARD DEVIATION OF SPEED TO IDENTIFY DESIGN INCONSISTENCIES

The fourth hypothesis, illustrated in figure 4, is that the standard deviation of speed can be used as an indication of the presence of a design inconsistency. Specifically, figure 4 hypothesizes that, as the radius of a horizontal curve decreases, the standard deviation of speed will increase. Some specified increase in standard deviation of speed could then be used to identify particular horizontal curves as inconsistent with the design of the preceding tangent or preceding horizontal curve.

In fact, the data do not support this hypothesis. A key observation from table 6 is that the standard deviation of speed is lower on horizontal curves than on tangents. This, of course, is opposite to the fourth hypothesis, although the observed difference in table 6 was not, in fact, statistically significant.

A further investigation was undertaken using regression analysis to evaluate the relationships between speed measures on horizontal curves and comparable speed measures on the preceding tangents and curve geometrics. These analyses were then repeated using the comparable speed measures for the preceding tangent to normalize the speed measures for each horizontal curve. These two sets of analyses (referred to as the analyses of unnormalized and normalized speed data) are presented below.

Analysis of Unnormalized Speed Data

From the 176 horizontal curves in the database, only those curves in level terrain or on constant grades were considered (i.e., combinations of horizontal and vertical curvature were excluded) in an evaluation of the effect of horizontal curvature on speed variance and other speed statistics. A total of 95 such curves were available. At each horizontal curve, speed data (mean, standard deviation, variance, and 85th percentiles) were provided separately for each of nine vehicle types. Similar speed data were also available for the tangent roadway upstream of each horizontal curve These speed statistics were weighted by the number of vehicles in each vehicle category (nine types of vehicles) and pooled into a single "all-vehicle type" category. These pooled speed statistics were then used in the statistical analyses.

Each curve was described by the following independent variables:

- Curve radius (m); three functional forms of the curve radius were used in all the models: R, $1/R$, and $R^{0.5}$
- Grade (percent)
- Deflection angle (deg)

The speed statistics provided in the raw database apply to either the tangent or the curve. We denoted these statistics as "unnormalized speed statistics" and used them as dependent variables for modeling.

Prior to the regression analyses, many two-variable plots were drawn to assess the form of the relationship, if any, between sets of variables. Single-variable models and multiple-variable models were developed. Based on these plots, linear regression models were developed between curve speed statistics and various geometric parameters at the curve and tangent speed statistics. In a few instances, based on residual plots, an additional term representing the square of the curve radius (R^2) was added to selected models. All regressions were performed using the PROC REG procedure of SAS.®

The findings of the regression analyses from unnormalized speed statistics were as follows:

- No relationships of practical importance were found between curve speed variance statistics (expressed as variance, standard deviation, or coefficient of variation) and tangent speed variance statistics and/or curve geometries.

- Of all the models relating various curve speed statistics to tangent speed statistics and/or curve geometries, only those models using either the (mean speed)$_{curve}$ or the (85th percentile speed)$_{curve}$ as the dependent variable indicate a significant relationship of practical importance (R^2 above 30 percent) with the corresponding tangent speed statistics and/or curve geometry.

- Generally, models including 1/R yielded slightly higher R^2-values than models including $R^{0.5}$. Either of these two forms of radius yielded considerably higher R^2-values than the radius.

- No significant improvement in the fit of the curve mean speed and 85th percentile speed models was obtained when including grade and deflection angle in addition to the corresponding tangent speed statistics combined with either 1/R or $R^{0.5}$.

- For selected models including R^2 in addition to combinations of 1/R, $R^{0.5}$, grade, and/or deflection angle, no significant improvement in model fit was obtained compared with the models without R^2.

- In summary, simple linear models relating (mean speed or 85th percentile speed)$_{curve}$ to (mean speed or 85th percentile speed)$_{tangent}$ in addition to either 1/R or $R^{0.5}$, provide the best relationships.

Analysis of Normalized Speed Data

Normalized speed statistics were created for each horizontal curve adjusting for the speed measures obtained on the preceding tangent. The following normalized speed statistics were obtained:

1. Mean speed reduction = (mean speed)$_{tangent}$ - (mean speed)$_{curve}$ in km/h
2. Log(mean speed reduction + 10 km/h), (a shift of 10 km/h was made to adjust for negative reductions)
3. Percent mean speed reduction = [(mean speed)$_{tangent}$ - (mean speed)$_{curve}$]/(mean speed)$_{tangent}$ in percent
4. Log(percent mean speed reduction + 10%), (a shift of 10% was made to adjust for negative percent reductions)
5. 85th-percentile speed reduction = (85th-percentile speed)$_{tangent}$ - (85th-percentile speed)$_{curve}$ in km/h
6. log(85th-percentile speed reduction + 10 km/h), in km/h (a shift of 10 km/h was made to adjust for negative reductions)
7. Speed variance reduction = (speed variance)$_{tangent}$ - (speed variance)$_{curve}$ in (km/h)^2
8. Speed standard deviation reduction = (speed standard deviation)$_{tangent}$ - (speed standard deviation)$_{curve}$ in km/h

9. Speed coefficient of variation reduction = (speed coefficient of variation)$_{tangent}$ - (speed coefficient of variation)$_{curve}$ (unitless)
10. Speed standard deviation ratio = (speed standard deviation)$_{tangent}$/(speed standard deviation)$_{curve}$ (unitless)
11. Speed variance ratio = (speed variance)$_{tangent}$/(speed variance)$_{curve}$ (unitless)
12. Speed coefficient of variation ratio = (speed coefficient of variation)$_{tangent}$/(speed coefficient of variation)$_{curve}$ (unitless)

For each of the above speed statistics, the speed data on the horizontal curve were adjusted for the speeds on the preceding tangent; we denoted these statistics as normalized speed statistics and used them as dependent variables for modeling. These pairwise differences between a speed measure for a horizontal curve on its preceding tangent provide a more powerful statistical approach for determining the effect of horizontal alinement geometry on speed measures than the two-sample tests presented earlier.

An approach was taken to model the normalized speed variables identified as a function of only geometric parameters of the curve (i.e., R, 1/R, and $R^{0.5}$, deflection angle, and grade). Single-variable models and multiple-variable models were developed. Again, based on residual plots, a few models were rerun with the addition of a second-order term, R^2. In addition, a few models were run based on an exponential decay [e.g., of the form Y=a exp(-bX)].

The following are findings of the regressional analysis for the normalized data:

- Overall, mean speeds are generally lower on the horizontal curves than on the preceding tangents. On the average, the mean vehicle speed on the horizontal curve was 2.8 km/h lower than on the preceding tangent; the 85th percentile speed was 3.0 km/h lower on the curve than on the tangent. In addition, the speed variance was 9.5 percent lower on the curve than on the preceding tangent. All of these differences were statistically significant at the 5 percent significance level.

- Generally, no statistically significant regression models could be developed relating any of the normalized speed variance measures listed above to curve geometries.

- Models in which any of the form of normalized mean speeds or 85th percentile speeds shown above was modeled as a function of curve geometries yielded R^2-values between 14 percent and 34 percent.

- Some of the relationships between forms of normalized mean speeds (or normalized 85th percentile speed) and curve geometries were modeled as exponential decay functions based on plots; however, although significant, these models did not add any new insight to the previous models.

- In summary, the models relating the (normalized) percent mean speed reduction to either 1/R and grade or to radius, grade, and deflection angle, provided the only R^2-values above 30 percent (34 percent and 32 percent, respectively).

Discussion of Results

The analysis results reported above are in conflict with the fourth hypothesis and, therefore, do not support the use of speed variance as a design consistency measure. This evaluation was undertaken to test the fourth hypothesis that speed variance might be a suitable design consistency measure if speed variance increased at locations with potentially inconsistent designs such as sharp horizontal curves. In fact, as the results presented above indicate, speed variance generally decreased on horizontal curves as compared with the upstream tangent. This finding is consistent with the observation that horizontal curves affect the speeds of faster vehicles more than that of slower vehicles, thus reducing the speed variance. Given this finding, the fourth hypothesis does not appear to be valid and it is inappropriate to consider speed variance as a design consistency measure for horizontal curvature.

SUMMARY OF FINDINGS

The hypotheses that would enable speed distribution measures to be used to evaluate geometric design consistency do not appear to be valid. In general, there was low correlation between geometric alinement features and speed variance, as well as between alinement features and other speed measures including skewness, kurtosis, and coefficient of variation. Large differences in speed variance existed for the different design and posted speeds. As expected, there was a relationship between speed distribution measures of successive features but this relationship was the result of sampling the same drivers. Standard deviation of speed does appear to change between horizontal curves and tangents, but the change is in the direction of lower, rather than higher, speed variance on horizontal curves than on tangents. This finding makes the use of speed variance inappropriate for identifying design inconsistencies.

5. DRIVER WORKLOAD—FIELD

Previous studies performed at TTI in the general area of roadway design and its impact on driver performance have focused considerable attention on the concept of mental workload as an approach to measuring or rating the design.[7] The driver is almost continuously processing visual and kinesthetic information, making decisions, and carrying out control movements.

In other words, the task of driving involves, among other things, tracking the lane or path selected by the operator (driver). This action is a compensatory tracking task that requires a driver to visually evaluate the path ahead, predict the steering and speed control inputs necessary for maintaining the desired path, make the control inputs, then, using visual feedback, manipulate the controls to compensate for deviations. The tracking process continues until the vehicle reaches the desired destination or is otherwise brought to a stop.

Generally, little visual information processing capacity is required of the experienced driver to perform this basic task. This task is performed almost automatically if the roadway is free of traffic and obstacles and if the driver's visual evaluations are consistent with the tracking requirements. The presence of traffic, or the potential for obstacles, requires the operator to devote more processing capacity to visually evaluate the path ahead and to modify control input predictions.

Consistency of the visual evaluation of the roadway with the actual roadway requirements is a function of the sight distance and the driver's experience with the roadway. Sight distance is the portion of the roadway available for view at any given time. The shorter the sight distance, the less visual information is available for evaluation and the more frequently a driver will need to update predictions. Also, when sight distance is limited, the importance of the driver's experience with the roadway is increased. Experience with the roadway is a function of the number of times a driver has driven a particular road, the similarity of the road to others in the driver's experience, and the accuracy of predictions about the road that have recently been made. Collectively, this experience has been referred to as expectancy. A driver expects the path, or roadway geometry, to be consistent and predictable even when sight distance is restricted.

A consistent roadway geometry allows a driver to accurately predict the correct path while devoting little visual information processing capacity, thus allowing attention or capacity to be dedicated to obstacle avoidance and navigation.

Several research efforts have been undertaken to measure geometric consistency. These studies have used various methods and parameters to model or rate geometric features, or combinations of features, in terms of the difficulty they might pose to a driver. The logic underlying these efforts is that the more difficult a feature or feature combination, the greater the visual information processing requirement and, in turn, the less desirable the feature.

GENERAL CONSIDERATIONS

Imagine a driver moving along a rural two-lane highway at design speed, with a certain amount of opposing traffic. It is a common-sense notion that the mental resources the driver brings to this driving task are finite. One cannot pay attention to everything at once. The driver is working at the control level (to use the Positive Guidance model) to steer the vehicle and perform the other tasks associated with second-to-second control, and at the guidance level to keep it on the nominal pathway constrained by the design of the facility and other factors, such as leading traffic.[55] This driver may also be allocating a certain amount of attention to wondering where he or she is (navigation level) while also attending to a radio talk show. Different models of attention allocation postulate either somewhat parallel capabilities for dividing attention, or more classically contend that people rapidly shift their attention among the various demands, somewhat like a computer timesharing arrangement.[56] As demand for attentional resources increases, performance on some or all of the different activities that a driver is doing tends to degrade. At the same time, as mental workload increases, different body functions and physiological processes also change in response to the "stress" that any kind of workload, mental or physical, brings. Some of these performance changes and physiological responses are easily measured. Others are rather difficult, especially in an actual driving situation. All such measures or indices are subject to a rather simple basic criterion concerning loading that is, however, somewhat suspect in engineering circles. Johanssen has perhaps said it best:

> "Rating scales must be regarded as central to any investigation. If the person *feels* loaded and effortful, he *is* loaded and effortful, whatever the behavioral and performance measures may show."[57]

Although many different techniques exist for measuring workload, Smiley identifies the four basic approaches:

1. Primary task measures: as the task becomes more difficult, performance deteriorates.

2. Secondary task measures: while performing a primary task, the driver also performs a secondary task such as doing mental arithmetic or discriminating audio or visual signals; the more difficult the primary task, the poorer the performance on the secondary task.

3. Physiological measures: as the primary task increases in difficulty, physiological arousal increases.

4. Subjective measures: as the primary task increases in difficulty, so does the driver's estimate of his/her own workload.[58]

There are five basic criteria for workload measures, in addition to the fundamental feeling of being loaded, however assessed:

1. Sensitivity: the measure should have a high signal/noise ratio.

2. Diagnosticity: the measure should be an indicator of the type of resource that is being stressed, e.g., physical vs. mental, visual vs. auditory, etc.

3. Selectivity: the measure should not be confounded with physical or emotional stress.

4. Obtrusiveness: the measure should be as transparent to the driver as possible. Ideally, the driver should not know he/she is being assessed, although this is normally unavoidable given human subject guidelines and requirements. The only counter-measure is sufficient acclimatization (a judgment call) to minimize interference effects from being a subject.

5. Compliance: the measure should track changes in workload rapidly enough to capture transient phenomena.[56]

Another criterion often identified is transferability: the measure should be applicable in a variety of operational situations.

Thus, the most direct way of determining the moment-to-moment mental load being placed on the driver is to simply ask him or her, in some structured way, how busy they are. This approach, however, is fraught with a number of objections: it is "subjective," introspective, relative, disruptive of the primary task, and only very roughly amenable to parametric analytic methods. Nevertheless, if any surrogate measure or indicant of mental workload suggests a level of stress inconsistent with self-report, that measure can and should be suspect.

Smiley contends that a combination of different types of measures is required to assess mental workload; no single measure is sufficient.[58] Thus, multiple regression methods are used to arrive at a weighted combination of measurement values to predict mental workload. Wierwille and Eggemeier have well summarized the state - of - the - art in a recent (1993) article.[59] Several important points are made by the authors. One supports Smiley's contention that a combination of measures is desirable or even necessary, but cautions that measures should not interfere with one another; a primary task measure should not be paired with a secondary task measure, for example. Another point is that multiple measures of workload may be appropriate in many conditions because they may provide an improved diagnosticity, with individual measures providing information not duplicated by other measures.

Subjective Ratings

Several excellent subjective rating techniques have been used by a number of researchers. TTI has used various forms of the Cooper-Harper Scale for many different continuous control

performance rating situations.[60] Other good scales include the Subjective Workload Assessment Technique (SWAT) and the NASA Task Load Index (TLX). The methods are thought to be "globally sensitive," i.e., they have the "...capability to reflect variations in different types of resource expenditures or factors that influence workload."[59] The ratings can be elicited before, after, and in the case of the Cooper-Harper Scale, by an experienced rater, during the actual loading. SWAT and TLX are multi-dimensional, and thus are more diagnostic than the Cooper-Harper Scale; however, SWAT and TLX are rather cumbersome and require a great deal of driver training to be an effective tool for estimating workload. The Cooper-Harper scale is nothing more than a 10-point Likert scale anchored by adjectives at each level. It can easily be taught to drivers, and has been used for many studies at TTI and validated in many other studies.[59,60]

Another approach developed at TTI is a composite rating approach (discussed in chapter 2), in which the overall workload rating is an additive and multiplicative aggregate of feature type, sight distance, driver expectancy, and the previous feature's workload.[31] The feature rating (derived from surveys of cognizant professionals in the field) is modified by considerations of sight distance, feature expectancy, and driver familiarity estimates. The carryover from the previous feature encountered is modified by the overall workload associated with that feature. These two terms are then added to arrive at the overall workload for the feature under consideration. The other problem, of course, is that to date no evaluation of the ratings thus derived has been done, in which other measures discussed below are correlated with these ratings, or traffic behavior studies are compared with these ratings.

Performance-Based Assessments

Primary task performance, i.e., driving the vehicle at the control and guidance levels of performance, can be measured to assess workload. If the driver is overtaxed, his or her performance will suffer. Up to some critical level, the driver will adapt and shed off secondary tasks and no differences will show up even though the geometric design of the roadway is considerably varied.[59] Hence, secondary task performance is a better choice to demonstrate shifting of mental resources in response to such roadway variations. It takes considerable ingenuity to devise realistic secondary tasks as opposed to arbitrary ones such as working arithmetic problems or responding to extraneous signals on a cathode ray tube, however.

Physiological Measurements

Wierwille and Eggemeier identify the most widely used measurements to be heart rate (HR), heart rate variability (HRV), brain activity, and eye activity (the last measure has aspects of performance assessment about it).[59] Heart rate changes with workload have long been documented as a general index of arousal and/or physical work. Changes in heart rate variability, i.e., the variance in the beat-to-beat interval (cardiac arrhythmia) have been found to reliably discriminate among various types of tasks relevant to driving. As workload increases, HRV decreases, while HR tends to increase with physical effort. Both statistical and spectral analysis

techniques have been employed to analyze electrocardiographic records. Heart rate measures are fairly unobtrusive once the electrodes are placed (only three or four are required for HR or HRV), and good results can be obtained by measuring and processing tidal blood volume changes in appendages such as an earlobe.

Brain activity measurement presents a much more complex recording and data interpretation situation. Event-related potentials (ERP) have been shown to relate to inferred levels of demand in a variety of flight simulator tasks and in driving. Specific events give rise to changes in cortical activity that can be correlated if the specific events leading to the ERP can be identified. Continuous tasks, in particular control tasks, do not lend themselves well to ERP analysis at the present state - of - the - art. Eye, body, and heart potentials pose a distinct problem because the evoked brain potentials are so small (10 to 20 micro volts). Electrodes are rather obtrusive and require careful placement for retention on heads of hair.

Eye activity measurements have been in use for many decades. Eye blinks, eye movements, and pupillary response have all been studied for application to workload assessment. Eye blink frequency and duration have both been shown to have a direct relationship with visual workload: blink rate decreases as workload increases, as does blink duration. Under stress, drivers tend to blink less, stare more, and minimize time that their eyes are closed during each blink. But, eye blink measurements do not correlate well with other types of cognitive tasks or those involving other sensory modalities. Pupillary responses have also been studied; they relate more to general arousal of the driver. As arousal increases, the pupil tends to dilate, if light levels are held constant.[61] Infrared reflection, direct imagery, and electro-oculographic techniques have all been used to study blinking and pupil responses.

Vision Occlusion Assessments

As synthesized by Johannsen, workload consists of several different attributes: input load, operator effort, and performance.[57] Several studies have used the vision occlusion method of assessing perceived visual information requirements for individual geometric features.[1,10] The vision occlusion method involves allowing a driver to observe the roadway ahead only when the driver perceives the need to update information for guidance and control purposes. Assuming no lane excursions occur, this process can produce a simple estimate of visual information needs. This measure has been referred to as visual or mental workload (WL).[7] The complement of this measure (1-WL) has been referred to as spare visual capacity.

TTI has conducted a number of studies of workload and roadway geometry using the vision occlusion approach.[7,62] The approach varies somewhat among researchers, but the basics are the same. The driver is assumed to need to attend to the roadway only for part of the total driving time. Glimpses of the roadway serve to confirm hypotheses about the task immediately ahead. As the roadway ahead becomes increasingly less predictable, for whatever reason, the driver spends more time looking at the cues that tell him or her how to guide the vehicle in the next few seconds. A pair of goggles or other similar device is equipped with either mechanical

or electronic means to blank out the driver's view of the road. One approach is to have the driver close the otherwise open goggles as much as he or she thinks they can and still drive safely. The other approach is to have the driver open the otherwise shut goggles for a glimpse of the road as often as they think they need to see the road.

Senders et al., in a study using five drivers, found that drivers requested more glimpses of the roadway as the complexity of the roadway increased, but did not find a direct relationship between roadway curve characteristics and glance frequency.[34] In this study, speed was also examined. Subjects directly controlled their speed while experimenters controlled glimpse frequency. Speeds were found to be lower in more complex portions of the roadway, indicating the tradeoff between selected speed and glimpse frequency. TTI's previous work, in a study using 24 drivers, examined vision occlusion at a fixed speed. The findings suggest that the frequency of glimpses (and hence the percentage of the total time that vision is not occluded) goes up as the degree of curvature increases, the inference being that workload is also increasing.[7]

In this current study, the vision occlusion method was employed, both in closed-course conditions and also on actual rural two-lane roadways under controlled conditions.

EXPERIMENTAL DESIGN

The evaluation of driver workload at TTI was somewhat exploratory in nature. Researchers focused on evaluating factors that had been studied in the past to examine repeatability issues while adding a limited number of other factors. With that in mind, the development of workload models focused on aspects of horizontal alignment. Primarily, researchers sought to determine the level of workload associated with encountering various types of roadway curves and sequences of curves. Curve characteristics were varied to assess the effects of radius and deflection angle, while curve sequences were examined in an attempt to assess workload carryover and expectancy issues. Through tests, it was hoped that researchers would gain insight regarding situations that produce changes in driver workload or response.

Because it is extremely difficult to quantify a limit to acceptable workload levels,[59] researchers also sought to examine issues related to driver tolerance for workload change. It has been suggested that a driver's prior experience with a roadway leads to an expectancy of the workload that will be required by that road ahead. This expectancy dictates the level of mental resources allocated to the visual search task. If the future geometry of the roadway is consistent with expectancy or predictions, then mental capacity can be allocated to driving and other tasks. If, however, the geometry of the road ahead does not match predictions, a driver may not have allocated sufficient mental resources to the guidance task. Sight distance limitations and inability to assess feature complexity may further add to the demand for mental resources. It is possible that a driver might not be prepared to deal with the workload requirements of a feature encountered. Certainly, drivers are able to tolerate some sudden increments in workload. The

question is, how great a deviation from the expected can be successfully managed? The answer to this question is the essence of geometric consistency. Roadways should be designed or redesigned in a manner such that the workload demands of their component features do not exceed the tolerance for demand change of the typical driver. If the characteristics of this tolerance variable are known, it then becomes a matter of measuring the workload values associated with various geometric features and specifying the maximum amount that successive features on a roadway could vary without exceeding the tolerance limit.

The approach for assessing this tolerance limit value was the method of limits. If drivers are able to successfully negotiate a given geometric feature at some workload level determined by the vision occlusion method, they have established their <u>perceived</u> level of needed visual information. If this level of information availability is artificially reduced by decreasing the glances at the roadway allowed, there will be a point at which lane excursion will occur. This level will define the <u>minimum</u> mental workload required by the feature. The difference, then, between the perceived workload level and the minimum workload level can be taken as an approximation of the tolerance for change in workload value that could be managed when the next geometric feature on the roadway is encountered.

Testing to evaluate driver workload was implemented at the Texas A&M Riverside Campus in a protected environment for drivers and then further tested for comparative purposes on actual roadways using drivers who were thoroughly familiar with the instrumented vehicle and the occlusion device. Testing to evaluate workload tolerance took place only at the Riverside Campus because of the necessary lane excursions. All subject drivers were volunteers, and were either current TTI employees or their spouses.

The two research objectives were determined as: (1) assess driver workload imposed by roadway geometric features, and (2) assess driver tolerance for increases in workload imposed by roadway geometric features. Three studies were developed to meet these objectives (see table 7). The studies of single curves sought to determine the relationship between driver workload and geometric characteristics of roadway curves, while the study examining paired curves sought to examine issues related to workload carryover and expectancy; further detail is provided in the sections describing each of the studies.

Test Track Study

Data collection for the driver workload effort at TTI centered around the use of vision occlusion while driving, although other workload measures were examined. The workload measurement approach using vision occlusion featured the use of a liquid crystal display (LCD) visor that was either under the control of the driver or the experimenter, depending on the stage of the experiment. Subjects drove a Ford Taurus station wagon at the Riverside Campus test facility in a controlled testing environment.

Table 7. Summary of Objectives and Studies.

Objective	Study	Description
Assess Driver Workload	Test Track: Individual Curves	Use objective and subjective measures to assess workload on isolated curves
	Test Track: Paired Curves	Use objective and subjective measures to assess workload on a sequence of two curves
	On-Road: Single Curves	Use objective and subjective measures to assess workload on isolated curves
Assess Driver Workload Tolerance	Test Track: Single Curves	Assess the difference in workload between the perceived level of needed information and the minimum level of needed information (i.e., workload tolerance)

Drivers

Twenty-four subject drivers were drawn primarily from TTI employees. Both research and administrative staff were part of the pool of available volunteers. Because of the large number of potential drivers, it was possible to select from among the volunteers such that a relatively diverse group of drivers actually performed the testing. The primary criteria used for selection were gender and age, with equal numbers selected in each of the categories used in the study (see table 8). All drivers were required to have a valid U.S. driver's license.

Because the information processing used in driving through geometric features is largely at the skills and psychomotor level, educational background should not have made a difference. However, it was considered desirable to provide as diverse an education level as possible considering the available subject pool. The drivers used in the study included a wide range of education levels, as shown in table 9. Additional information obtained from the drivers was the approximate number of miles driven annually (42 percent reported 10,001 to 15,000 miles) and where they drove most (79 percent reported a mix of all locations).

Although it was desirable from an analytical point of view that all drivers drive all of the test conditions, three drivers were unable to complete the testing program. One driver resigned from the study after completing approximately one-third of the study, and two other drivers were unable to complete the final third of the study because of scheduling conflicts.

Table 8. Gender and Age Balance of Drivers.

Gender	Age (years)		
	18-24	35-54	55+
Male	4	4	4
Female	4	4	4

Table 9. Education Level of Subjects.

GED or High School Diploma	Some College	Associate Degree	Bachelor's Degree	Master's Degree	Doctoral Degree
5	6	0	8	2	3

Features Tested

Initial testing was performed at Texas A&M University's Riverside Campus Test Facility. This facility, a former military air field, provides the opportunity to display a wide variety of large-scale driving scenarios. The various runways available range in width from approximately 90 m to more than 150 m and lengths of greater than 2000 m. The various runway and taxiway intersections provided researchers with a variety of testing configurations in a controlled environment.

Test Courses

Three separate courses, shown in figures 17, 18, and 19, were designed to accommodate the various curves included in the test plan. Lanes 3.6 m wide were delineated through use of removable yellow markings. The markings were 10 cm wide by 5 cm high, and were placed at 6-m intervals on both sides of the marked lane. Figure 20 shows a view of one curve and its delineation. As shown in the figure, some extraneous pavement markings were present on the track, although subjects did not generally appear to be adversely affected by the markings.
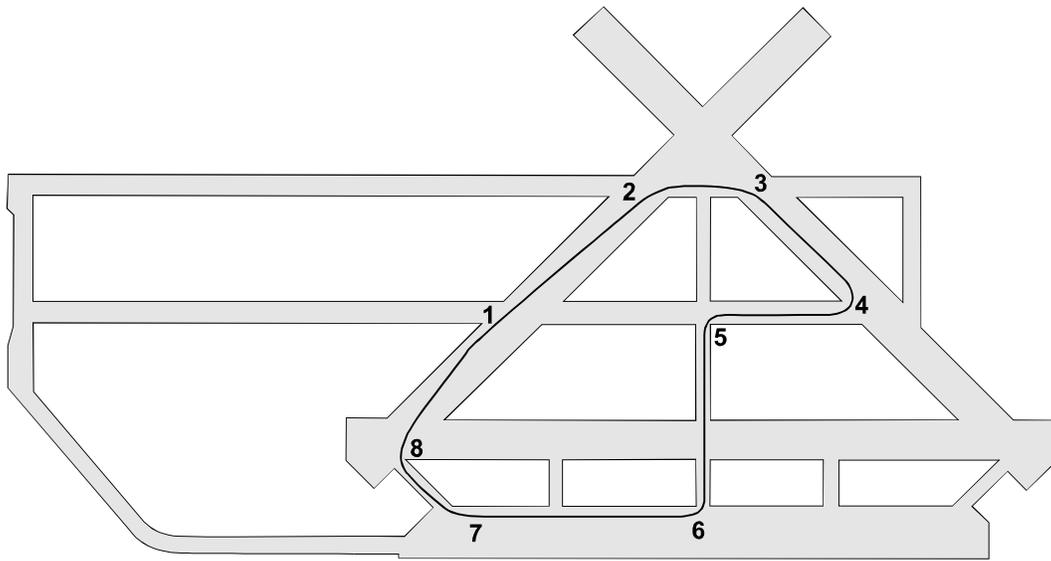
Figure 17. Closed Loop Test Course 1 (test curves indicated in table 10).
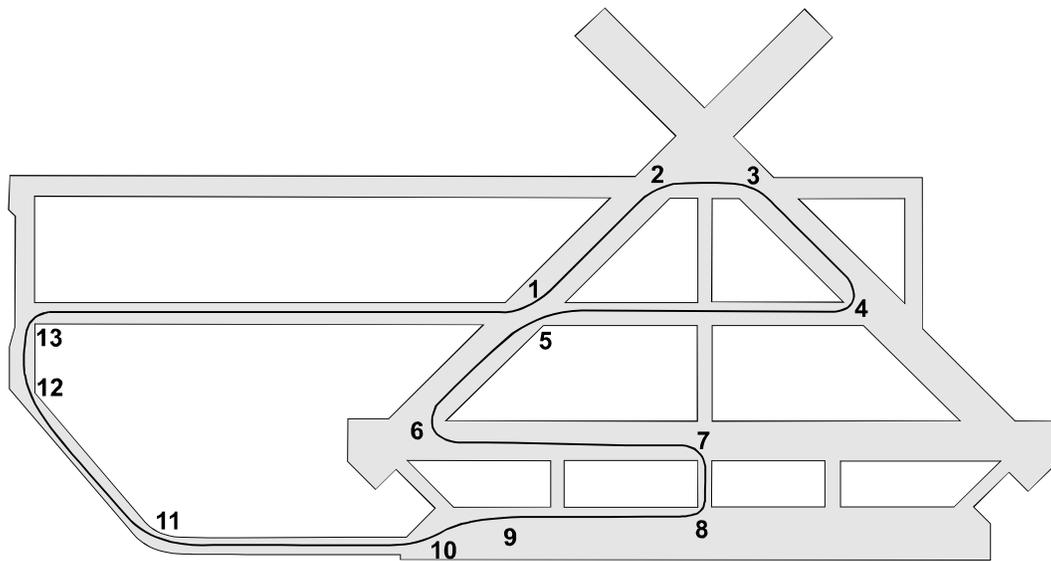
Figure 18. Closed Loop Test Course 2 (test curves indicated in table 10).
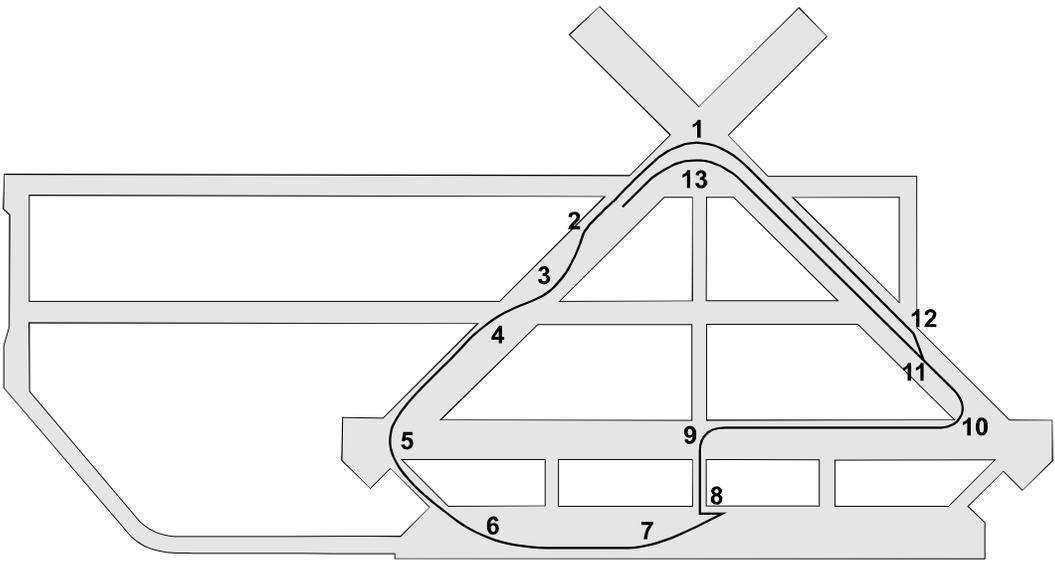
Figure 19. Closed Loop Test Course 3 (test curves indicated in table 10).

Figure 20. View of Test Course Markings.

Geometric Variables

Geometric variables amenable to study at the Texas A&M Riverside Campus included:

- Deflection angle, i.e., the angle formed by the approach and departure tangents to a curve
- Radius of curvature
- Direction of travel of the next curve with respect to the curve just traversed
- Tangents

Because it was not possible to construct a single test course that contained all of the features that researchers wanted to examine, three different courses were designed and delineated. The test track courses featured individual horizontal curves that fit the matrix shown in table 10, although tangents were also tested on all three courses. The courses were constructed and used for testing in the order indicated by the course numbers in table 10.

Table 10. Test Track Curves.

Radius, m	Deflection Angle, deg	Course	Curve
145	20	1 (shown in figure 17)	1
145	45	2 (shown in figure 18)	1
145	90	3 (shown in figure 19)	1
290	20	2 (shown in figure 18)	9
290	45	2 (shown in figure 18)	5
290	90	3 (shown in figure 19)	13

A limited number of curve sequences were also tested. Separation distance and sequence type (i.e., an S-curve has the second curve opposite in direction to the first curve while a broken-back curve has the second curve identical in direction to the first curve) were tested for their effects on driver workload. Broken-back curves have been cited as violating expectancy because drivers do not expect to be confronted with two closely - spaced turns in the same direction; this is contrasted with the more typical pattern of the S-curve.[2] The spacing between the paired curves was varied in a controlled manner in the hope of detecting any carryover effect, as portrayed in the work done by Messer, Mounce, and Brackett.[31] Each curve in the sequence had a radius of 145 m and a deflection angle of 45 deg. Table 11 shows the sequences tested.

Table 11. Curve Sequences.

Sequence Type	Separation Distance, m	Course	Curves
S-Curve	61	3	4-3
S-Curve	274	2	1-2
Broken-Back Curve	61	1	2-3
Broken-Back Curve	274	3	6-7

Occlusion Visor

The LCD visor was worn by the driver (see figure 21). This visor provides clear vision if an AC voltage is applied across it, but is otherwise opaque. When opaque, diffused light is still transmitted through the visor, although objects or features are not visible. This diffused light greatly reduces the amount of light adaptation for the driver that would otherwise be necessary when the visor is "closed" and "opened." Two testing phases were completed at the Riverside Campus test facility to examine and contrast data obtained when (1) drivers controlled the occlusion visor and (2) when the researcher was in control of the occlusion visor.

Driver Demand Occlusion

In this phase of the testing, the driver could request a glimpse of the road for a set interval of time by pressing a floor-mounted button with his or her left foot. Drivers were instructed to only request as much vision as necessary to stay on the course. The vehicle was equipped with cruise control, and for the purposes of this study the speed was set to 72 km/h (45 mph). This speed was selected primarily because of previous successful studies conducted at similar speeds at TTI and in the literature and the desire to compare results obtained in the current study with those obtained earlier.[7,62] This speed also permitted the layout of a challenging but drivable course in the available test area.

During the testing, vision requests and the locations of the vehicle were recorded on a personal computer. The length (fixed at 0.5 s) and location of each vision request were related to the test course. Research reported in the literature suggested a nominal fixation time of 450-600 msec, hence 500 msec was chosen as the glance length. A visual demand "observation" was calculated from this data and was computed as the ratio of the glimpse length divided by the time elapsed from the last glimpse until the time of the present request, or:

Figure 21. LCD Visor in Clear, Opaque Settings.

$$VD_i = \frac{t_{glance\ length}}{t_{request} - t_{last\ request}}$$

(7)

where: VD_i = visual demand
t = time, sec

This calculation provides a measure of the percentage of time a driver is observing the roadway at any point along the roadway. It can readily be seen that a given observation's value increases as the time between successive glances grows shorter and decreases as the interval between glances increases. The more information the driver needs to carry out his or her control function in driving, the more often the scene ahead must be sampled, i.e., the workload increases.

The visual demand rating for a given feature of the roadway is simply the sum of the individual observations that occurred during a set distance in or before the feature divided by the number of those observations, i.e., the mean visual demand during the distance in question:

$$VD_{avg} = \frac{\Sigma VD_i}{N}$$

(8)

The practical limits on this assessment of visual demand range from a maximum of approximately 1 (assuming a glance duration of 0. 5 s and the driver's request for a glance almost instantaneously with the close of the glance interval) to a minimum of 0.08, reflecting a given observed time of 6 s between glances (obtained on a tangent section of track). The circuit does

not reset for the next glance request until the previous glance period has elapsed, and requires at least 0.1 s between successive presses to reset.

Researcher-Controlled Occlusion

The occlusion workload assessment described above provided an estimate of the amount of visual contact desired by the driver to feel comfortable with the driving task at a particular point in time and the immediate future. What is missing is how much visual contact the driver needs to have before the driver leaves the lane or fails to move the steering wheel in time to meet the upcoming feature. This can be thought of as a tolerance interval. If this interval is narrow, there is little margin for driver adaptation to the level of work demanded; if it is wide, the driver has plenty of leeway. The lower threshold of "need to know" is determined through occlusion methods, but this time with the experimenter in charge of requesting glances rather than the driver. This approach follows that used by Godthelp.[63]

In this phase of testing at the test track, the driver was gradually deprived of visual coverage by lengthening the time between glances until the vehicle left the lane. The difference between the average workload for the feature and the threshold average workload for the same distance at which the driver "loses control," represents a response for the feature which may be thought of as a "pad" or tolerance. It was postulated that the greater the tolerance, the more consistent a feature is with respect to the feature that immediately preceded it. That is, in the expected situation the driver would be able to summon more than enough resources to cope with the actual needs of the situation; in an unexpected situation, the driver might underestimate the situational demands and be more likely to make a driving error.

Subjective Rating

A subjective rating scale was developed based on the modified Cooper-Harper (MCH) scale used widely in aircraft testing.[64,65] Modified descriptive terms were developed to relate the scale to the driving environment, and anchor definitions were provided to ensure that drivers compared the scaling with familiar circumstances. The complete scale is shown in table 12; a simplified version without the "Demand" column was placed on the dash of the test vehicle as a reminder for the drivers.

Subjective ratings of the difficulty of driving the test curves were obtained during the first passes through the respective features. Ratings were obtained while subjects were using the visor, just after completing each feature in turn. The ratings were recorded manually by the experimenter.

Table 12. Modified Cooper-Harper Scale Used Prior to Test.

Difficulty Level	Demand	Anchors	Rating
Very easy	No mental effort needed to drive	As easy as driving a straight, flat road	1
Easy	Little mental effort needed to drive		2
Little difficulty	Some mental effort needed to drive		3
Minor difficulty	Moderate mental effort needed to drive		4
Difficult	Considerable mental effort needed to drive	By concentrating you can steer a smooth path	5
Very difficult	High mental effort needed to drive		6
Major difficulty	Maximum mental effort needed to drive		7
Very major difficulty	Maximum mental effort needed to stay in lane		8
Almost impossible	Maximum mental effort needed to stay on road		9
Impossible	Cannot stay on the road	Curves are too sharp to stay on road	10

Procedure

Subject drivers drove the test courses under the two regimens of occlusion, beginning with an examination of workload (driver-controlled occlusion) and ending with an examination of workload tolerance (researcher-controlled occlusion). In all cases the subject drove the test vehicle with a researcher in the back seat and an assistant in the front passenger seat.

The researchers began the testing program by giving the drivers instructions that provided information regarding the nature of the experimental task (i.e., driving while using the occlusion visor). The use of equipment and vehicle were demonstrated by the experimenter; the demonstration included informing the subjects of emergency overrides for the visor and the availability of a trainer brake for use by the researchers in the event of an emergency. The drivers next signed informed consent statements and were asked to put on the heart rate

variability sensor (an elastic band that fits around the torso just below the sternum point). They were also taught to rate their workload using the subjective rating scale.

After the experimenters drove the subjects to a practice area, the subjects sat in the driver's seat of the test vehicle (see figure 22). Wearing the occlusion visor and practicing with the foot switch and emergency overrides, the drivers drove around a special course apart from the test setups to familiarize themselves with the equipment and the vehicle.

After the drivers became relatively comfortable with the use of the equipment (judged by their willingness to engage in casual conversation while driving), they were directed to the starting point for the test. The drivers were first asked to drive naturally through the set of experimental features, without instruction or use of the occlusion device to assess "comfortable" speeds through the features and provide a limited degree of familiarity with the test facility.

The drivers then completed the driver-controlled occlusion part of the experimental sequence. They drove in continuous fashion through each of the features, with the occlusion system in place. The drivers controlled the occlusion visor while driving on cruise control (set at 72 km/h) through the test sections of the course, pushing the foot switch to obtain glimpses of the roadway. In sections of the course where unrestricted vision was necessary for safety, the researchers cleared the visor. The drivers also rated their workload on command during the initial run through the various features. They drove each test feature at least six times, three in each direction where feasible.

Figure 22. 1991 Ford Taurus Station Wagon Used for Testing.

Drivers then began the researcher-controlled occlusion tests. They attempted to drive through the features with a fixed inter-glance interval. The initial inter-glance interval used for the curves was 4 s (i.e., 4 s elapsed between glimpses of the roadway); for the 150-m tangent, the initial interval used was 7 s. On each succeeding run the inter-glance interval was decreased by 0.5 s. In two cases, drivers were able to traverse several curves and the tangents at the initial intervals. For these drivers, the initial interval was increased to 7 and 9 s for the test curves and tangents, respectively, then reduced in 0.5-s increments until the drivers were able to successfully traverse the curves or curve sequences in question.

The inter-glance interval was decreased incrementally until the driver was able to successfully traverse the feature in question. Failure was judged by the vehicle's leaving the lane, the driver braking because of uncertainty or unwillingness to drive the curve, or the vehicle infringing on the lane markings. The mean workload for a feature minus the workload calculated from the inter-glance interval obtained in the researcher-controlled occlusion tests established the tolerance for the feature in question.

Safety Precautions

Because the subjects were driving a full-size automobile at relatively high speeds, the provision of adequate safety precautions was critical for the safety of the drivers and experimenters. Several different mechanisms were provided to ensure the safety of the study participants.

A takeover switch was provided to the driver so that occlusion could be terminated at any time and full visual capacity could be restored. To accomplish this, the horn switch was modified to provide input to the control circuitry for the occlusion visor. If the horn was actuated, the visor cleared and stayed clear until reset by the experimenters. Override switches were also provided to the two experimenters, enabling either of them to terminate occlusion and restore full visual capability to the driver. Because the occlusion device works by applying a voltage across it to clear the visor, a completely independent battery-operated inverter was connected such that if the primary power supply failed, the backup power supply was switched on automatically to clear the visor and terminate the run. The driver could also quickly remove the visor at any time. Although the preferred recovery method was to clear the driver's vision and allow the driver to safely stop the vehicle, the experimenter's assistant was also provided with a trainer brake to facilitate stopping in the event of an emergency.

Instrumentation

The occlusion visor has been described previously. The visor was controlled by a laptop computer with associated analog/digital conversion module. The control program permitted the glance time to be set by the experimenter and the vision requests to be sent by the driver or by the experimenter. The laptop created a data file that recorded the times at which vision requests took place and recorded downrange distances. Distance and velocity were sensed by means of a

Datron electronic (no contact) fifth wheel suspended from the back of the vehicle. Path excursions were denoted by an input by the experimenter to the data file (in the "event" column). The sampling rate was set at 10 s. A backup camcorder recording from behind the rearview mirror was available for confirmation of the data or an excursion if necessary. The videotapes included an imprint of the driver number, run and course number, and the running distance and time. The major data point, in any event, was whether or not a lane excursion occurred.

The heart rate monitor was also connected through the analog to digital conversion module, such that both instantaneous rate and R-R interval (the time between successive ventricular contractions, the "R" spike on the electrocardiographic wave form) were recorded. The standard deviation of the R-R interval times, divided by the mean R-R interval, i.e., the coefficient of variation, comprises the HRV measure of mental workload. In addition, further measures developed using fast Fourier spectrum analytic techniques can be used to examine workload.[59]

On-Road Study

The same instrumentation, occlusion equipment, and test vehicle used in the test track study were used in a study conducted on local rural roadways.

Drivers

A sample of 6 volunteer drivers was selected from the 24 TTI employees who participated in the on-road study. These subjects were not selected randomly, but rather were the drivers judged best qualified to drive in potentially hazardous on-road tests, based on their confidence and skill as observed during closed-course maneuvers. The sample set included equal numbers of males and females, and included representation from each of the three age groups used in the test-track study.

Features Tested

Two rural two-lane highways within 30 min driving time from Bryan-College Station were used. Construction plans detailing the alignments of these highways were obtained from the Texas Department of Transportation. Horizontal curves with parameters similar to those created at the Riverside Campus were found and tested, although exact matches to the test-track curves were not found. The facilities varied in cross-section from the test-track, including borrow ditches and other restricting components, and did include vertical curves, although the curves tested did not exhibit sight distance restrictions because of the relatively modest vertical curvature present at the test curves. These elements were wholly lacking at the Riverside Campus test facility.

It was not possible to locate curves in the field that were exact duplicates of those tested at the Riverside Campus test facility; instead, researchers concentrated on locating curves that

"covered" a substantial range of the same individual curve experiment space. Figure 23 provides a comparison of the two experiments, while table 13 shows the radii and deflection angles for the on-road test curves. Figure 24 shows a photograph of a typical roadway used in the testing.

Figure 24. Typical On-Road Test Site.

Table 13. On-Road Test Curves.

Deflection Angle, deg	Radius, m
16.9	249
20.0	175
32.2	146
38.3	349
60.9	291
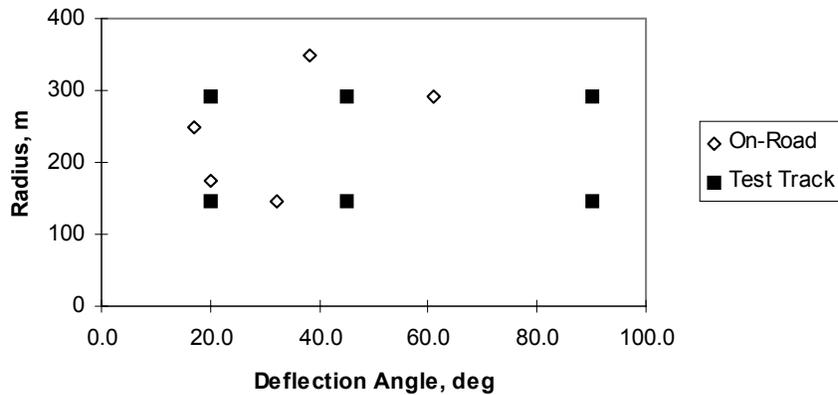
**Figure 23. Comparison of On-Road
Curves to Test Track Single Curves.**

Safety Precautions

Because these runs were on public highways, certain precautions were taken to prevent a mishap with a driver who was periodically "blinded." These precautions included those provided on the test track (i.e., override switches available to the subject, the experimenter, and the assistant; battery backup; and the trainer brake available to the assistant). They also included a safety driver ahead of the instrumented car in cellular telephone contact with the on-board safety person. Any advisory from this car concerning opposing traffic or overtaking traffic, encroaching traffic, or other hazards resulted in aborting the run.

Procedure

An initial run with each driver was made through the course. This run was accomplished without closing the occlusion device and without speed control. The driver then drove with the occlusion device not occluded, back to the starting point. He or she next drove through the features of interest, with cruise control set, and occlusion system working in the driver-controlled mode of operation. No attempt, of course, was made to determine the loss of control threshold.

With the richness of cues in the actual driving environment, only a limited number of passes through the features needed to be done before the driver was familiar with each feature and thus workload levels would flatten out. Four test runs were completed with each driver through each of the on-road test curves.

In addition to the primary workload estimations by the occluded vision method, drivers were also asked to provide a workload rating using the Modified Cooper-Harper Scale as they departed each feature of interest during the first pass only. They were taught the feature rating procedure in their Riverside Campus runs, although the procedure was briefly reviewed prior to the on-road testing.

RESULTS

In this study, several different independent and dependent variables were analyzed in an attempt to provide a better understanding of the effects of roadway geometry on driver workload. Visual demand (VD, defined in equation 7) served as a means of examining driver workload. As evaluated in the study, VD represents a measure of one attribute of workload, input load. This measure examined the amount of visual information that the driver felt was needed to drive various types of curves. Another measure used in the study, the Modified Cooper-Harper Scale, represents a subjective measure of the driver's workload. The final measure used in the study, tolerance, examines the difference between the input load as perceived necessary to the driver and the minimum input load required to successfully perform the task.

Another potential measure, heart rate variability (HRV), was ruled out after an extensive effort indicated that it was unlikely to yield satisfactory results. Researchers examined the applicability of HRV to short-term events (similar to the traversal of highway curves at speed) and found that it was generally not useful for events shorter than 2 or 3 min. The extremely short times spent traversing some of the study curves precluded recording an adequate amount of data to permit analysis.

The results of the study have been separated into three different sections, corresponding to the three major studies:

1. A test track study examining single curves.
2. A test track study examining paired curves.
3. An on-road study examining single curves.

The studies examining individual curves sought to determine the relationship between driver workload and geometric characteristics of roadway curves, while the study examining paired curves sought to examine issues related to workload carryover and expectancy.

Test Track: Single Curves

In this examination of the effects of individual curves, researchers varied the basic geometric parameters of the curves to learn their effects on visual demand. Following the basic questions asked by Krammes et al., radius and deflection angle were systematically varied and the resulting effects were measured.[7] Several different measures were used to determine driver response, including visual demand, a Modified Cooper-Harper Scale, and visual demand tolerance. Six curves were included in the study (covering all possible combinations of radii of 145 and 290 m and deflection angles of 20, 45, and 90 deg—see table 10).

Visual Demand

As discussed previously, visual demand (VD) was measured to examine driver workload. Essentially a measure of the proportion of the time that a driver was looking at the road, VD provided a way to construct a profile of the workload on the driver as the roadway was driven. For clarity, profiles were constructed that consist of the average of the VD values found in 30-m segments of the roadway. The segments were anchored to the beginning of the curve (the point of curvature, PC) for reference. Profiles showing average VD in 30-m segments for each subject and run for the test curves are shown in figure 25, indicating the overall variability. Figure 26 shows the average VD averaged over all the subjects. A systematic trend is apparent, with a peak generally occurring in the first 30-m segment after the beginning of the curves. It is apparent that VD values for curves with a 145-m radius are generally higher when compared with VD values for curves with a 290-m radius.
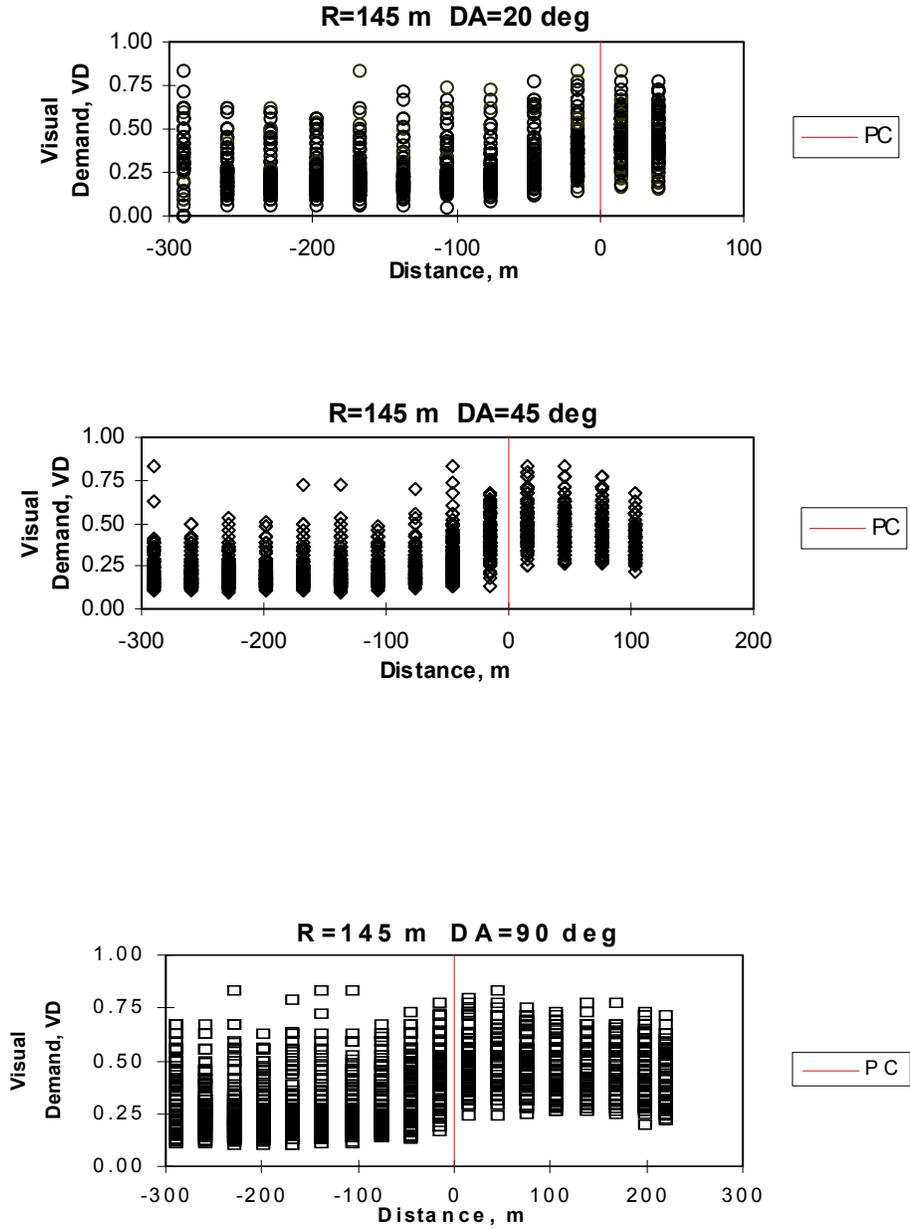
**Figure 25. Visual Demand (Averaged in 30-m Segments):
All Drivers and Runs.**
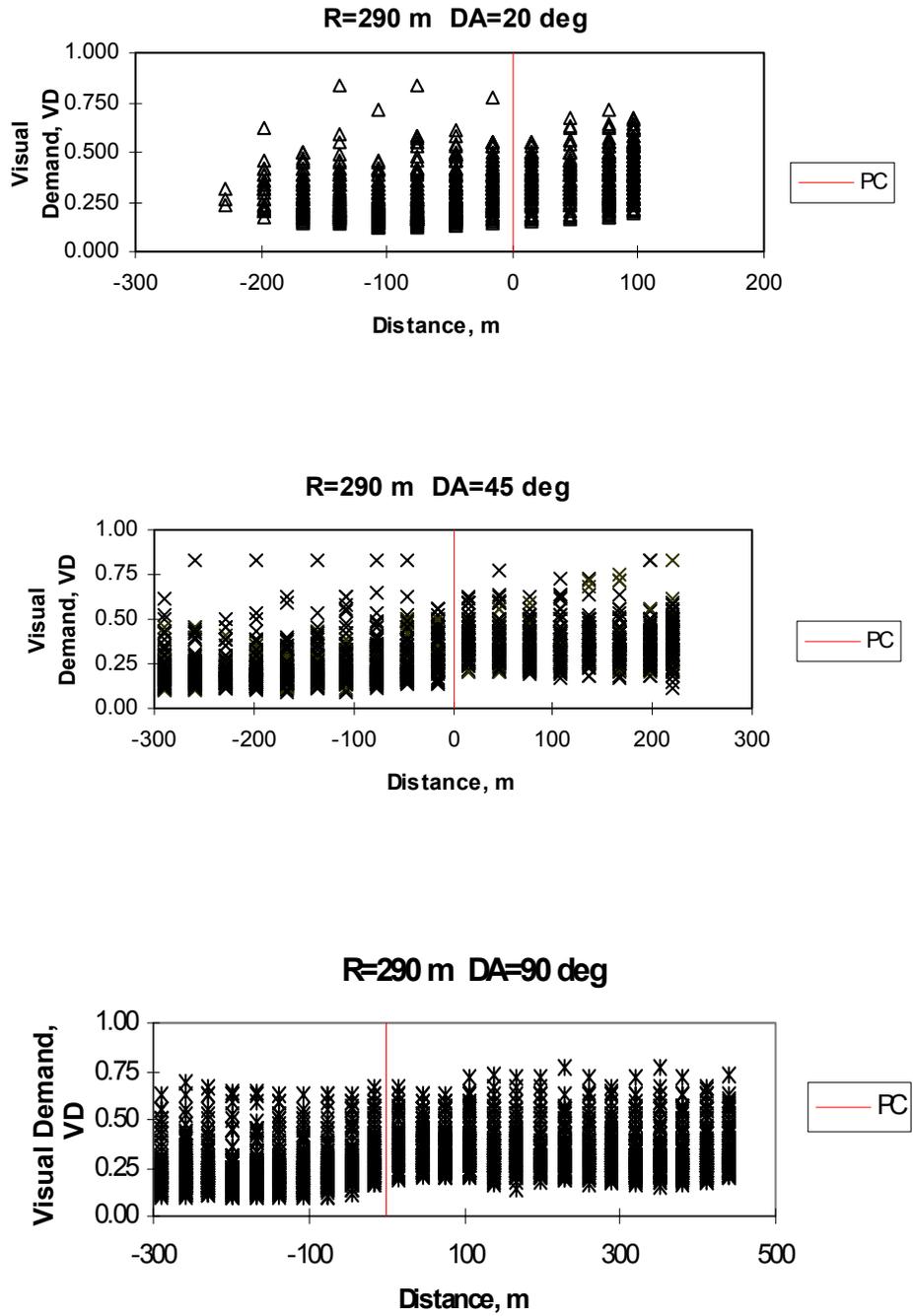
**Figure 25. Visual Demand (Averaged
in 30-m Segments): All Drivers and Runs (continued).**
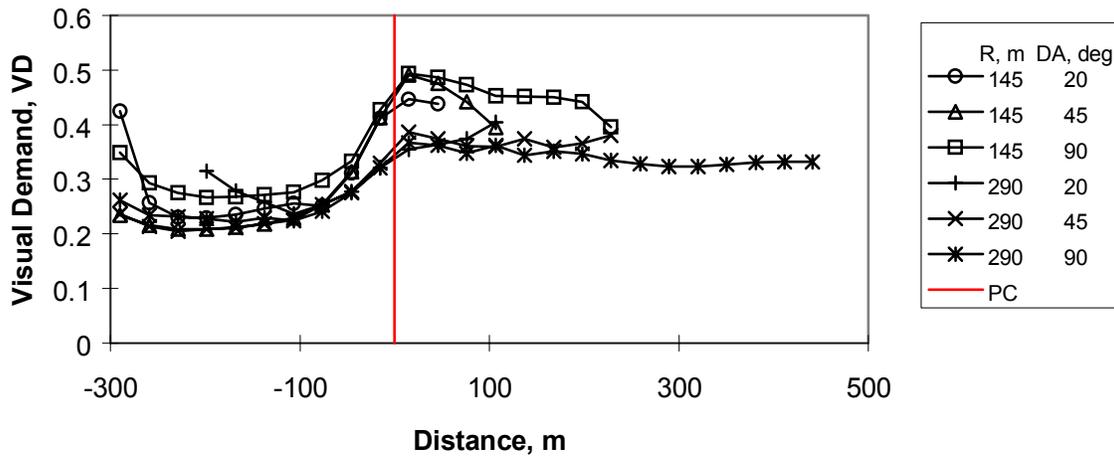
**Figure 26. Visual Demand (Average in 30-m Segments) Averaged Over
All Subjects for Each Single Curve.**

Several different methods of examining the data were explored, including averaging the VD over the length of the curve, averaging the VD over a portion of each curve (i.e., the first half, etc.), and averaging the VD over a fixed length in each curve (i.e., the first 30 m). Each of these methods was considered for analysis; each had its advantages and disadvantages.

Averaging the visual demand over the length of the curve provides a measure of workload that is intuitively appealing and that provides a value representative of the entire curve (called VD_L for the remainder of the report). A problem with this measure, however, is that VD reaches a peak near the PC and then declines to a much lower value for the remainder of the curve. If two curves of unequal length are compared, the lengths of the curves are confounded with the magnitude of the estimate of VD. In other words, the length is directly proportional to the product of the radius and the deflection angle, thus averaging in a larger portion of the curve with a lower VD "tail" for the longer curve. This method does provide an overall impression, however, for how VD varies for different combinations of roadway geometry.

The second method, averaging the VD over the first half of the curve, reduces but does not eliminate the above effect (called $VD_{0.5\,L}$ for the remainder of the report). The length is again confounded with the measurement. The third measure used, averaging the VD over the first 30 m of the curve (called VD_{30} for the remainder of the report), provides a fixed comparison between curves that is not confounded with the measurement used. This measure gives a better understanding of the effect of the roadway geometry in or near the peak VD, although the absolute peak associated with a particular run might or might not be included in the 30 m. When comparing the 30-m segments immediately before and immediately after the point of curvature (PC), or the beginning of the curve, approximately 80 percent of the tests indicated that the peak occurred in the section immediately after the PC with no systematic differences. The first and last methods described (VD averaged over the complete curve, VD_L, and over the first 30 m of the curve, VD_{30}) were used in the analysis, with results discussed below.

The dependent variables considered in this analysis included average VD and VD tolerance. Independent variables considered included the reciprocal of radius (1/R), deflection angle (DA), the interaction between 1/R and DA, and run. The Modified Cooper-Harper (MCH) was analyzed to evaluate how it correlated with average VD_L and VD_{30} values measured on the first test run.

Visual Demand—Analysis of Variance

Of the 24 drivers who participated, 22 drivers tested 6 individual test curves, each 6 times (i.e., 6 runs per driver per curve), 2 tested 5 of the 6 curves, and driver number 35 only tested 1 curve. The analysis was performed without the latter driver. Thus, 23 drivers provided a total of 804 measurements where each measurement represents the visual demand for a given driver in a given curve for a given run.

The effects of the inverse of curve radius, 1/R (1/145 and 1/290 m); deflection angle (20, 45, and 90 deg); and their interaction on visual demand, (1/R)·D, were analyzed using two sets of data: (1) visual demand averaged over the entire curve, VD_L, or (2) visual demand averaged over the first 30 m of the curve, VD_{30}. In addition, two statistical approaches were used: analysis of variance (ANOVA) and regression analysis. In both types of analysis, the 23 drivers were always included as a random blocking factor. This was done to systematically remove the variability between drivers from the experimental error and thus obtain more sensitive significance tests for the factors under study. Next, the potential learning effect from run to run was also addressed, i.e., the correlation within each driver between successive runs was taken into account in the models to estimate the learning effect, if any, over time.

All analyses were performed using a repeated-measures ANOVA with driver as a blocking factor. The PROC MIXED procedure of SAS was used for all models, including the random blocking factor (drivers), the variables (R, DA, (1/R)·DA), and runs (the repeated measure). The distinction between the ANOVA and the regression analyses lies in the fact that the main factors, radius and deflection angle, are treated as categorical variables in the ANOVA and as continuous variables in the regression analyses, all other considerations (drivers and runs) remaining unchanged. In all regression analyses, inverse of radius rather than radius was used in the models.

Figures 27 and 28 show the distribution (in the form of box plots) of visual demand for each of the six curves calculated over the entire curve and the first 30 m of the curve, respectively. The following sections present the ANOVA and regression results for entire curves and the first 30 m of the curves.
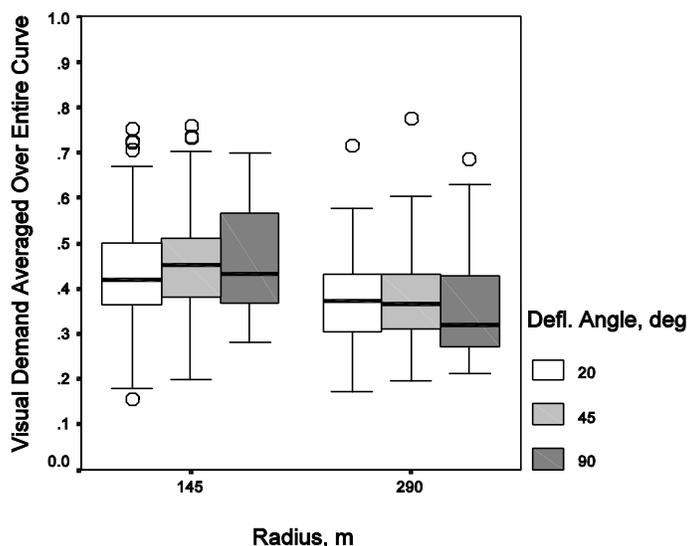
Figure 27. Visual Demand Averaged Over the Entire Curve, VD$_L$.
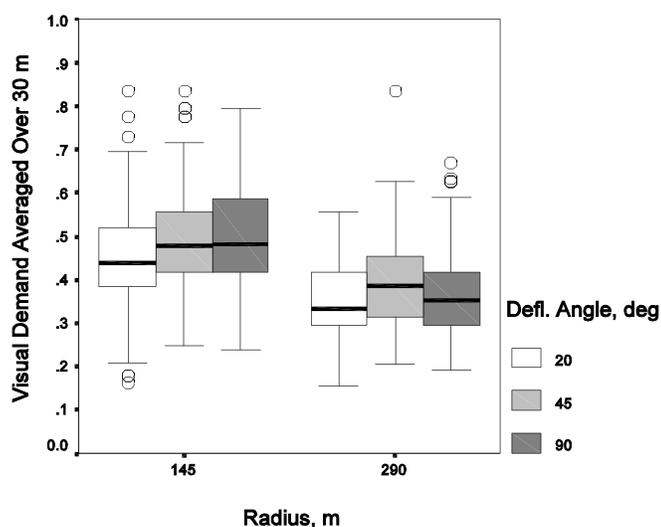
Figure 28. Visual Demand Averaged Over the First 30 m, VD$_{30}$.

Entire Curve. The effect of 1/R, DA, and their interaction on VD$_L$ was examined by ANOVA. The blocking factor (driver) was statistically significant (p=0.0013), indicating

significant differences among the 23 drivers. The run effect was also statistically significant (p=0.016), an indication that the repeated driving of the curves had an effect on VD_L. Overall, VD_L results for run 1 were approximately 6 percent higher than those for runs 2 through 6, while runs 2 through 6 showed no statistically significant difference in VD. Overall, the ANOVA model was statistically significant, with an R^2 of 56 percent. All factors were statistically significant: 1/R (p<0.0001), DA (p=0.046), and (1/R)·DA (p=0.0017).

In light of the run effect and based on the assumption that the first run is more likely to represent a real-life situation, it was decided to rerun the ANOVA using run 1 data only. Based on this reduced data set, the DA (p=0.076) and the interaction (1/R)·DA (p=0.53) were no longer significant. The final model including 1/R only was significant (p<0.0001) with an R^2-value of 71 percent.

Although the researchers generally accepted the premise that the data from the first run more accurately represents real-life situations, an alternative view was that runs 2 through 6 might better represent real-life situations because of increased familiarity with the experimental apparatus. Because of this alternative interpretation, results from runs 2 through 6 are also presented. The following ANOVA results were found based on the data from the last five runs. There is no longer a run effect (p=0.91) on VD_L, i.e., the learning curve after run 1 has stabilized. Furthermore, deflection angle was no longer significant (p=0.103), although the interaction term, (1/R)·DA remained significant (p=0.002). A model with 1/R, but without the interaction (1/R)·DA term, was rerun. The R^2-value dropped slightly from 53.8 percent to 52.6 percent, with a highly significant radius effect (p<0.0001) and driver effect (p=0.0015).

Table 14 provides a summary of basic statistical measures on the curves measured, shown for run 1 only and for runs 2 through 6. The results from the final (within-driver) regression model including only 1/R are shown in table 15 (and illustrated in figure 29) based on run 1 only and, alternatively, runs 2 through 6 only. The predictive power of these models are 71.1 and 52.6 percent, respectively.

Overall, across all runs and considering all drivers, the mean VD_L was 0.449 (standard deviation of 0.113) for curves with a 145-m radius and 0.367 (standard deviation of 0.096) for curves with a 290-m radius, based on all 23 drivers and all runs (402 measurements for each curve).

Table 14. Simple VD$_L$ Statistics for Single Curves.

Type of Tangent/Curve	VD$_L$ Run 1			VD$_L$ Runs 2 through 6		
	Sample Size	Mean	Standard Deviation	Sample Size	Mean	Standard Deviation
Tangent	68	0.242	0.101	340	0.218	0.088
145 m, 20 deg	23	0.431	0.123	115	0.424	0.122
145 m, 45 deg	23	0.455	0.106	115	0.449	0.101
145 m, 90 deg	20	0.461	0.108	106	0.461	0.107
290 m, 20 deg	23	0.367	0.092	115	0.368	0.091
290 m, 45 deg	23	0.377	0.090	115	0.370	0.089
290 m, 90 deg	21	0.354	0.106	105	0.353	0.107

Table 15. Regression Results for VD$_L$.

Run 1 Model:

$$VD_L = \beta_0 + \beta_1 \frac{1}{R} + \varepsilon$$

p=0.0001, R^2=0.711,
sample size=134

Variable	Parameter Estimate	p-value
Intercept	0.297	0.0001
1/R	25.832	0.0001

Runs 2 through 6 Model:

$$VD_L = \beta_0 + \beta_1 \frac{1}{R} + \varepsilon$$

p=0.0001, R^2=0.526,
sample size=670

Variable	Parameter Estimate	p-value
Intercept	0.285	0.0001
1/R	23.133	0.0001
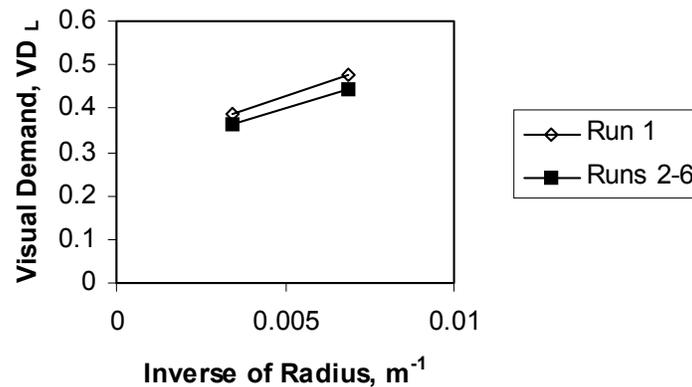
Figure 29. VD$_L$ Regression Models.

First 30 m of the Curve Results. Analyses similar to those performed for the visual demand data averaged over the entire curve were repeated using visual demand calculated only over the first 30 m of the curves (VD$_{30}$). A repeated-measures ANOVA was performed using radius, deflection angle, and their interaction. As before, drivers were included in the ANOVA as a blocking factor to account for the variability among the 23 drivers. The six runs were used as repeated measures to estimate the effect of learning with consecutive driving of the curves. Radius was the single most significant factor affecting visual demand (p<0.0001). The interaction between radius and deflection angle was not significant (p=0.055) and was subsequently dropped from the model. A significant learning effect (p=0.031) was observed, with the run 1 VD$_{30}$ being significantly higher (by approximately 6 percent) than the VD$_{30}$ for runs 2 through 6. The R^2 for this model was 56.5 percent.

Visual demand was generally slightly higher over the first 30 m of a curve than over the entire curve. Overall, the mean VD$_{30}$ is 0.477 (standard deviation of 0.117) for curves with a 145-m radius and 0.369 (standard deviation of 0.099) for curves with a 290-m radius, based on all 23 drivers and all runs (402 measurements for each curve).

The VD$_{30}$ data were also analyzed by means of regression analysis using 1/R, deflection angle, and their interaction, while accounting for driver variability (blocking factor) and learning effect (repeated measures). As previously noted for VD over the entire curve, the learning effect was found to be in run 1 only, while no statistically significant difference was found between runs 2 through 6. Average VD$_{30}$ for run 1 was approximately 5.5 percent higher than that for runs 2 through 6. The regressions are reported separately for data from run 1 and runs 2 through 6. The final regression results are shown in table 16 and figure 30.

Table 16. Regression Results for VD_{30}.

Run 1 Model:

$$VD_{30} = \beta_0 + \beta_1 \frac{1}{R} + \varepsilon$$

p=0.0001, R^2=0.705
sample size=134

Variable	Parameter Estimate	p-Value
Intercept	0.269	0.0001
1/R	34.012	0.0001

Runs 2 through 6 Model:

$$VD_{30} = \beta_0 + \beta_1 \frac{1}{R} + \beta_2 DA + \varepsilon$$

p=0.0001, R^2=0.530
sample size=670

Variable	Parameter Estimate	p-Value
Intercept	0.262	0.0001
1/R	30.672	0.0001
DA	0.000442	0.0001
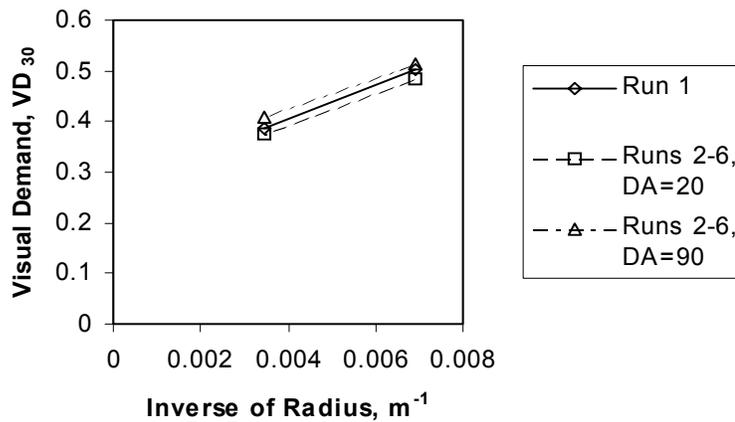
Figure 30. VD_{30} Regression Models.

The two models reported in table 16 differ slightly: deflection angle was not a significant factor (p=0.293) during run 1, but was significant (p<0.0001) during runs 2 through 6. Also, the R^2-value for run 1 is somewhat higher than for runs 2 through 6 (70.5 percent vs. 53.0 percent, due mainly to the larger sample size for runs 2 through 6).

Derivative Measures—Single Curves

The visual demand and related results from the single curve testing were analyzed by ANOVA to assess the effect of curve geometrics (tangents excluded) on visual demand tolerance. A model that included radius, deflection angle, and their interaction was used. The ANOVA results are summarized in table 17. For comparison purposes, simple statistics for visual demand and tolerance were calculated for tangents and are shown in table 18; a box plot is shown in figure 31. Tolerance was significantly related to curve characteristics, with an R^2 of 57.2 percent when accounting for driver variability through the use of a driver blocking factor.

Table 17. ANOVA Results for Tolerance.

Measurement	Sample Size	R^2-value	Radius Significant?	Deflection Angle Significant?	Interaction Significant?
Tolerance	132	0.527	Yes (p=0.0001)	No (p=0.3945)	No (p=0.5317)

Table 18. Descriptive Statistics for Derivative Measures.

Curve radius (m)	Visual Demand (averaged across runs)		Tolerance	
	Mean	Standard Deviation	Mean	Standard Deviation
145	0.447	0.011	0.235	0.098
290	0.370	0.011	0.175	0.093
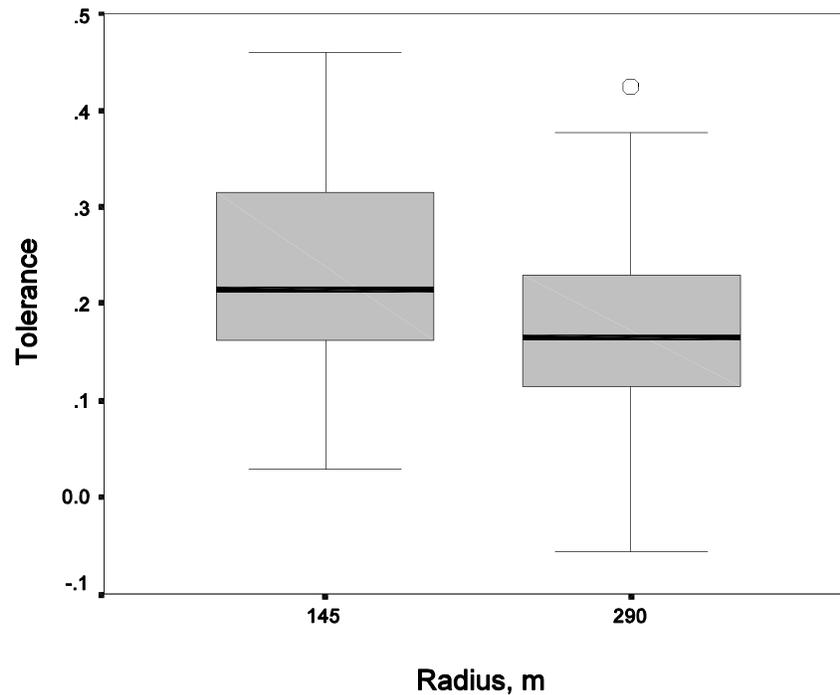
Figure 31. Box Plot of Visual Demand Tolerance.

MCH Rating—Single Curves

Another dependent variable examined was the MCH subjective rating. This rating (shown in table 12) was provided by the driver during the first run for each curve, while wearing the occlusion visor. The measure is very qualitative and findings based on it should be interpreted carefully. Table 19 provides simple statistics for the curves studied, while table 20 provides correlation results when relating MCH to first run measurements of VD_L and VD_{30}. Significant positive correlations between MCH were observed with both VD_L and VD_{30}, although the correlations were low.

Table 19. MCH Rating Statistics.

Type of Curve	Sample Size	MCH Rating	
		Mean	Standard Error
20 deg, 145 m	24	3.71	0.309
20 deg, 290 m	23	3.57	0.316
45 deg, 145 m	22	5.18	0.323
45 deg, 290 m	23	4.09	0.316
90 deg, 145 m	21	5.05	0.331
90 deg, 290 m	21	3.57	0.331
20 deg	47	3.64	0.221
45 deg	45	4.63	0.226
90 deg	42	4.31	0.234
145 m	67	4.65	0.185
290 m	67	3.74	0.185

Table 20. Non-Parametric Correlation Analysis[1] Using MCH.

Measure	Coefficient	p-Value	Sample Size
Run 1 VD_L	0.199	0.020	134
Run 1 VD_{30}	0.246	0.004	134

[1]Spearman's rho.

Test Track: Paired Curves

The 24 drivers tested pairs of curves for which the distance (61 m or 274 m) between otherwise identical curves and the direction of the second curve relative to the first curve (S-curve or broken-back curve) were varied. The curves tested had radii of 145 m and deflection angles of 45 deg.

Paired Curves—Visual Demand

Visual demand was calculated over the entire second curve of each curve pair for six runs per driver. The resulting data were analyzed by means of repeated-measures ANOVA to estimate the effect of direction and type of curve on visual demand. To account for driver variability, a blocking factor was included in the models as was done previously. Data from driver 35 were excluded because that driver tested only one type of curve pair. Thus, a total of 524 observations were available.

The effect of direction of curve, separation of curves, and their interaction on visual demand was estimated as well as that of the six repeated runs. The run effect was significant (p=0.0321), with run 1 resulting in a slightly higher VD_L (by approximately 5 percent) than runs 4 through 6; no significant difference was found between runs 1, 2, and 3 and between runs 2 through 6, respectively. Thus, although there was not as clear a learning pattern over time as that found previously, the results were analyzed separately for run 1 and runs 2 through 6 as was done in the analysis of VD_L for single curves.

The run 1 ANOVA showed the following: neither direction of curve (p=0.298) nor separation of curves (p=0.828) had a significant effect on VD_L. However, their interaction was significant (p=0.049), showing that S-curves (least-squares mean VD_L=0.492) resulted in significantly higher VD_L (by approximately 8.8 percent) than broken-back curves (least-squares mean VD_L=0.452), each with a 61-m separation. No other comparisons were statistically significant. The model's R^2-value was 75.3 percent.

Only curve separation had a significant effect (p=0.002) on VD_L when analyzing the results of runs 2 through 6. However, the relative increase in VD_L from 61-m separation (least-squares mean VD_L=0.440) to the 274-m separation (least-squares mean VD_L=0.459) was only 4.3 percent. The model's R^2-value was 64.4 percent. Simple means and standard deviations are shown for visual demand for each type of curve pair in table 21.

Paired Curves—MCH

Subjective ratings (MCH) were obtained for the second curve of each curve pair on the first run using the occlusion visor. The scale, described previously, ranged from 1 to 10, with 1 being "easy" and 10 being "impossible." Analyzing the relationship between the observed MCH and visual demand values, the Spearman correlation coefficient (non-parametric) did not show any significant relationships with average visual demand (p=0.6020) or tolerance (p=0.3717).

Table 21. Simple Paired Curve Statistics.

Direction/Separation	Visual demand, VD$_L$				
	Sample size	Mean	Standard deviation	Minimum	Maximum
Broken back S-curve	262 262	0.446 0.456	0.104 0.101	0.164 0.271	0.780 0.763
61 m 274 m	262 262	0.443 0.458	0.103 0.102	0.164 0.271	0.780 0.774
Broken back, 61 m Broken back, 274 m	137 125	0.436 0.457	0.109 0.099	0.164 0.275	0.780 0.774
S-curve, 61 m S-curve, 274 m	125 137	0.452 0.460	0.097 0.105	0.278 0.271	0.701 0.763

On-Road: Single Curves

Six subjects selected from among the 24 who took part in the test track experiment also participated in testing curves on 2 local rural roadways. Analyses were performed using VD$_L$ and MCH results.

On-Road Visual Demand

A regression analysis using 1/R, DA, and their interaction was performed within a repeated-measures approach, including a blocking factor for driver on the five test curves. Run was found to be a significant factor ($p \leq 0.0001$). As before, run 1 VD$_L$ was significantly higher than the runs 2 through 4 VD$_L$ by approximately 10 percent. The regressions were run separately for run 1 and runs 2 through 4. In the final models, neither the interaction between radius and deflection angle nor the deflection angle was significant. In addition, the variability among drivers was not significant (p=0.76) when compared with the overall error. Thus, the blocking factor (driver) was excluded from the model for run 1. The only significant factor for run 1 and runs 2 through 4 was 1/R. The regression results are shown in table 22.

Table 22. Regression Analysis of On-Road Data Using VD_L.

Run 1 Model:	$VD_L = \beta_0 + \beta_1 \dfrac{1}{R} + \varepsilon$	
p=0.0001, R^2=0.715 sample size=30		
Variable	**Parameter Estimate**	**p-Value**
Intercept	0.173	0.0001
1/R	43.0134	0.0001
Runs 2 through 4 Model:	$VD_L = \beta_0 + \beta_1 \dfrac{1}{R} + \varepsilon$	
p=0.0001, R^2=0.634 sample size=90		
Variable	**Parameter Estimate**	**p-Value**
Intercept	0.198	0.0001
1/R	29.160	0.0001

On-Road MCH

Drivers provided subjective ratings of the difficulty of driving each of the on-road test curves. The ratings, provided during the drivers' first passes through the curves while wearing the occlusion visor, correspond to the same 1 through 10 scale used previously. A correlation analysis was performed, relating the MCH ratings to the average visual demand values measured on the first test run. The calculated p-value of 0.034 for Spearman's rho correlation coefficient (non-parametric) indicates that a statistically significant relationship was observed between MCH and VD_L. The correlation coefficient was 0.387.

SUMMARY OF FINDINGS

A wide variety of analytical and measurement techniques were used in this examination of driver workload. The findings are discussed below.

Single Curves

A number of dependent variables were investigated in the course of the research project. Findings related to each are summarized in turn.

Visual Demand and Derivatives

Visual demand was found to be significantly related to either radius or the reciprocal of the radius. Although models were found that showed significant relationships between VD_L and deflection angle and the interaction between radius and deflection, these contributions were generally quite low and provided little practical change in the predictive model over a model based solely on radius.

The models developed had relatively high R^2-values, indicating that the models explained much of the variation observed. These R^2-values were calculated after the variation among drivers was accounted for by the model. It was found that visual demand was significantly higher on curves with sharper radii.

Models were developed that successfully predicted tolerance for curves, with relatively high R^2-values. The development of a method for predicting tolerance could lead to the development of recommendations for limiting acceptable changes in workload between adjacent features.

An on-road testing program provided researchers with the opportunity to confirm whether the relationships discerned in the test track environment could be observed in the real world of actual highways. Similar to the test track results, the only significant relationship between visual demand and curve geometry was based on radius. Further comparisons may be found in chapter 7.

Modified Cooper-Harper Rating

A subjective rating scale was developed from the well-known Cooper-Harper Scale and was tested. The scale was found to be significantly correlated with visual demand, although the observed correlations were relatively low.

Paired Curves

The examination of paired curves showed that neither type of curve pair nor curve pair separation greatly influenced VD_L. Somewhat contradictory results were found, indicating different responses depending on the run. Run 1 results indicated that closely spaced S-curves had a significantly higher workload than closely spaced broken-back curves. Runs 2 through 6 results indicated that widely spaced curves had a higher VD_L than closely spaced curves. Both of these findings were unexpected. It was anticipated that S-curves would be more consistent with driver expectations (and would be associated with a lower workload) and that more closely spaced curves would impose a greater workload. The VD_L changes observed were relatively small, however, and further research should be conducted to confirm or extend these results.

On-Road Single Curves

On-road testing using visual occlusion was successfully completed in the study. A model relating the inverse of radius to VD_L was developed, with resulting R^2-values ranging from 63 to 72 percent, indicating that much of the VD_L variability was explained by the model. A statistically significant correlation (0.387) was found between MCH and visual demand.

6. DRIVER WORKLOAD / EYE FIXATION—SIMULATION

As noted in chapters 2 and 5, there is a significant linkage between crashes, roadway-based geometric inconsistency, and driver workload.[66,14,32] Numerous methods have been developed to assess operator workload in general[67,68] and driver workload in particular.[69,71] As noted in chapter 5, workload measurement techniques fit into several broad categories: (1) primary task measurement (measures of steering performance such as lane variance), (2) secondary task measurement (where an additional task is provided such as reaction time), (3) physiological measures (e.g., heart rate variability), (4) subjective techniques (ratings), and (5) vision occlusion (described in chapters 2 and 5). Historically, the correlation between workload measures and either driving performance or crashes has been good, but not extraordinary, except for measures of occlusion, on which the literature is sparse.

Part of the problem may be the choice of measure. It is apparent that driving is primarily a visual task.[72] Although the absolute amount of visual information may not be quantifiable, it is obvious one can drive effectively with only vision cues, and one cannot drive more than a few seconds without them. Hence, this logic suggests that vision occlusion measures (e.g., visual demand, the percentage of time looking at the road) should be highly correlated with workload.

The limited use of occlusion measures is most likely due to the risk of asking drivers to close their eyes (or having some equivalent limitation imposed) while they drive. Noteworthy contributions to the literature on visual occlusion and driving include:

- Sender et al.'s development of the method and identification of the tradeoff between speed and acceptable occlusion duration[73]
- Safford's examination of the effects of carboxyhemoglobin and other related work at Ohio State in Rockwell's group[74,75]
- Farber and Gallagher's work on simulated nighttime driving[76]
- Hicks and Wierwille examination of alternative workload measures[70]
- Godthelp's extensive studies linking occlusion, time-to-line crossing, and vehicle dynamics[77-80]
- The work at TTI by Krammes and Shafer on occlusion profiles[7, 62,81]
- Research by Mourant and Ge in a virtual reality-based driving simulator[82]

Only Senders, Godthelp, Shafer, Mourant explicitly examined driving on curves, though Senders and Mourant did not present explicit results concerning the effects of curve radius or length. Godthelp's work is similar, although it concerned a single occlusion period at the beginning of the curve rather than intermittent occlusion as the curve was driven. Particularly intriguing is Godthelp's finding that the relationship between occlusion time (Tocc) and Time-to-Line Crossing at the end of an occlusion interval (TLCe) is fixed:

$$[Tocc / (Tocc + TLCe)] = 0.38 \qquad\qquad (9)$$

Validation that this relation holds for other than driving on straight sections is desired.

As a refresher, the driving simulator experiment conducted at the University of Michigan Transportation Research Institute (UMTRI) was developed to address several issues related to the replicability and generality of the TTI research.

One indication of the level of replicability comes from the prior TTI work, where the same two curves were examined in two different TTI studies with different subject samples. The differences in the visual demand (workload) estimates were 7 and 8 percent, reportedly due to difference in the age distributions of the two samples.[81] (The first study had proportionally more older drivers.) Confirming visual demand estimates based on the means for each age group were not provided. An alternative, but unlikely explanation is that the two samples of drivers had different quality of driving criteria (i.e., lane maintenance), with higher quality leading to a greater visual demand. Since lane variance data were not collected, this hypothesis cannot be tested.

Funding for scientific research is never lavish. The current push to do things faster and cheaper, but with improvements in quality, has had an impact on the research community as well. In driving research, the key development has been low-cost driving simulators, of which the UMTRI driving simulator is an example. Simulator-based research has the promise of being less costly than on-the-road experiments in some situations. Furthermore, simulator studies may not be constrained by the local availability of certain road geometries needing to be tested, a key factor in this program. Simulator studies are not impacted by the uncertainties of the weather (rain in Texas, snow in Michigan) and provide for test conditions that can be precisely replicated, something that cannot be done on the road (as was the case in chapter 5). Hence, a demonstration that a simulator study of occlusion provides data consistent with driving a real vehicle was desired, ideally, both on test tracks and on public roads.

Finally, although occlusion studies have considered when drivers need to look, where drivers look when vision is occluded has not been addressed. Accordingly, several questions were examined. The questions pertain to validation and eye fixation analysis.

Question 1. In a driving simulator, how does the visual demand for curves vary as a function of curve radius and length?

Question 2. In a driving simulator, how does the visual demand vary as a function of driver age and gender?

Question 3.   Can some of the previous occlusion data collected by TTI be replicated by UMTRI using a similar test course but different subjects and a different vehicle?

Question 4.   Do the occlusion data obtained in a driving simulator agree with data collected on a test course or on the road?

Question 5.   When driver vision is limited (by occlusion) during driving, where do drivers look when they can see?

During the planning of this project, UMTRI was unable to find a suitable local test track or similar facility that contained ample space to replicate the courses described in Krammes et al. and elsewhere.[7,62,81] While there were locations available (e.g., Pontiac Silverdome parking lot, Chrysler Chelsea proving grounds), the costs of using those facilities were beyond the project budget. Although the full set of tests originally envisioned were not conducted, useful pilot data was collected at the Michigan State Police Precision Driving Facility in Lansing, Michigan. These data provided key insights into the nature of the simulator experiment. Even without this information, a reasonably comprehensive test of the replicability of the previous work was completed.

TEST PLAN

Test Materials and Equipment

Driving Simulator

To provide the desired context, this experiment was conducted using the UMTRI Driver Interface Research Simulator, a low-cost driving simulator based on a network of Macintosh computers.[83,84,85] Version 6.7.0a (February 1997) was used. See the UMTRI driver interface web site for information on the latest version of the simulator.[86]

The simulator (figure 32) consists of an A-to-B pillar mockup of a car, a projection screen, a torque motor connected to the steering wheel to provide realistic, damped torque feedback, a sound system (to provide engine, drive train, tire, and wind noise), a computer system to project images of an instrument panel, and other hardware. The projection screen, offering a 30-deg field of view, was 6.1 m in front of the driver, effectively at optical infinity. Although the simulator is classified as fixed-base design, bass shakers provided limited, random vertical vibration to induce some sensation of motion and reduce the likelihood of simulator sickness. The dynamic model simulated a 1588-kg (3500-lb) car with 57 percent of its weight on the front wheels.

Projector screen

3.7 m

4.6 m

Camera on face

6.1 m

IP projector
(not used)

Torque motor

Bass shaker

Steering
wheel

1985 Chrysler Laser body
with simulated hood

11.0 m

Bass shaker

Eye fixation, occlusion, and
heart rate equipment and
computers

Curtain

Overhead projector and
LCD (for road service)

IP computer
(not used)

Curtain

Main
computer

Sound
computer

Video rack

Audio rack and
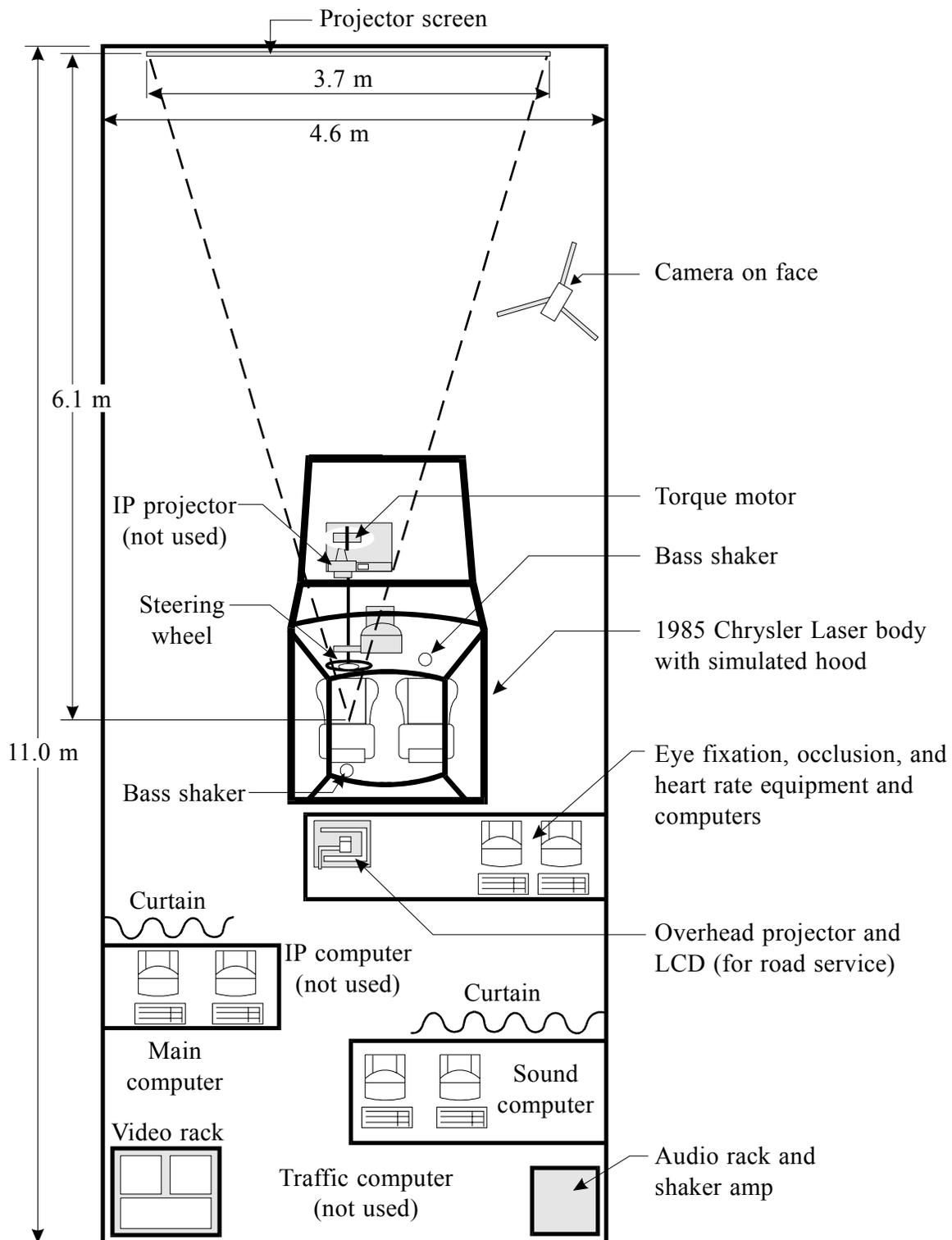shaker amp

Traffic computer
(not used)

Figure 32. Plan View of the Driving Simulator Facility.

Driver facial expressions and head position were recorded by a small hidden camera facing the subject. This recording helped confirm proper operation of the occlusion hardware and the eye fixation recording device. Fixation behavior was recorded using a video system described in the next section. Comments were recorded by miniature microphones, one on the driver's side A-pillar and a second near the inside mirror location. The computer-generated output of the road scene, the subject's face, the subject's left eye, and the head-mounted camera's forward view were recorded using a quad-split image on video tape and displayed on monitors in the video rack. Since the speedometer was not used, that image was not generated so subjects would not glance at the instrument panel. Figure 33 shows a sample of the recorded material.
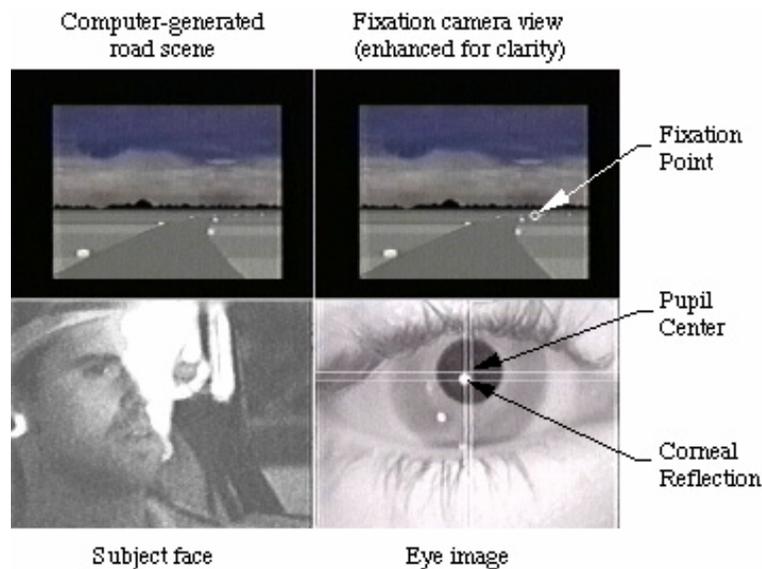
Note: The image of the subject's face suggests a blinding light was illuminating it. In fact, the source was infrared, detectable by a video camera but barely detectable by a human eye.

Figure 33. Typical Recorded Image.

Occlusion Apparatus

To maximize comfort and avoid interference with the eye fixation recording system, an LCD plate from commercial occlusion goggles (Translucent Technologies PLATO S-2 spectacles) was mounted on the lens of the overhead projector presenting the road scene. (For additional information see figure 34, Milgram, and a web page.[87,88]) The plate was activated by a foot switch mounted on the firewall near the resting position of the driver's left foot. Each depression of the switch allowed the road scene to be presented for 0.5 sec. Holding the switch down did not extend the duration the shutter was open, even if it was held down after the 0.5-s period had elapsed, but the shutter did open if a new keypress had occurred after the 0.5-s period had elapsed. The occlusion device was synchronized with the simulator by manually starting the simulator the first time the driver pressed on the foot switch.

Eye Fixation Apparatus

Driver eye fixations were recorded by a prototype version of the Headhunter recording system being developed by ISCAN, Inc. of Burlington, Massachusetts. This corneal reflection-based system consists of a headpiece and two cameras (one capturing an IR source being reflected off of the eyeball and a second showing a head-slaved scene), an IR reflective mirror, computers to process and store the data, and two video monitors. The fixation point appeared as a small circle on the scene. Hardware to record head position was under development for the study and was therefore not available at the time of the experiment. Figure 35 shows the head gear.
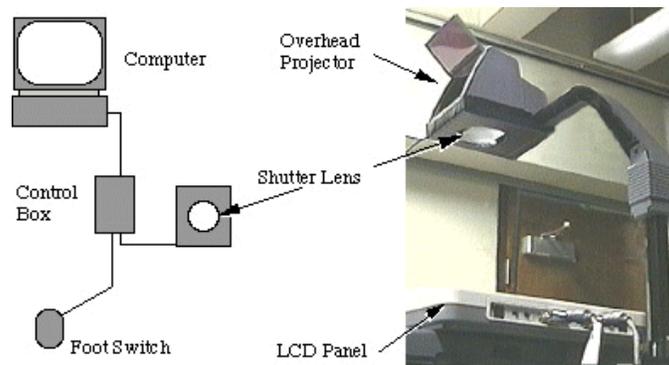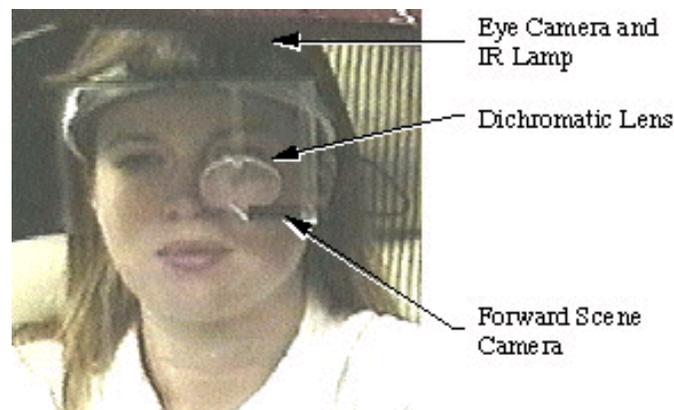

Figure 34. Occlusion Shutter as Installed on the Overhead Projector for the Road Scene.

Note: This picture was taken from slightly above; the lens appears low in respect to the eye.

Figure 35. Eye Fixation Head Gear.

Miscellaneous Equipment

The subject's heart rate was recorded by a Vernier Software heart rate monitor (model HRM-DIN). The ear clip sensor was connected via a serial interface box to a personal computer. Heart rate data were not analyzed and are not presented in this report. In addition, a Titmus model OV-7M Vision Tester was used to check visual acuity of the subjects.

Test Course

This experiment was an attempt to replicate the results of Krammes et al. and to compare the results to some of the current efforts discussed in chapter 5.[7] Both efforts were conducted at the Riverside facility of TTI, which is a former Air Force base (see figures 17 to 9). Two roads were used in the UMTRI replication experiment, a practice road and a test road, both with 3.7 m-wide lanes as in the prior TTI research.

The original plan called for exactly duplicating the TTI course. However, because of space limitations at TTI, a course containing all of the curvature-inflection angle combinations of interest could not be explored in the original study. That was not a constraint of the simulation. Furthermore, to create a physically achievable course, the TTI course required the addition of several sections where no data was collected, including a section that required speed adjustments. Omitting these unused sections from the simulation improved the quality of the data collected by reducing boredom, reducing opportunities for motion sickness, and allowing for additional curves of interest within the available time frame, improving the comprehensiveness of the simulator study.

The test course was composed of 12 curves, representing all combinations of 4 degrees of curvature with 3 deflection angles, 10 of which were examined in studies 1 and 2 of Krammes et al.[7] (See table 23 and figures 36 and 37.) Measurements of degree of curvature and degree of inflection are provided here to facilitate comparison with that study.

Table 23. The 12 Curves Implemented in the Course.

		Curve Radius (m) [Degree of Curvature, deg]			
		582 [3]	291 [6]	194 [9]	146 [12]
Degree of	20	D	F	G	A
Inflection	45	H	E	J	M
(deg)	90	B	L	C	K

Table 24 provides complete specifications for the test course. The direction of several curves was switched to prevent prediction by the driver of the curve direction, an enhancement that became apparent as a result of pilot testing on the Michigan State Police Precision Driving Facility.
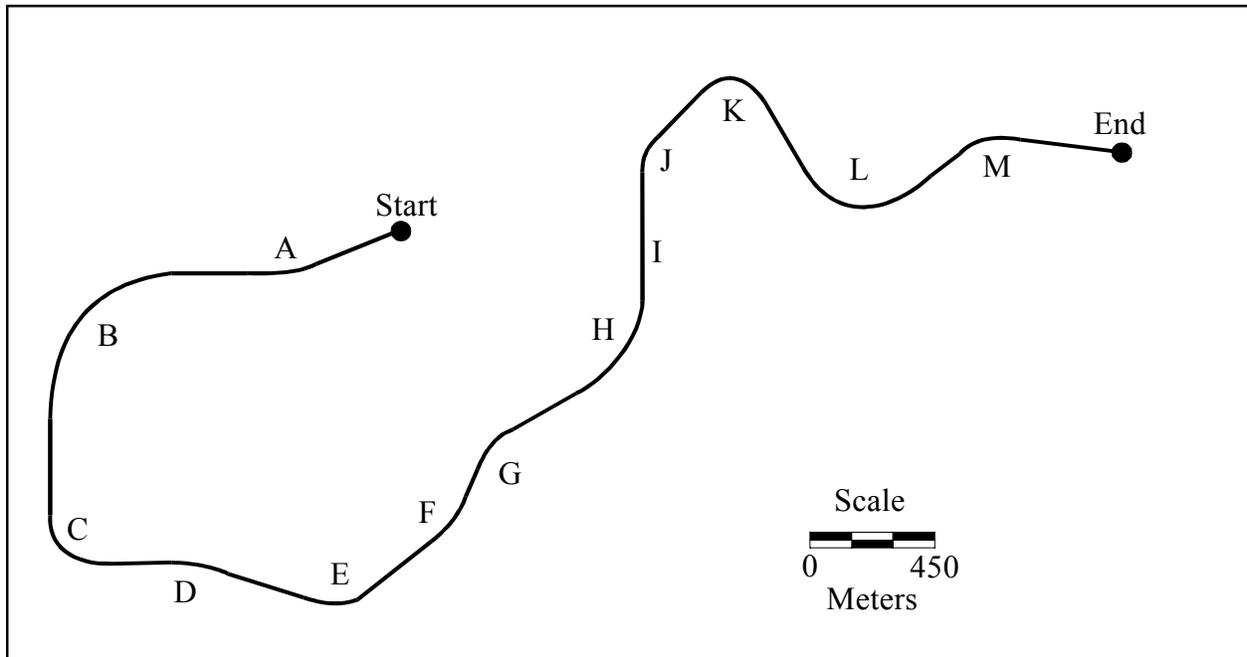
**Figure 36. The Modified Test Course for the Occlusion Simulator Study
(see table 23 for Curve Information).**

Point of
intersection
(PI)

- Deflection Angle:
the external angle between
PC and PT at PI

Point of
curvature
(PC)

Point of
tangency
(PT)

Degree of curvature (DC):
the angle subtended at the
center of the curve by an
arc of 30.5 meters (100 feet)

Radius

Center
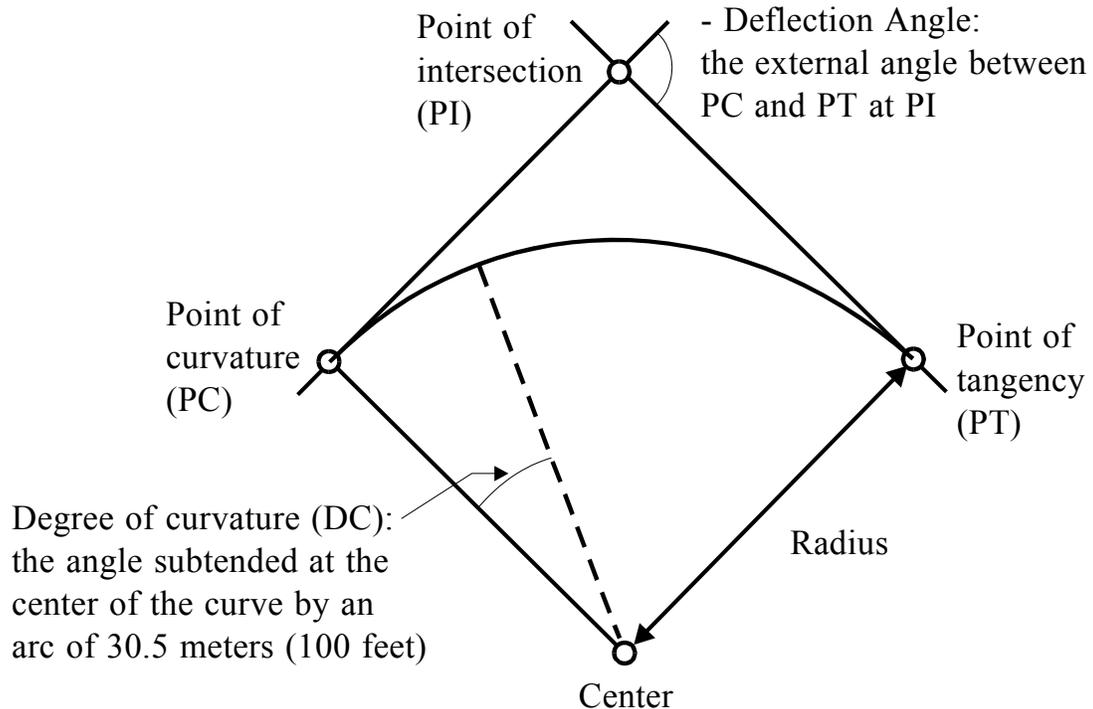
Figure 37. Road Geometry Definitions.

Table 24. Description of the Curves in the Simulator Course.

Road Segment	Curve Direction	Degree of Curve (deg)	Radius (m)	Deflection Angle (deg)	Length (m)	Curve in Previous TTI Research[7]
Start A					457	
A	Right	12	146	20	55	new
A-B					366	
B	Left	3	582	90	914	new
B-C					457	
C	Left	9	194	90	302	study 2
C-D					302	
D	Right	3	582	20	201	study 1, curve 2
D-E					366	
E	Left	6	291	45	229	study 1, curve 4 & study 2
E-F					457	
F	Left	6	291	20	101	study 1, curve 5
F-G					274	
G	Right	9	194	20	64	study 1, curve 6
G-H					274	
H	Left	3	582	45	457	study 1, curve 9
H-I					519	
I		0		0	155	study 2, 152 m tangent
I-J					219	
J	Right	9	194	45	155	study 1, curve 10 & study 2
J-K					366	
K	Right	12	146	90	229	study 2
K-L					366	
L	Left	6	291	90	457	study 2
L-M					366	
M	Right	12	146	45	119	study 2
M-End					457	

Figures 38 and 39 show two simulated road scenes from the subject's perspective. (The actual images were in color.) Notice the simulator background was identical to the Riverside facility, obtained from scanned panoramic images provided by TTI. Graphically, there were minor differences between the TTI test track and the simulation. Both simulated roads had 15-cm (6-in) high posts on alternating sides of the road, simulating the markers used by TTI. Posts on each side were 18.3 m (60 ft) apart, somewhat greater than in TTI tests. To make the path to be driven equally visible to that at TTI (where the road driven and background were the same color), the simulated road was a slightly darker color than the background (a striped pattern in the simulation, a grid at TTI). To avoid a computational overload that would drop the scene update rate below 30 Hz, the sight distance was set to 180 m (600 ft). Note that in straight sections (figure 38), the end point of the road was somewhat more evident than was the case for curves (figure 39). Based on videotapes of the test track and experimenter experience in driving in both contexts, it is believed the difficulty of following the simulated road based on visual cues was equivalent to that of the test track. Software and cost limitations made exact replication of the TTI course in the simulation prohibitive.

In addition to the test course, a practice road was constructed. (See table 25.) A separate practice road was used to provide subjects with an ample opportunity to learn the handling of the simulator and become accustomed to the occlusion device, while reducing the likelihood the test course would be memorized and curves anticipated before they were visible. The practice course contained nine curves, including five from the test course, but not all in the same direction. The practice sequence was constructed so that curve difficulty roughly increased from the beginning to the end of the loop to avoid overwhelming subjects. To emphasize driving curves, straight sections between curves were generally shorter than for the test course.

Test Activities and Their Sequence

Experimental Design

Each subject drove at least two practice runs, one preliminary run, and then six test runs, three times in each direction. To control for order effects, half of the subjects started the series of six test runs at the opposite end of the road. In this experiment, the vehicle behaved as if it were operating with an enhanced cruise control system. In all runs, the vehicle smoothly accelerated to 72 km/h (45 mph) and held that speed without throttle inputs from subjects. Since the information presentation rate of the road was proportional to speed, fixing the speed avoided confounding effects.[73]

The experimental design was based on a repeated measures design with two between-subject factors (1) age (young, middle, old) and (2) gender (male, female) and four within-subject factors (1) radius of curvature (582, 291, 194, and 146 m), (2) deflection angle (20, 45, 90), (3) curve direction (right, left), and (4) run (1, 2, 3). The order of the curves was fixed throughout the runs as was the case in Krammes et al.[7] The direction of curves was randomized throughout the road so that half of the curves were in each direction in each run.

Figure 38. Example Straight Section.

Figure 39. Example Left Curve Section.

Table 25. Practice Road Geometry.

Road Segment	Curve Direction	Degree of Curvature	Radius (m)	Deflection Angle (deg)	Length (m)
Start to 1					805
Curve 1	Right	3	582	10	101
1 to 2					457
Curve 2	Left	3	582	20	201
2 to 3					366
Curve 3	Left	6	291	45	229
3 to 4					302
Curve 4	Right	6	291	60	302
4 to 5					274
Curve 5	Left	9	194	30	101
5 to 6					247
Curve 6	Right	9	194	90	302
6 to 7					183
Curve 7	Right	12	146	75	192
7 to 8					119
Curve 8	Left	12	146	90	229
8 to 9					91
Curve 9	Left	3	582	45	448
9 to Sign					46

Preparation

Upon arrival to UMTRI, subjects read a general overview of the purpose of the study, completed the consent and biographical forms, and had their visual acuity checked. The experimenter then escorted the subject to the simulator bay. After adjusting the seat, a detailed overview of the experiment procedure was provided. The eye fixation device was placed on the subject's head and the ear lobe sensor for the heart rate device was also put into place. The eye fixation device was calibrated and the heart rate device was checked to ensure a good signal was being received.

Practice and Preliminary Sessions

When the subject indicated he or she was ready, the experimenter started the simulator. During the first practice session the subject drove the practice course under cruise control to become familiar with the handling of the simulator. The occlusion device was not used during this run. The subject was instructed to drive the simulator as if it were a normal car. At the end of the course, if the experimenter observed that the subject was comfortable driving the simulator, the first practice session was stopped. If the experimenter felt that another drive around the practice course would be beneficial, the subject continued driving past the stop signs indicating the course end for another loop. The need for additional practice in all instances was determined by the subject's ability to converse with the experimenter while driving curves. If they fell silent, they were considered to be overloaded and additional practice was provided. Additional practice was also provided if subjects said they did not feel comfortable with the simulator. The test loop took just over 4 min to drive.

The purpose of the second practice run was to familiarize the subject to driving with the occlusion apparatus. After a brief stop, the operation of the occlusion device was described. Subjects were told that each discrete press would provide a 0.5-s view of the screen and holding the switch down would not increase the duration. The subject practiced using the button and observing the outcome. Subjects were then told to "request only as many glances as necessary to stay on the path." To begin the second practice run, the subject pressed the foot switch and the experimenter started the simulation. That foot switch closure was used to synchronize those two data collection systems. The second practice run used the same road as practice run 1. If at any time during the run the experimenter believed the subject was not following the instructions of only requesting vision when necessary, the experimenter repeated the key instructions. Practice with the occlusion device was provided until subjects appeared comfortable using the device, typically 2 loops (8 min).

The preliminary run was used to gather subjective ratings of the curves on the test road without the occlusion device. The subjects were shown a sheet that consisted of ratings between 1 (easy curve) and 10 (impossible to drive). This scale is the Modified Cooper-Harper Scale used to evaluate aircraft handling qualities as was described in chapter 5.[89] Subjects verbally indicated the difficulty rating for each curve immediately after it was driven. Verbal reminders were provided by the experimenter when the subject did not respond spontaneously. Practice required approximately 20 min to complete.

Actual Testing

These next six runs were completed on the actual test course representing the matrix of curves described in the experimental design section. Runs alternated between starting at the beginning and the end of the course in an order counterbalanced across subjects. The cruise control was set and the occlusion apparatus was activated for all of these runs. For the first and fifth runs, subjects were instructed to give difficulty ratings after driving each curve.

There was approximately a 2-min break between runs to save the data and specify the road

to be driven. Often, a few additional minutes were required to recalibrate the eye fixation device.
During these breaks, the subject remained in the simulator.

To avoid fatigue, subjects were given a longer (5 to 10 min) mandatory break between the
third and the fourth test runs. The room lights in the simulator bay were turned on (normally off).
Although most subjects remained in the car during this break, a few visited the bathroom at this
point. The actual testing required about 80 min to complete.

The post-test segment took approximately 10 min to complete. After the six test runs,
subjects responded to a survey concerning the adequacy of practice, problems with the eye
tracking equipment and the occlusion device footswitch, comfort with the set speed, the realism of
the simulator, and their comfort with the experiment. Subjects were then paid $30 and thanked
for their participation.

Test Participants

A total of 24 licensed drivers participated as subjects in this experiment. Most of the
subjects were obtained through a local newspaper advertisement. Seven had participated in
previous studies involving the simulator, but none had participated in an occlusion experiment.
Subjects drove a wide range of post-1990 vehicles. Only two drove trucks or vans as their
primary vehicle. There were four subjects in each of six cells (three age groups x two gender
groups) of the experiment. (See table 26.) The age categories were selected to be consistent with
previous TTI work.[7] In previous UMTRI studies, the older category was associated with 65 years
of age and above.

<div align="center">Table 26. Age and Gender of Subjects.</div>

Age Group	Men		Women	
	Number of Subjects	Age mean (standard dev.)	Number of Subjects	Age Mean (standard dev.)
18-24	4	23 (1)	4	21 (2)
35-54	4	43 (7)	4	39 (7)
55+	4	63 (3)	4	63 (4)

The mean annual mileage driven by the subjects was approximately 20,800 km, with a
range of 8,000 to 56,000 km per year. Only one subject had a commercial driver's license.

Because glasses or contacts made sensing the direction of gaze more difficult, subjects
who did not require vision correction were preferred for this experiment. However, in this
sample, about half of the subjects wore contacts and two of the older subjects wore glasses. The
mean corrected visual acuity for subjects was approximately 20/23, with a range of 20/13 to 20/50
(the maximum allowed).

As a group, participants were not aggressive drivers or risk seekers. When asked where
they would drive on a three-lane highway (3=left, 2=center, or 1=right lane), the mean was 1.8,

indicating subjects were somewhat passive drivers. Only five of the subjects had been involved in a crash within the past 5 years.

RESULTS

Visual Demand

The raw data from this experiment consisted of key presses to obtain vision, collected from 24 drivers from 6 runs through the test course. Each key press provided drivers with a 0.5 – view of the road scene. A total of 50,177 key presses were recorded in this experiment.

The individual observations represent visual demand during the time interval between requests for vision. The equation for calculating visual demand (workload) as cited by Shafer et al. (and chapter 5) is:[81]

$$VD_i = \frac{t_{glance\ length}}{t_2 - t_1} \qquad (10)$$

Where: VD_i = visual demand over time interval from t_1 to t_2
t_1 = clock reading at previous information request (s)
t_2 = clock reading at current information request (s)
$t_{glance\ length}$ = time increment during which subject had vision (s), fixed at 0.5 s

When a subject needed more information to guide the vehicle along the path without error, the time between requests was shorter. Thus, shorter intervals indicated a higher visual demand. Some researchers, as well as lay individuals, have loosely referred to what has been measured as workload. In a strict technical sense, workload is the consequence of visual demand.

The development of a method to obtain visual demand profiles was an important result of this project. Preliminary analysis showed slight but not insignificant differences in visual demand estimates between methods. For this experiment, each data file consisted of visual demand values from one road. The file was imported into a Microsoft Excel file (version 5.0) and the starting time was calibrated based on the first key press. Then a template of curve start and end times was added and the data were manually divided into curves based on the template. Each curve had an approach tangent of approximately 200 m and a departure tangent of the same length, based on the physical dimensions of the road (sight distance was 200 m). Using a Visual Basic miniprogram executed from within Excel, curves from all runs of each subject were merged into one file. These files were used for plotting visual demand profiles for representative subjects. An additional miniprogram was then run to sort the data by curves into 13 files. These files were analyzed using several averaging methods as described later in the section concerning visual demand estimates. Data points for each curve were grouped into intervals of 30.5 m (100 ft) relative to the PC. Where no glances were requested in an interval, linear interpolation was used to provide a representative value, preventing a bias toward higher values.

Visual Demand Profiles

As was noted above, the initial step was to develop profiles for each driver for each test run. Figure 40 illustrates the visual demand observations for a representative subject (Subject 22, a 62 year-old woman). The values are for curves with a radius of 582 m, 291 m, 194 m, and 146 m (3, 6, 9, and 12 deg of curvature) respectively, each with a 45-deg deflection angle. The visual demand observations for each of three runs through the curve are plotted versus distance relative to the PC of the curve. Negative values on the distance scale represent locations on the approach tangent upstream of the PC. On the vertical scale, zero corresponds to the scene always being occluded and one corresponds to it always being visible. Only the odd-numbered runs are shown because every other run was in the opposite direction (so left curves become right curves and vice versa). The plots for each curve show a similar pattern of visual demand. The visual demand values are low at the beginning of the approach tangent, increase toward the end of the approach tangent, peak near the PC, decrease throughout the curve, level off by the PT, and remain at the same level through the departure tangent. The variability between different runs was moderate, but this prototypical pattern was maintained throughout the runs for all the subjects.

Figures 41, 42, and 43 show the average profiles for curves of 20-, 45-, and 90-deg deflection angles, respectively. The average visual demand profiles in figure 41 for the 20-deg deflection angle curves have a bell-shaped pattern. The four curves in the figure, representing the different curve radii (degrees of curvature), are almost identical up to 100 m before the PC. At that point they start diverging to reach different peak values very close to the PC. Where visual demand starts to decrease was affected by the length of the curve. Sharper curves are shorter, therefore visual demand starts decreasing at an earlier point. There are two reasons why the curve is bell shaped: (1) visual demand increases gradually until it reaches a maximum and then, when workload is reduced, visual demand gradually decreases, (2) based on the central limit theorem, averaging over a large number of subjects, with various locations of maximum demands, results in a bell-shaped curve around the average of these locations.

The average visual demand profiles in figures 42 and 43 are for 45- and 90-deg deflection angles, respectively. Similar to figure 41, bell-shaped curves are apparent, and the initial divergence point is also near 90 m before the point of curvature. The location of the maximum visual demand is once again located around the PC for most of the curves.

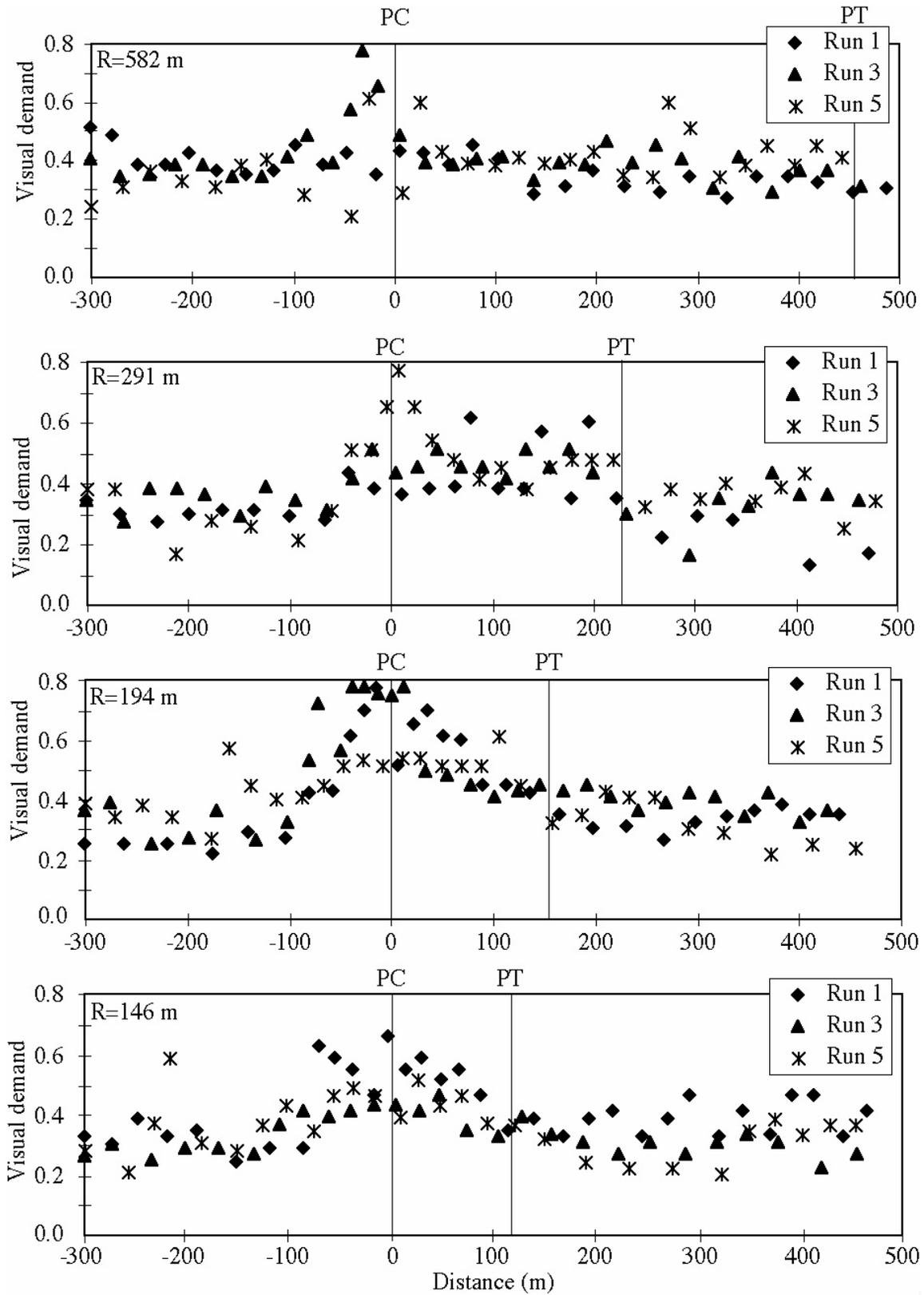**Figure 40. Scatter Plot of Visual Demand Observations for a Representative Subject on Curves With a Deflection Angle of 45 Degrees and Radii of 582, 291, 194, and 146 m.**
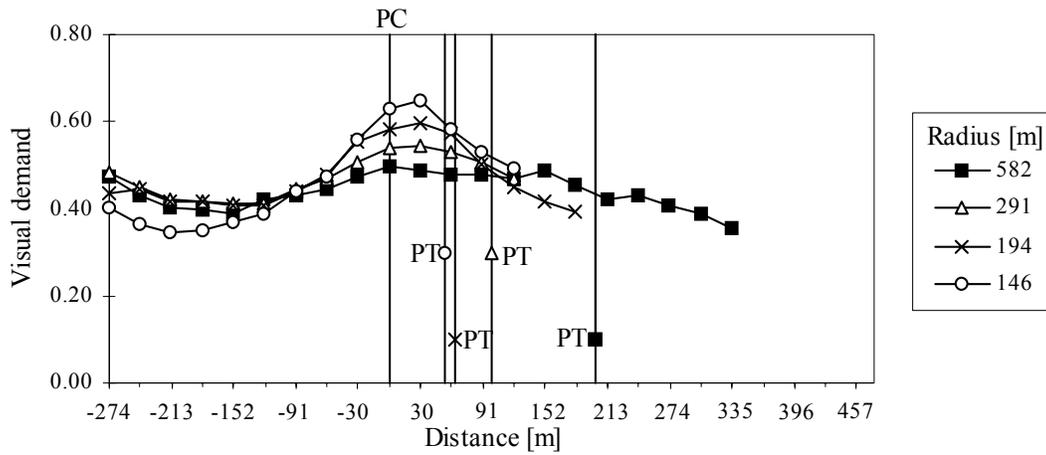
Figure 41. Average Visual Demand Profile for 582-, 291-, 194-, and 146-m Radius Curves With a 20-Degree Deflection Angle.
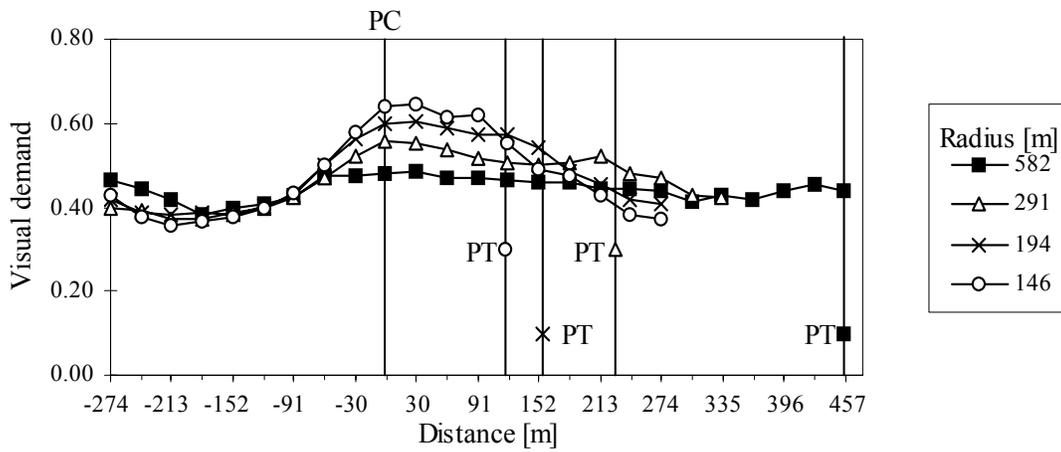

Figure 42. Average Visual Demand Profile for 582-, 291-, 194-, and 146-m Radius Curves With a 45-Degree Deflection Angle.
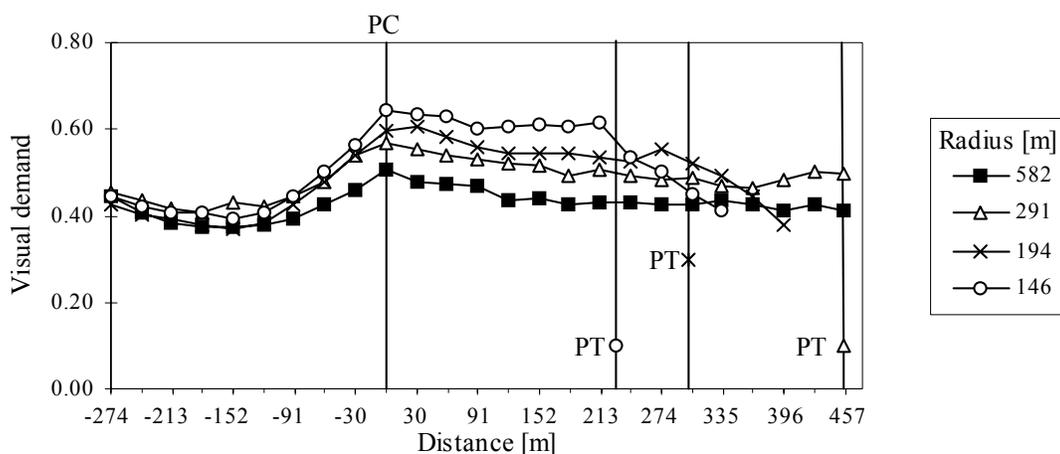
Figure 43. Average Visual Demand Profile for 582-, 291-, 194-, and 146-m Radius Curves With a 90-Degree Deflection Angle.

Average Visual Demand Estimates

Three methods of calculating driver visual demand estimates were utilized. The first method (full-interval method) was to compute the mean value of all visual demand observations between the PC and the PT for each curve (called VD_L in the report). The rationale for this value was that the demand measure should reflect the entire curve. The second method (half-interval method) was to average only the observations between the PC and the midpoint of the curve (called $VD_{0.5L}$ in the report). The reason for only going to the midpoint was that most of the information was in the beginning of the curve. In the second half of the curve, visual demand was not as high, especially in the longer curves. The third method (peak-interval method) was to average only the observations between 50 m before the PC and 100 m after the PC. The argument for this measure was that the values of visual demand were higher around the PC and tended to decrease after a fixed time; therefore, averaging a constant length of the curve around the PC would result in values that were not confounded with the length of the curve, as could be the case with the other two methods. All three methods resulted in valid ANOVAs that highlighted the same factors as significant. The results for the second method are reported here (in table 27 and in the next section) to follow the analysis done in the previous TTI study.[7]

Table 27. Mean Visual Demand Averaged Across Subjects Using the Half-Interval Method, $VD_{0.5}$.

Radius of Curve (m) (Degree of Curvature [deg])	Deflection Angle [deg]		
	20	45	90
582 (3)	0.46 ± 0.13	0.44 ± 0.14	0.42 ± 0.12
291 (6)	0.52 ± 0.13	0.52 ± 0.12	0.51 ± 0.11
194 (9)	0.56 ± 0.13	0.58 ± 0.12	0.56 ± 0.11
146 (12)	0.61 ± 0.14	0.63 ± 0.11	0.61 ± 0.11

Statistical Analysis of Visual Demand

Estimated visual demand observations for all the curves (using the half-interval method) were analyzed using a repeated-measures ANOVA model. Since the differences between subjects were very large, a repeated-measures model, which compares the factors using the baseline of each subject, was the most appropriate model. Factors in the model included two between-subject factors: (1) age (young, middle, older) and (2) gender (male, female). There are four within-subject factors: (1) radius (582, 291, 194, 146 m), (2) deflection angle (20, 45, 90 deg), (3) curve direction (right, left), and (4) run (1, 2, 3). All levels of interaction were included in this model.

For simplification, only statistically significant and near significant effects of the ANOVA are discussed in this section. P-values are provided to assist in interpreting the findings; $p \leq 0.05$ was used to establish statistical significance.

The results of the ANOVA of the $VD_{0.5L}$ data indicate that the effects of curve radius (p=0.0001) and of deflection angle (p=0.0084) were statistically significant. Figure 44 shows the effect of the curve radius on $VD_{0.5L}$ as a function of the driver age group. As expected, the sharper the curve, the higher the visual demand. For this and all subsequent figures, the standard deviations were not plotted on the graphs to avoid clutter and degrading readability. However, for most of the points, the standard deviation was roughly 0.12.

Also, in figure 44, there are consistent differences in $VD_{0.5L}$ due to age group, with each increment in age group being associated with about a 5-percent increase in visual demand (p=0.061), although this is not statistically significant. The interaction between curve radius and age was significant (p=0.0001). The age effect was not as substantial in the curves with the short radii (high degrees of curvature) as in the curves with longer radii (smaller degrees of curvature).

Figure 45 shows the effect of deflection angle on visual demand as a function of age group. Deflection angle and the interaction between deflection angle and age group were both significant (p<0.05); however, no consistent trend can be seen here. Curves with 90-deg deflection angles are longer, therefore drivers can stabilize the vehicle and need fewer glances than at the beginning of the curve.
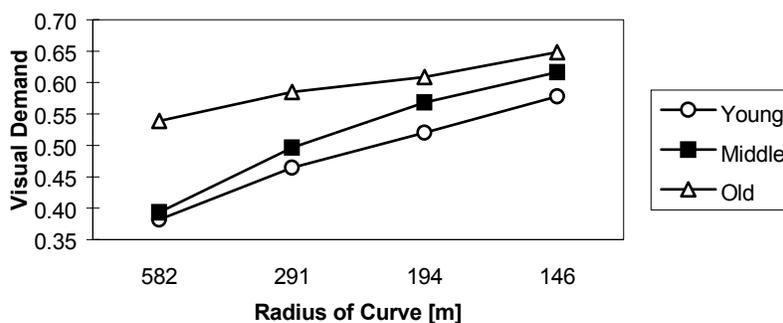
Figure 44. Interaction Between Curvature and Age With Respect to $VD_{0.5L}$.
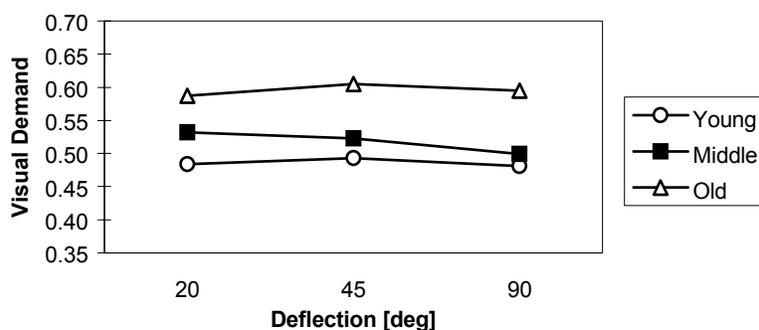

Figure 45. Interaction Between Deflection and Age With Respect to $VD_{0.5L}$.

On the other hand, these curves may be perceived as more demanding and, therefore, curve entry effects are negated. Thus, increasing the length of a curve does not increase the mean $VD_{0.5L}$, though increasing the length of a curve does increase the duration that a driver would be exposed to an elevated workload level.

Figure 46 shows a three-way interaction between the direction of the curve, the gender of the subjects, and their age. Age was significant (p=0.061), gender was not significant (p=0.34), and direction was not significant (p=0.84). The three-way interaction between age, gender, and direction of curve was significant (p=0.041). While not statistically significant, an age-gender interaction can be seen in each of the directions. In general, men had higher levels of visual demand than women. In the young age group, young men required much less visual demand than young women.

The interaction between curve radius and deflection angle is shown in figure 47. At a radius of 582 - m, there was a reduction in visual demand average as a function of the deflection angle. This may be attributed to the length of the curve and the method of calculating the mean across curves. As can be seen in figures 41 through 43, a decrease in visual demand occurred

after the middle of the 20- and 45- deg deflection curves, but before the middle of the 90-deg deflection curve. Since the curve means were calculated using the first half of the curve, the 90-deg deflection angle curve mean included data points after the decrease in visual demand, which resulted in a lower mean. At the other curve radii, this trend of decreasing was not present.
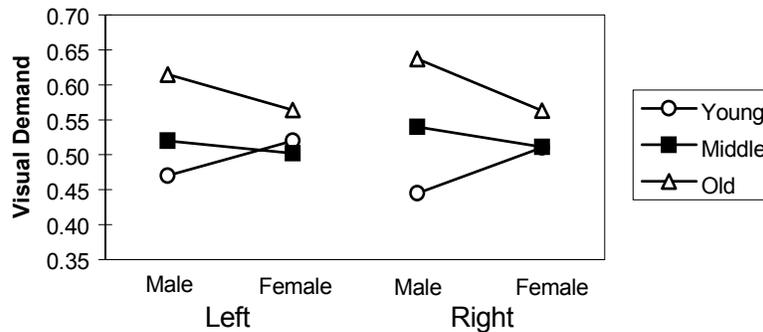

Figure 46. Interaction Between Direction of Curve, Gender, and Age With Respect to $VD_{0.5L}$.
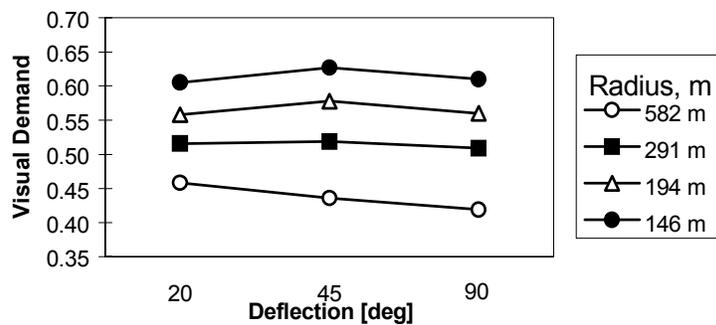

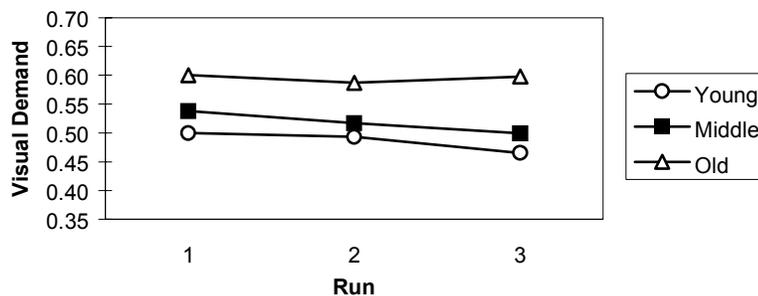**Figure 47. Interaction Between Deflection and Curvature With Respect to $VD_{0.5L}$.**

Figure 49. Interaction Between Run and Age With Respect to $VD_{0.5L}$.

As previously mentioned, the direction of the curve did not prove to be significant on its own (p=0.84). However, there was a significant interaction (p=0.002) between the curve radius and the direction of the curve (see figure 48). $VD_{0.5L}$ for right curves was greater than in left curves with a radius of 194 m (9 - deg of curves), whereas for a radius of 146 - m (12-deg curves), the opposite was true. It may be that the significance of this interaction is merely a statistical aberration.

Figure 49 shows a two-way interaction between run and age. This interaction was not significant (p=0.12). However, the run effect was significant (p=0.002), indicating that some learning still occurred during the runs. The older drivers did not reduce $VD_{0.5L}$ throughout the runs, whereas the middle and younger drivers reduced $VD_{0.5L}$ by about 4 percent. In pilot studies that were performed prior to the experiment, small learning effects were still present after 2 to 3 hours of driving. However, the effect was small in size and consistent in magnitude.

As mentioned before, the full-interval method was an alternative method of averaging visual demand across curves. A complete ANOVA was computed using this measure, but only major findings are reported here. The significant factors in this model were almost exactly similar to those that were significant in the first model. Average values of VD_L were lower by about 0.01. This difference appeared more frequently in long curves (curves with a large deflection angle, curves with a large radius, or both). Another related effect that was slightly different was the effect of deflection angle. In all curves, the higher the deflection angle, the lower the average VD_L. This finding was a consequence of the decrease in visual demand throughout curves. As mentioned before, in the half-interval method, only the curve radius of 582 m was affected by this trend.
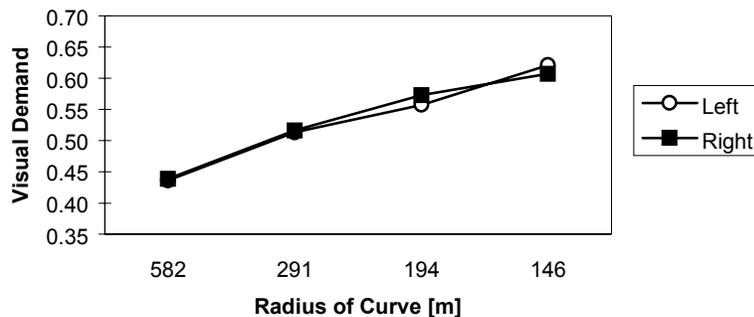

Figure 48. Interaction Between Curvature and Direction of Curve With Respect to $VD_{0.5L}$.

Visual Demand Regression

Regression analyses were performed using a repeated-measures ANOVA with driver as a blocking factor. The PROC MIXED procedure of SAS was used for all models, including the random blocking factor (drivers), the variables (R, DA, age, and interaction terms), and runs, the repeated measure. The inverse of the radius, rather than the radius, was used in the models.

$VD_{0.5L}$ was used as the dependent variable; subject, gender, age, reciprocal of curve radius (curvature), deflection angle, runs, and their interactions were examined for inclusion as independent variables. Run was significant and indicated a learning effect. Early runs (1, 2, and 3) were not significantly different from each other; later runs (4, 5, and 6) were also not significantly different from each other. Significant differences were determined between run 1 and runs 4, 5, and 6; and run 3 and runs 4 and 6. Further analyses were performed on data grouped by runs: runs 1, 2, and 3 were analyzed separately from runs 4, 5, and 6.

Runs 1 Through 3

The inverse of the radius (1/R), deflection angle (DA), age, and their interactions were examined in the analysis. Significant terms included the intercept (p=0.0077), 1/R (p=0.0001), age (p=0.0001), and the interaction between 1/R and age (p=0.0001). The model is:

$$VD_{0.5L} = 0.141 + [55.1 * 1/R] + [0.00558 * Age] - [0.492 * (1/R) * Age] \qquad (11)$$

where *R*, the radius of the curve, was measured in meters and age in years.

The R^2-value of the model was 0.76 when the variability between subjects was accounted for. A simpler model including only the intercept (p=0.0001) and 1/R (p=0.0001) resulted in an R^2 of 74 percent, indicating that little explanatory power was added by including age and the interaction term. That model is:

$$VD_{0.5L} = 0.373 + 34.7 * 1/R \qquad (12)$$

Runs 4 Through 6

Repeating the general approach taken for runs 1 through 3, 1/R, deflection angle, age, and their interactions were examined for their influence on $VD_{0.5L}$. The model tested with the highest R^2 (0.664) included the intercept (p=0.0001), 1/R (p=0.0001), DA (p=0.0053), age (p=0.0001), and the interactions 1/R*age (p=0.0036) and 1/R*DA (p=0.0046):

$$VD_{0.5L} = 0.260 + [40.3 * (1/R)] + [0.004 * Age] - [0.000932 * DA] - \qquad (13)$$
$$[0.367 * (1/R) * Age] + [0.200 * (1/R) * DA]$$

A much simpler model, including only the intercept (p=0.0001) and 1/R (p=0.0001), had an R^2 of 0.65, indicating that most of the variability was explained by 1/R. That model is given by:

$$VD_{0.5L} = 0.394 + 34.8 * 1/R \tag{14}$$

Figure 50 provides a visual comparison of the models developed using 1/R for runs 1 through 3 and runs 4 through 6.

Visual Demand in a Straight Road Section

Visual demand was measured in a straight road section of 150 m (called VD_T in the report). To avoid influence from adjacent curves, this section was both preceded and followed by a 200-m straight section. Since the sight distance was under 200 - m, it was assumed that no visual demand would be carried over from the previous curve to the measured section nor would the straight section be affected by the following curve. As suggested by the means in figures 41
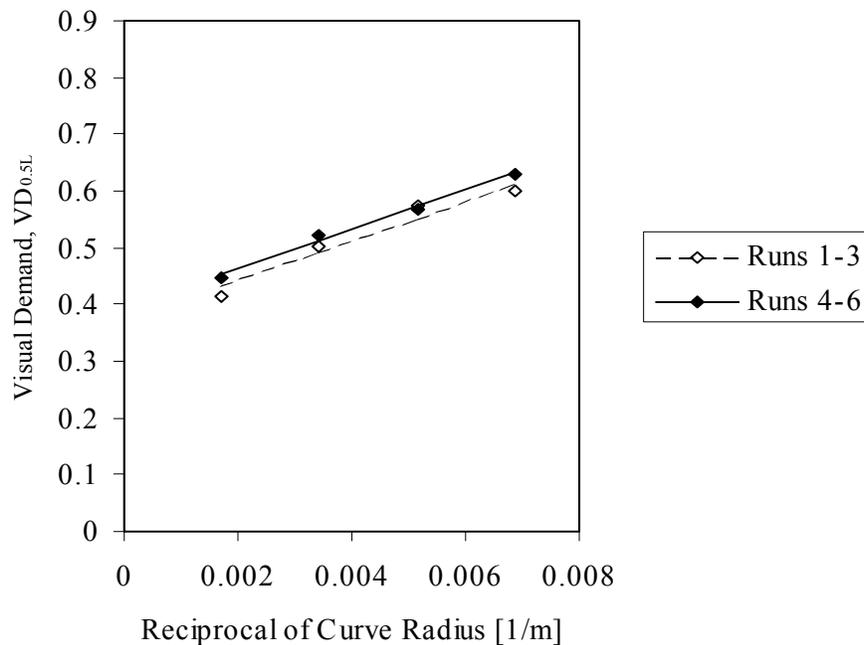
**Figure 50. Regression Model of $VD_{0.5L}$
and the Reciprocal of the Curve Radius.**

through 43, visual demand was at baseline levels this far in advance of the curves.

The visual demand for the straight section averaged across subjects was 0.34±0.12. This value was moderately high in comparison with other vision occlusion studies. Lack of locomotion cues and a limited amount of visual cues accounted for drivers' higher visual demand. In designing the simulator road scene, it was very important that it looked as similar as possible to the test road used by TTI. Therefore, visual cues such as the contrast in colors between the road and the road sides, and between consecutive stripes of the road side were reduced in comparison with the contrasts that are normally used in the UMTRI simulator. It may have partly increased visual demand, but was judged to be necessary for providing an acceptable replication of the TTI study.

The difference between the older drivers and the other drivers was significant (p<0.0001). The basic pattern that was found in curves existed in the straight section as well (see figure 51). Older drivers, particularly older men, had significantly greater visual demand than the two younger age groups.

Maximum Visual Demand

For each curve, a maximum visual demand was determined along with its location. A distribution of the locations of these maximums is shown in figure 52. Most of the maximum values were achieved within 100 m of the PC. The values that correspond to locations are shown in figure 53. The locations and values were scattered because of the large variability between subjects and within curves. However, many of the maximum values occurred near the beginning of the curve regardless of their value.
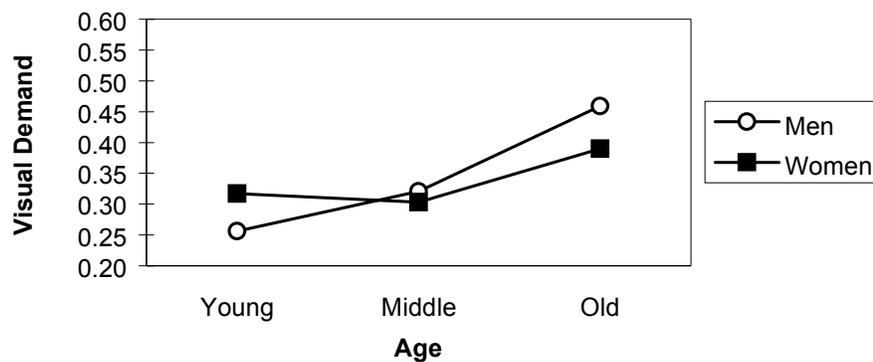
**Figure 51. Visual Demand in a Straight Road Section
as a Function of Age and Gender.**

A close look at figure 53 reveals a discrete behavior at the high end of the value scale. Due to limitations of the occlusion data collection software, precision was only 50 milliseconds. When visual demand values were under 0.50, visual demand precision was not affected at all. At higher visual demand values, the precision went down to 0.02 and at the highest values of 0.85 and above, the precision was only 0.05. This is why there were no observations at a maximum visual demand between 0.83 and 0.91; they were either rounded off to 0.91 or to 0.83.
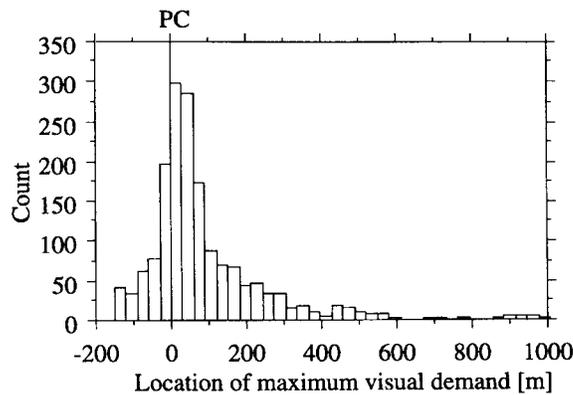
Figure 52. Maximum Visual Demand in Curves - Distribution of Location.

Point of Rise in Visual Demand

An exploratory attempt was made to determine at what point drivers started looking more
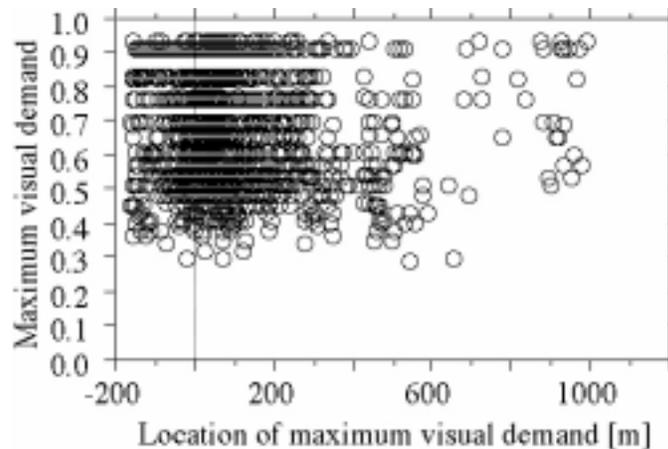
Figure 53. Maximum Visual Demand in Curves - Value Versus Location.

frequently at the road. Data files for each of the curves were analyzed and a point of rise was determined for each run through them. This process was first done by plotting out the visual demand profiles of several drivers and manually determining the point at which it seemed that the graph started to rise. Several computational methods were investigated to try to mimic this manual method. Based on insights from the manual method, rising visual demand earlier than 160 m before the point of curvature was discarded. All rises more than 90 m after the point of curvature were discarded as well. A set of four consecutive observations was examined. A rise in visual demand was determined when the visual demand of the second glance was higher than the visual demand of the first glance and in addition, the value of the fourth glance was yet higher than that of the second glance. By using this method, all linear rises were captured, as well as rises that had a local drop (at the third glance), but continued to rise. Figure 54 shows the distribution of points of rise as a function of the location on the road. Most of the rising points occurred ahead of the point of curvature. The average location of the rising point was 92 m ahead of the point of curvature, with a standard deviation of 47 m. Not much difference was noted in the result when the algorithm was run on the entire curve instead of starting at 160 m before the point of curvature.
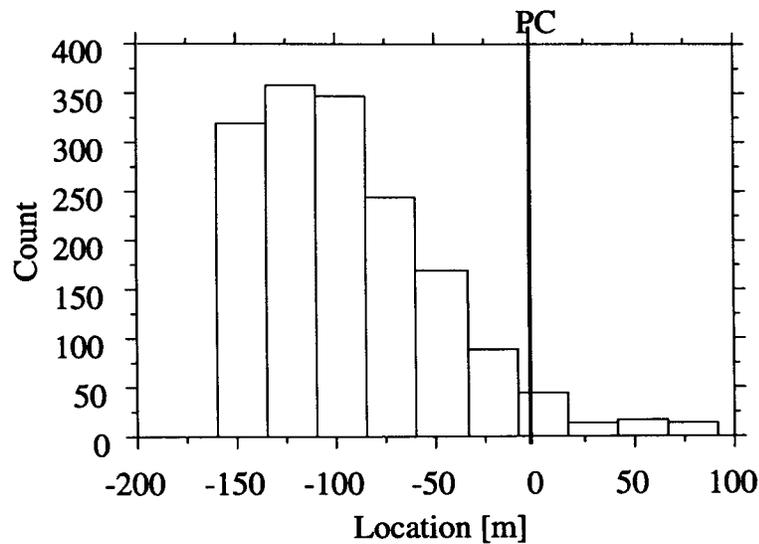
Figure 54. Distribution of Point of Rise in Visual Demand.

A repeated-measures model, similar to the model that was run for visual demand values, was applied to the rise point data. Due to the large variability in the data, only a few factors were found to be significant. Moreover, it is not clear whether their significance can be attributed to a real effect or to the algorithm by which the points were calculated. Some insights are reported in table 28, but should be regarded cautiously.

Table 28. Effects Influencing Point of Rise in Visual Demand.

Effect	Earliest Point of Rise (m)		Latest Point of Rise (m)	
Curve Radius	146 m:	-100 ± 40	582 m:	-88 ± 54
Direction of Curves	right:	-95 ± 50	left:	-90 ± 50
Age * Gender	older women:	-101 ± 48	young men:	-83 ± 45

Eye Fixations

Characteristics of One Subject

Information about eye fixations was recorded on video, in the form of a small circle superimposed on the forward scene image from the camera mounted on the driver's head. Data were reduced by watching the video and noting where the circle was located. The first part of the analysis concerned the exact location of the eye fixations of one driver for the entire road. The data reduction for this part of the study was extremely time-consuming and is therefore reported for only one representative subject.

Figure 55 shows the grid that was used for locating the eye fixations. The locations were collected relative to the road ,with the zones shifting laterally with curvature. Four categories of depth position were considered: (1) above the horizon, (2) at the horizon level, (3) below the horizon, and (4) near the car. Most of the eye fixations were at the horizon level. At this level, five categories of lateral division were used: (1) far left - eyes are fixated more than half a width of lane to the left of the road, (2) left - eyes are fixated on the left edge of the road or beyond it, (3) middle - eyes are fixated on the middle of the road, (4) right - eyes are fixated on the right edge of the road or beyond it; and (5) far right - eyes are fixated more than half a width of lane to the right of the road. The choice of these categories is consistent with the literature and the accuracy of the recording system.

The lateral distribution of eye fixations relative to the road for one representative subject (subject 1, a 39-year-old man) is presented in figure 56. This figure is stylistically consistent with results provided by Bengler et al.[90] To best characterize driver fixation behavior, each 0.5-s interval in which the shutter was open was observed three times, once at the beginning, once in the middle, and once at the end. This was done to capture changes in the direction of gaze that could occur at various times when the shutter was open. In the figure, every three data points corresponds to an interval of 0.5 - s.
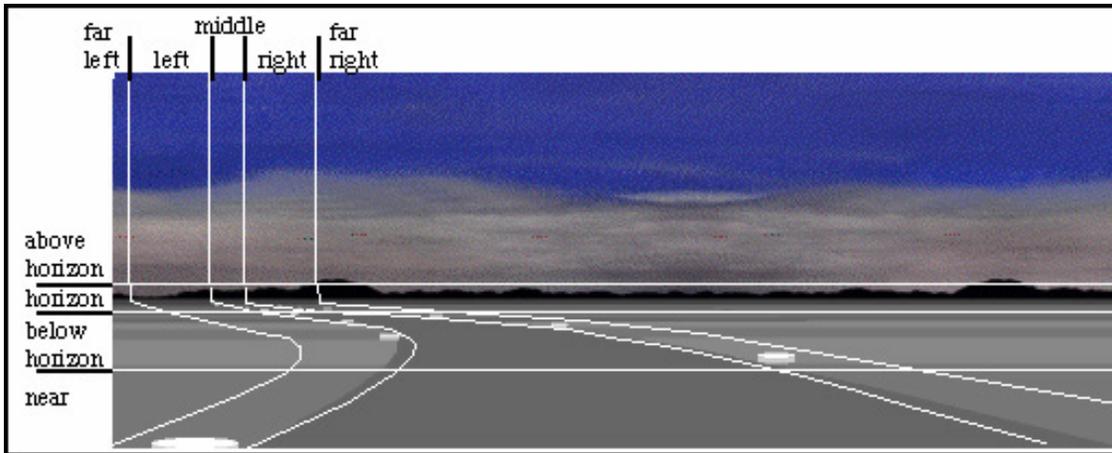
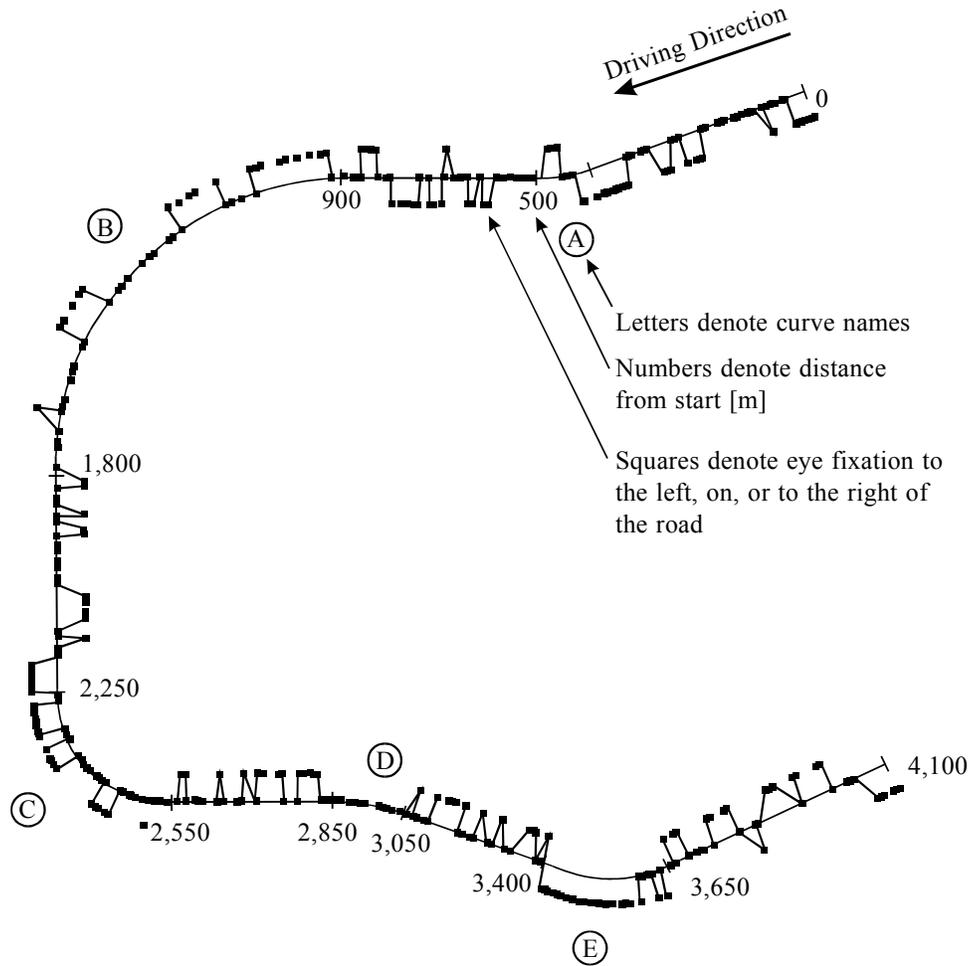**Figure 55. Grid for Eye-Fixation Data Reduction.**

Figure 56. Direction of Lateral Eye Fixation Along a Curved Road.

Summary of Right/Left Glance Behavior Across Subjects

The second part of the eye-fixation analysis examined data from 12 subjects (2 from each age-gender group) to provide a sense of the lateral glance behavior when driving curves. Data collection problems, resource constraints, and the need for an age-gender balanced sample led to the selection of these particular subjects.

In general, drivers tended not to change the position of their gaze very often. Most of the time, they preferred looking at the end of the road near the horizon. In some cases, the drivers seemed as if they were staring in one general direction, trying to capture as much as possible in the scarce amount of time in which their vision was not occluded. When they felt comfortable enough, they turned their eyes away from the road, to either side, looking for anticipated changes in the curvature of the road. When a curve was recognized, drivers usually started to look at the beginning of the curve. Upon entering the curve, the typical eye-fixation pattern became slightly different as a consequence of the presence of the occlusion device. When driving without occlusion, drivers tended to follow one of the edges in backwards sequences, a fast saccade to the next marker, and then slow pursuit of the marker and its near location until it was close to the vehicle. By contrast, when the drivers' vision was occluded, they did not perform full backward sequences. They tended to maintain their head and eye position relatively stable as they passed the curve, basically looking at a point in the mid-range on one of the edges of the road. The high contrast between the road and its edge, and the constant movement of markers on the edge, may have drawn drivers' attention to the sides of the road.

A quantitative analysis of drivers' eye fixations revealed that drivers preferred looking inside the curve when the radius of the curve was large (R=582 m: 0.35±0.4). However, with sharper curves, more drivers preferred looking outside the curve (R=146 m: 0.62±0.4 for left curves and 0.48±0.4 for right curves). The difference between a sharp curve with a radius of 146 m and a curve with a radius of 582 m was significant (Scheffe's post hoc two-way comparison p=0.02). The difference was more prominent in left curves than in right curves (see figure 57). It could be that for broader curves, the inside of the curve (having a smaller radius) showed the curve more prominently, causing drivers to look to the inside of the curve. However, as the radius of the curve decreased (the curve became sharper), the outside provided sufficient path cues. Furthermore, on sharp curves, looking inside would divert the driver's eyes more to the side, requiring more time to move from the direction immediately ahead.

Readers are reminded that this experiment was a simulation of driving a single-lane road at the TTI facility. In the UMTRI study, the driver's head position was both to the left of the centerline of the lane being driven and to the left of the path being followed. This lateral shift may account for the left-curve/right-curve differences for shorter curve radii (larger degrees of curvature). On a real two-lane highway, the driver's head would be on the right-hand half of the path being followed, there would be a centerline to indicate curvature, and both leading and following traffic might be present. Accordingly, these data should be viewed as tantalizing and thought-provoking rather than as definitive. However, these data may provide some cues as to where pavement markings and roadside signs might be placed to better inform drivers as to the nature of the curves being driven and to assist them in speed selection. As part of the evaluation of revised marking strategies based on geometrically driven eye fixations, the vehicle fleet mix
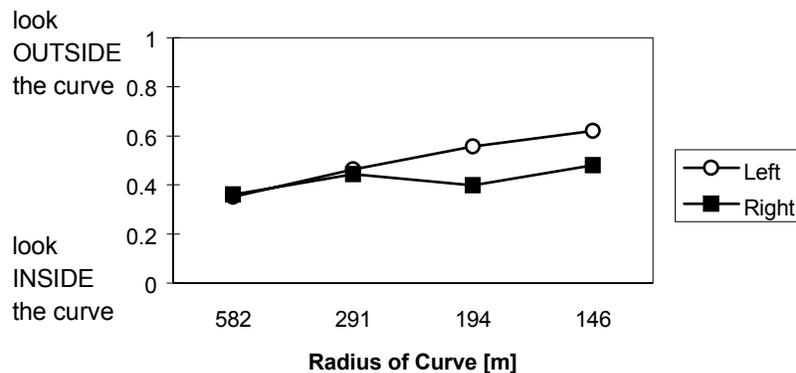
**Figure 57. Where Do Drivers Look as a Function
of Curve Radius?**

(in particular, the impact of light trucks and minivans where drivers sit higher than in passenger cars) needs to be considered.

Subjective Rating

As a reminder, subjective ratings of the difficulty of the curves were collected using the Cooper-Harper Scale as modified for the TTI study (see table 12). Subjects were first asked to rate the test road without using the occlusion device (the preliminary run), and then rate it twice again (runs 1 and 5) with the occlusion device in place.

The ratings were analyzed using ANOVA, employing an identical model for the occlusion data. The values were assumed to be from a continuous scale, though, in fact, they were discrete. Figure 58 shows rating as a function of run, divided into the three age groups. The run main factor was significant (p=0.02). The subjects rated run 1, with the occlusion device activated, as being more difficult than the preliminary run (without it, the significance of the main factor would be p=0.0001). However, run 5 was rated lower than run 1, indicating that subjects became used to the occlusion device. Although the rating of run 5 was not as low as the preliminary run, it was not possible to reject the hypothesis that they were different.

Figure 59 shows the rating as a function of age and gender. Neither the main effects (age: p=0.21, gender: p=0.68) nor the interaction (p=0.54) were significant, though there was a slight trend for difficulty ratings to increase with age. This is mainly due to the large variance between subjects, not only in the way they perceived the difficulty of the curves, but also in the way they anchored their perceptions to the Modified Cooper-Harper Scale. The clear trend of older females to report the curves as being harder, and of older males not to report it as being so seems to be outweighed by this large variance between subjects.

Figure 60 shows the effect of curve radius and deflection on the difficulty rating. Increases of either angle increased the rating in a highly linear manner.
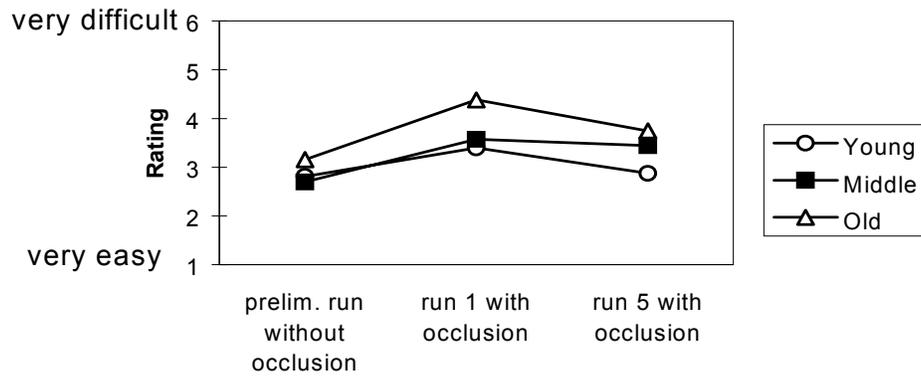
Figure 58. Rating as a Function of Run and Age.
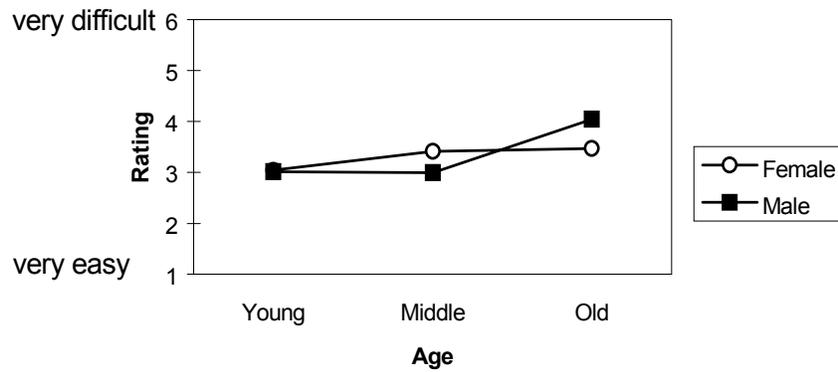
Figure 59. Rating as a Function of Age and Gender.
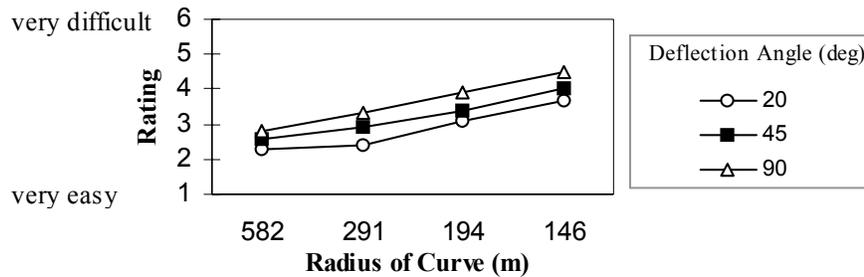
Figure 60. Rating as a Function of Curve Radius and Deflection.

Rating Regression

A stepwise regression analysis of the ratings, with reciprocal of curve radius (curvature), deflection angle, and driver age as the independent variables (p<0.05 for inclusion) was computed. The ratings were assumed to be continuous (not actually true). Due to the large variability between subjects, the regression model does not explain a large portion of the variability ($R^2 = 0.20$). In comparing the impact of various effects, readers should keep in mind that the regression coefficient for the reciprocal of the radius was much greater than that for the deflection angle. The model is:

$$Rating = 1.1 + 303.9 * 1/R + 0.013 * Deflection + 0.017 * Age \tag{15}$$

CONCLUSIONS

Each of the five main questions addressed in this study is answered briefly in the following section.

Question 1.   In a driving simulator, how does the visual demand for curves vary as a function of curve radius and length?

Visual demand for curves proved to be linearly related to curvature. On average, drivers experienced greater visual demand for sharper curves. While the average visual demand for a straight section was 0.34, it was 0.44 in curves of 582-m radius, and 0.61 for curves of 146-m radius. A linear relation was observed when plotting visual demand as a function of degree of curvature. Since the degree of curvature was a linear function of the reciprocal of the curve radius, visual demand was also linearly related to the reciprocal of the curve radius. This trend agrees with the expected behavior of drivers. When a driver approaches a sharp curve, more visual information is required for changing the orientation of the vehicle. In addition, more visual information is required in terms of feedback for controlling the vehicle.

Visual demand did not vary considerably as a function of deflection angle of the curve. The values of average visual demand were 0.53, 0.54, and 0.52 for deflection angles of 20, 45,

and 90 degrees, respectively. When inspecting only the area around the PC, no difference whatsoever was observed. This finding is surprising; one would have expected the visual demand imposed by the preparation for a long curve to be higher than that for a short curve. Examination of the subjective ratings shows that drivers thought that longer curves were harder. They did not use more visual demand, yet they rated those curves as being more difficult to maintain. What happens is that lengthening the curves does not raise the average visual demand, only the period it is experienced.

Question 2. In a driving simulator, how does the visual demand vary as a function of driver age and gender?

Age was only slightly significant (p=0.061); gender and the interaction between gender and age were not significant. Moreover, the number of subjects in each age-gender group was only four. In spite of this, a consistent age trend was observed in all the analyses. Older drivers required higher values of visual demand. This trend was present in all curve radii as well as in straight road sections. In addition, the slight learning effect that was seen within runs did not affect older drivers. In other words, they did not decrease visual demand throughout the runs. The subjective ratings of the curves were higher for older drivers than for younger drivers. At least one older driver served as an exception to this trend, he insisted that all the curves were easy and gave most of them a rating of 1. There was not enough statistical power in this study to significantly highlight the effects of age and gender on visual demand, but the trends seemed to be consistent with other known effects of aging. It is important to note that the older age group consisted of drivers whose ages were between 58 and 68. While only two subjects in this study were older than 65, experience from previous UMTRI studies has shown that age effects would be more pronounced if all of the subjects were older than 65.

Question 3. Can some of the previous occlusion data collected by TTI be replicated by UMTRI using a similar test course but different subjects and a different vehicle?

Occlusion data collected by TTI was successfully replicated by UMTRI in the current study with specific details appearing in a following chapter. In addition to the 10 curves that were run by TTI, 2 more curves were run by UMTRI in order to complete the experimental design. There was no problem in collecting valid data in the simulator in a similar test course with different subjects and a different vehicle. The older age group consisted of slightly older subjects than in TTI's study. The experimenters felt that some of these subjects were having a very hard time adapting to the use of occlusion apparatus.

Question 4.   Do the occlusion data obtained in a driving simulator agree with data collected on a test course or on the road?

The pattern of results between the two sites is similar. A more comprehensive comparison between the results obtained by UMTRI and by TTI appears in a following chapter.

Question 5.   When driver vision is limited (by occlusion) during driving, where do drivers look when they can see?

Driver eye fixations were observed both with and without occlusion. No consistent pattern was found to describe the eye-fixation patterns of all the subjects in all runs. In general, drivers preferred to look at the imaginary focus of expansion in straight sections. In curved sections, there was a tendency to fixate on one of the edges of the road while using backward sequences (saccade forward, and several pursuits backwards). From time to time, drivers looked at random locations for short periods. These locations included scanning for approaching curves to the right or the left of the horizon line, and short glances to various points closer to the car.

When driver vision was limited by occlusion, many of the extraneous glances were not observed. In straight sections, drivers tended to fixate on the imaginary focus of expansion, perhaps relying more extensively on the periphery. In curved sections, drivers fixated on one of the edges of the road and performed discrete forward sequences until the curve ended. Drivers did not follow a continuous pattern because the occlusion device did not allow that. Drivers did not look at additional random positions because they were probably not considered necessary for survival.

Drivers did not show a clear preference for looking at either side of the road. On average, drivers preferred looking inside the curve when the radius of the curve was great. In sharper curves, more drivers preferred looking outside the curve. This preference was more prominent in left curves than in right curves.

7. COMPARISON OF WORKLOAD VALUES

The examination of driver workload has considerable promise in evaluating the design consistency of roadways. In response to this perceived promise, several different driver workload efforts were conducted in this study. Other research studies conducted at TTI have also focused on driver workload. To utilize driver workload as a reliable source of information about a roadway alinement, designers must know whether the information is reliable and consistent. A basic tenet of the scientific method is that research must be reproducible. In the interests of evaluating the reproducibility of those aspects of driver workload studied in this research project, comparisons were made between similar aspects of the workload efforts conducted at TTI on a test track and on local highways, at UMTRI in a simulator, and previously at TTI on a test track.

Comparisons centered around the current test track study. Each of the other studies was compared to that study, in turn. Although other variables or measures were also examined in the other studies (see chapters 5 and 6), a focus is placed on those aspects that provided the opportunity for comparisons. Although a limited number of models were developed in some of the individual studies that included the effects of deflection angle or the interaction between deflection angle and the inverse of radius, the great majority of successful models developed used only the inverse of radius and a constant; accordingly, the comparisons that follow use only equations that were developed with those terms. Key points of those studies are listed in table 29.

ON-ROAD STUDY

The on-road study was completed largely for the purposes of evaluating the workload measures obtained in the test track study. The key differences between this study and the test track were that only 6 drivers were tested (compared with 23) and only 4 repetitions per curve per driver were made (compared with 6). In addition, it was not possible to select curves which were exactly comparable to those tested at the Riverside Campus test facility; instead, researchers selected five curves that provided a wide range of radii and deflection angles.

VD_L Comparisons

Comparisons were made using VD_L (visual demand averaged over the complete curves). Comparisons were systematically made between regression equations developed from the two databases, examining both slope and intercept for differences and similarities.

In a first approach, researchers examined the overall model using all available data. In this approach, the data from 6 drivers and 4 repetitions were directly compared with data from 24 drivers and 6 repetitions. Using an F-test, it was found that no statistical difference between the regression slopes (with respect to the inverse of radius) existed at the 95 percent confidence level (used hereafter as the standard of comparison). A significant difference was found, however, with respect to the intercept, indicating only an offset across all radii (see table 30). Plots of the regression lines for the two databases are shown in figure 61.

Table 29. Comparison of Studies.

Study	Test Track	On-Road	Simulator	Previous Test Track
Characteristics	Three closed courses	Two local rural highways	One closed course	Mix of closed courses and individual curves (two separate studies)
Location	TTI	TTI	UMTRI	TTI
Sample	23 drivers	6 drivers	24 drivers	40 drivers in one study, 15 in second study (some overlap)
Number of Repetitions	6	4	6	4
Independent Variables	1/Radius	1/Radius	1/Radius	1/Radius
Dependent Variables[†]	$VD_L{}^*$ $VD_{30}{}^{**}$	$VD_L{}^*$	$VD_L{}^*$ $VD_{30}{}^{**}$	$VD_L{}^*$ $VD_{30}{}^{**}$
Location of Detailed Information	Chapter 5	Chapter 5	Chapter 6	Krammes et al.[7]

[†]Although other measures of VD may have been used in the referenced studies, VD_L and VD_{30} values were calculated and/or provided for the purposes of the comparisons presented in the chapter.
*Visual demand averaged over the length of the curve.
**Visual demand averaged over the first 30 m of the curve.

Table 30. Comparison Between On-Road Study and Test Track Study: VD$_L$.

Run 1 On-road model		Run 1 Test track model	
$VD_L = 0.173 + 43.013\dfrac{1}{R} + \varepsilon$		$VD_L = 0.297 + 25.832\dfrac{1}{R} + \varepsilon$	

Comparison	p-Value	Interpretation
Slopes	0.0588	No significant difference
Intercepts	0.0001	Significant difference

Runs 2-4 On-road model		Runs 2-6 Test track model	
$VD_L = 0.198 + 29.160\dfrac{1}{R} + \varepsilon$		$VD_L = 0.285 + 23.133\dfrac{1}{R} + \varepsilon$	

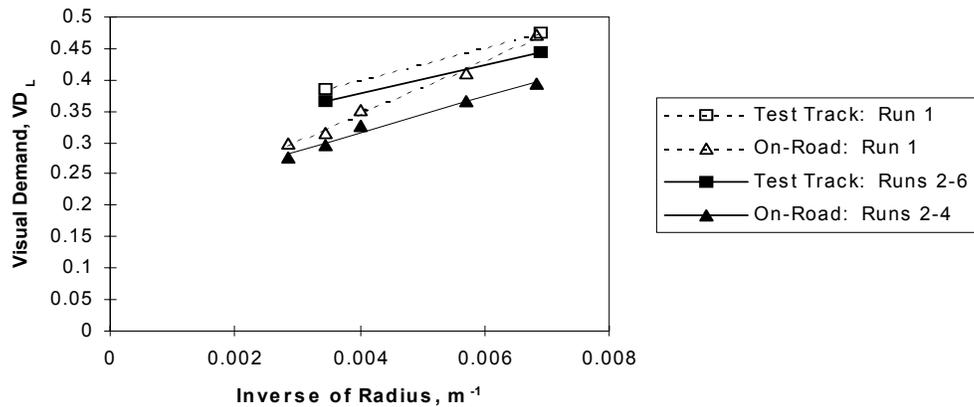| Comparison	p-Value	Interpretation
Slopes	0.2777	No significant difference
Intercepts	0.0001	Significant difference

Figure 61. Comparison Between On-Road Study and Test Track Study: VD$_L$.

Next, researchers attempted to increase the similarities between the two databases, with only four runs being utilized from the test track data to match the four runs available from the on-

road data. Results similar to the comparisons to the complete database were found, with no significant difference between the coefficients of the inverse of radius and a significant difference between intercepts. Finally, a comparison was made using only the test track data from the six drivers who participated in the on-road study. The same pattern was observed as in the previous two comparisons, with no statistically significant slope differences and a significant difference between intercepts.

SIMULATOR STUDY

The study completed in the simulator was similar in size and make-up to the test track study. Both studies tested 24 drivers, and both studies completed 6 repetitions per curve per driver. Because the simulator study was conducted on a "virtual" course, researchers were able to construct a single test course that encompassed all of the desired test curves.

VD_L Comparisons

Comparisons were first made between regression equations developed using both complete databases. The test track study examined curves with 145- and 290- m radii, but the simulator study also included curves with 194- and 582-m radii. In this comparison, the slopes and intercepts were both found to be significantly different for the two databases for run 1 and for runs 2-6, although the slopes did have similar trends (i.e., VD_L increased with increasing radius). Table 31 provides a summary of the comparisons. Figure 62 provides a visual comparison of the two regression equations. In an attempt to discover whether the inclusion of curves with dissimilar radii influenced the resulting regression coefficients (and hence the comparisons), the simulator database was reduced to include only those curves with similar radii to the test track study. For runs 2-6 similar findings resulted, with both regression coefficients significantly different in the two studies. For run 1, however, no significant difference was found for slope (p=0.2692); the intercept was significantly different (p=0.0001).

Table 31. Comparison Between Simulator Study and Test Track Study: VD$_L$.

Run 1 Simulator model		Run 1 Test track model	
$VD_L=0.388+34.663\dfrac{1}{R}+\varepsilon$		$VD_L=0.297+25.832\dfrac{1}{R}+\varepsilon$	
Comparison	**p-Value**	**Interpretation**	
Slopes	0.0317	Significant difference	
Intercepts	0.0001	Significant difference	
Runs 2-6 Simulator model		Runs 2-6 Test track model	
$VD_L=0.367+36.487\dfrac{1}{R}+\varepsilon$		$VD_L=0.285+23.133\dfrac{1}{R}+\varepsilon$	
Comparison	**p-Value**	**Interpretation**	
Slopes	0.0490	Significant difference	
Intercepts	0.0001	Significant difference	
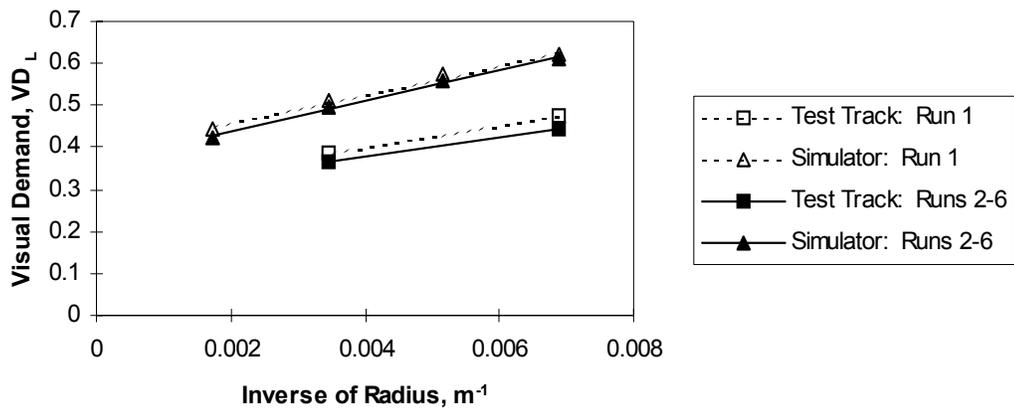
**Figure 62. Comparison Between Simulator Study and
Test Track Study: VD$_L$.**

VD$_{30}$ Comparisons

Next, researchers compared the regression equations using the dependent variable VD$_{30}$, or visual demand averaged over the first 30 m of the test curves. Comparing findings from curves with similar radii, researchers found that there was no significant difference between the test track and simulator slopes, although a significant difference was found between the respective intercepts. Details of the comparison are shown in table 32, while figure 63 provides a visual comparison of the plots of the equations.

Table 32. Comparison Between Simulator Study and Test track Study: VD$_{30}$.

Run 1 Simulator model:		Run 1 Test track model:	
$VD_{30}=0.429+29.806\dfrac{1}{R}+\varepsilon$		$VD_{30}=0.269+34.012\dfrac{1}{R}+\varepsilon$	
Comparison	**p-Value**	**Interpretation**	
Slopes	0.7932	No significant difference	
Intercepts	0.0001	Significant difference	
Runs 2-6 Simulator model:		Runs 2-6 Test track model:	
$VD_{30}=0.400+31.214\dfrac{1}{R}+\varepsilon$		$VD_{30}=0.262+30.672\dfrac{1}{R}+\varepsilon$	
Comparison	**p-Value**	**Interpretation**	
Slopes	0.5794	No significant difference	
Intercepts	0.0001	Significant difference	
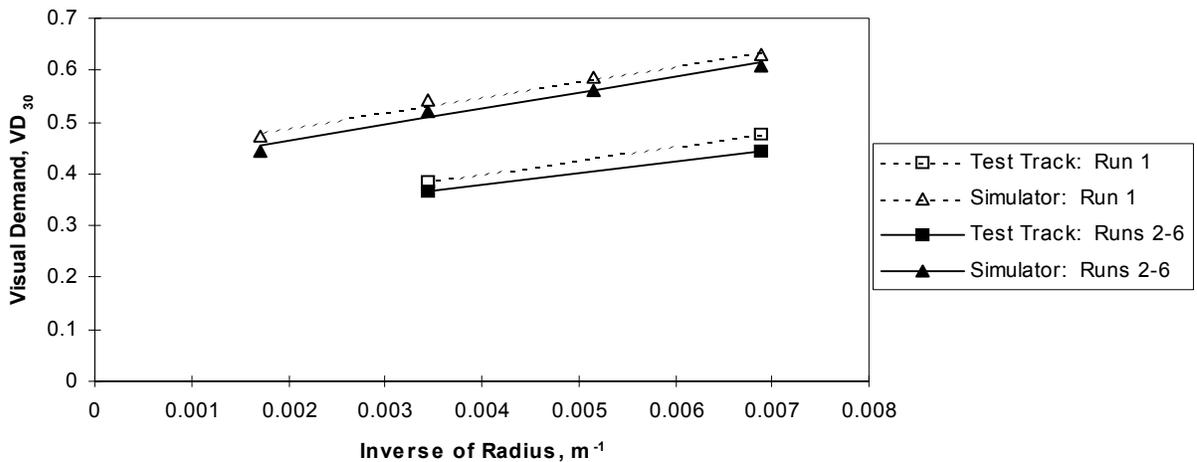
Figure 63. Comparison Between Simulator Study and Test Track Study: VD_{30}.

PREVIOUS TEST TRACK STUDY

In the final study comparison, researchers compared the current test track study with a test track study previously reported in January 1995.[7]   Key differences in the two studies included a larger number of subjects used in the previous study, a reduced number of repetitions (four rather than six), and a mix of test curve layouts (one closed course and several individual curves rather than three closed courses). Available data were limited to values averaged across runs only.

VD Comparisons

The first comparison with this database was with regard to VD. The comparison of slopes revealed no significant differences, although the intercepts were found to be significantly different. The previous test track study used four repetitions, rather than six repetitions as in the test track study. Therefore, an additional comparison was made that restricted the test track database to the first four repetitions only. Repeating the results made previously, the slopes were again found to have no statistically significant differences, and again the intercepts were found to be significantly different. Table 33 provides details regarding the models compared on the basis of the complete databases, while figure 64 provides a visual comparison of the regression equations.

Table 33. Comparison Between Previous Test Track Study and Test Track Study: VD_L.

Previous test track model:	Test track model:
$$VD_L = 0.202 + 19.0\frac{1}{R} + \varepsilon$$	$$VD_L = 0.286 + 23.5\frac{1}{R} + \varepsilon$$

Comparison	p-Value	Interpretation
Slopes	0.804	No significant difference
Intercepts	<0.001	Significant difference

VD_{30} Comparisons
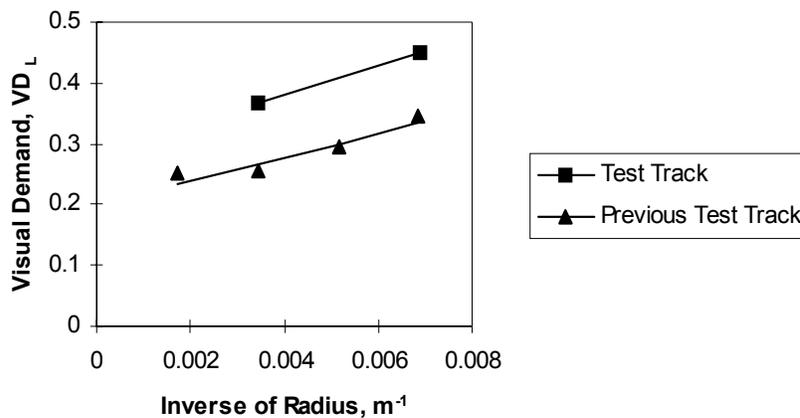
Figure 64. Comparison Between Previous Test Track Study and Test Track Study: VD_L.

Researchers next compared VD_{30} values for the previous and current test track studies.[1] Similar to the VD comparisons, the comparisons are limited by the available data: the VD_{30} values available were averaged across runs. Initial comparisons were made using the complete databases for the two studies. Comparing slopes, no significant differences were found but, repeating the findings for the VD values, the intercepts for the two studies were found to be statistically different (see table 34). Similar findings were made when the database for the current study was restricted to only four runs to match the previous study. Figure 65 provides an overview of the two models.

**Table 34. Comparison between Previous Test Track Study
and Test Track Study: VD$_{30}$.**

Previous test track model:	Test track model:
$VD_{30} = 0.195 + 27.086\dfrac{1}{R} + \varepsilon$	$VD_{30} = 0.262 + 31.2\dfrac{1}{R} + \varepsilon$

Comparison	p-Value	Interpretation
Slopes	0.5332	No significant difference
Intercepts	0.0001	Significant difference
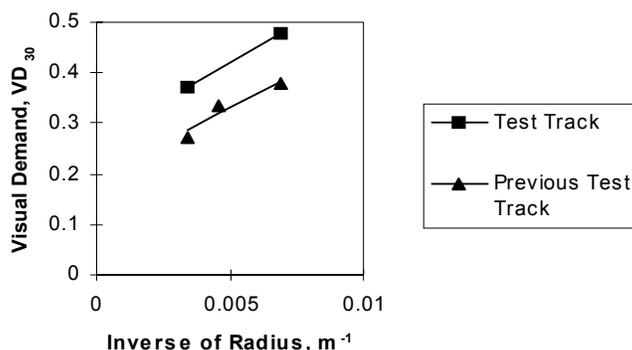
**Figure 65. Comparison Between Previous Test
Track Study and Test Track Study: VD$_{30}$.**

FINDINGS

Several different workload measures and testing environments were used in the course of this research project. Table 35 summarizes the overall comparisons made between those studies; figures 66 and 67 provide overall visual comparisons for VD$_L$ and VD$_{30}$, respectively, and tables 36 and 37 provide the equations for predicting visual demand. Examining the tables and figures, it is apparent that the measures used in the project to represent driver workload were relatively robust. Of the six possible comparisons, five resulted in the conclusion that no significant difference in slope (with respect to the inverse of radius) existed between the TTI test track study regression equations and the comparison equations. This provides a level of confidence that workload differences between features can be reliably predicted. The exception to this finding was between the current test track study and the simulator study for one measure of workload, VD$_L$.

**Table 35. Summary of Comparisons of Test Track Study
With Other Studies.**

Study	VD_L		VD_{30}	
	Slope of 1/R	Intercept	Slope of 1/R	Intercept
On-Road	NSD[1]	SD[2]	*na*	*na*
Simulator	SD	SD	NSD	SD
Previous Test Track	NSD	SD	NSD	SD

[1]NSD: No significant difference
[2]SD: Significant difference

The comparisons between intercepts, or constants, showed that those intercepts were usually significantly different. The cause of these differences is difficult to fully explain, but differences in roadway markings (i.e., alternating markers every 9 m compared with markers on both sides every 6 m, painted center stripes and edge lines compared with the lack of lateral motion cues in the simulator, raised markings, etc.), testing environments (test track versus simulator, test track versus highway), the lack of lateral motion cues in the simulator, and the use of different subjects probably account for at least part of these differences.

The finding that there is no difference in the slope of the regression line when comparing test track results with on-road results, but there is a difference in the intercept, would indicate that *relative* levels of workload can be ascertained, but not *absolute* levels. This finding shows promise in determining *differences* in workload levels between successive highway features, but not baseline levels.

Because most applications of driver workload are expected to be with respect to changes in level rather than in absolute terms, the general agreement with respect to the slope of the workload measures used is very encouraging. The overall robustness in measures should yield a greater confidence in the measures used and lead to further use, research, and future applications.

Table 36. Curve Equations for Overall Comparisons Using VD$_L$.

Test Track	Run 1: $$VD_L = 0.297 + 25.8\frac{1}{R} + \varepsilon$$
	Runs 2-6: $$VD_L = 0.285 + 23.133\frac{1}{R} + \varepsilon$$
On-Road	Run 1: $$VD_L = 0.173 + 43.0\frac{1}{R} + \varepsilon$$
	Runs 2-4: $$VD_L = 0.198 + 29.2\frac{1}{R} + \varepsilon$$
Simulator	Run 1: $$VD_L = 0.388 + 34.7\frac{1}{R} + \varepsilon$$
	Runs 2-6: $$VD_L = 0.367 + 36.5\frac{1}{R} + \varepsilon$$
Previous Test Track[7]	$$VD_L = 0.202 + 19.0\frac{1}{R} + \varepsilon$$
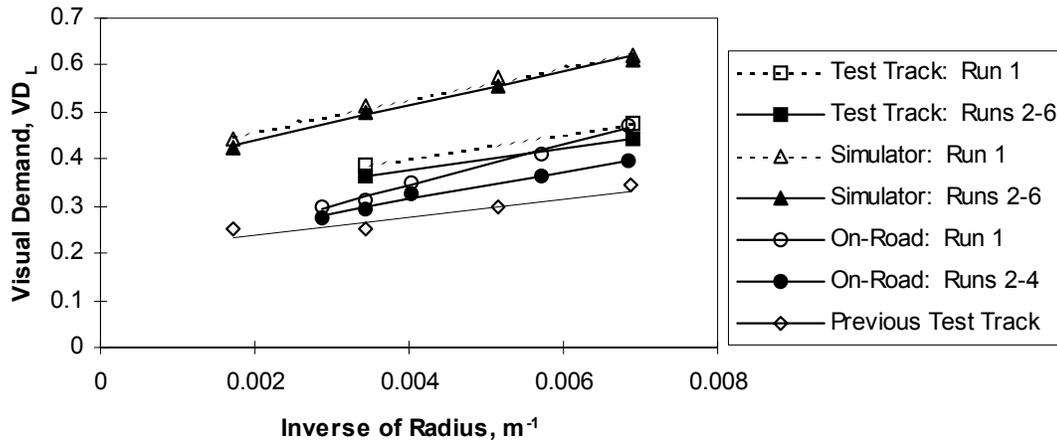
Figure 66. Overall Equations: VD_L.

Table 37. Curve Equations for Overall Comparisons Using VD_{30}.

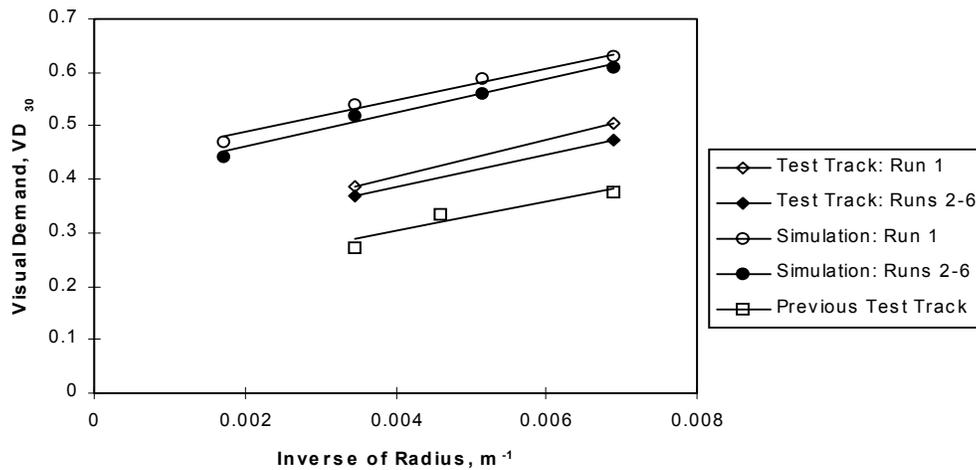|	
Test Track	Run 1: $$VD_{30}=0.269+34.0\frac{1}{R}+\varepsilon$$
	Runs 2-6: $$VD_{30}=0.262+30.7\frac{1}{R}+\varepsilon$$
Simulation	Run 1: $$VD_{30}=0.429+29.8\frac{1}{R}+\varepsilon$$
	Runs 2-6: $$VD_{30}=0.400+31.2\frac{1}{R}+\varepsilon$$
Previous Test Track[7]	$$VD_{30}=0.195+27.1\frac{1}{R}+\varepsilon$$

Figure 67. Overall Comparisons: VD$_{30}$.

8. SUMMARY, FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

SUMMARY

Phase II of the "Design Consistency Evaluation Module for the Interactive Highway Safety Design Model" project focused on investigating design consistency rating methods other than speed prediction. The three methods studied included: alinement indices, spot speed variability measures, and driver workload. The scope of the data collection and model development was limited to rural, two-lane highway alinements.

Alinement indices are quantitative measures of the general character of a roadway segment's alinement. They have been used in other countries, specifically Germany and England, as a measure of the design consistency of their roads. Proposed indicators of geometric inconsistency occur when there is a large increase in the magnitude of the alinement indices for a successive roadway segment or feature or when a high rate of change occurs over some length of road.

Speed distribution measures—including variance, standard deviation, coefficient of variation, coefficient of skewness, and coefficient of kurtosis—were investigated as potential candidates for a consistency rating method. The rationale for using spot speed measures is that inconsistent features are expected to cause more driver errors and greater variation in spot speed variance. Graphical evaluations were initially performed to obtain an appreciation of how the speed distribution measures varied in relationship to roadway geometry and speed measures, such as posted speed. In addition, an evaluation using regression was also performed. The results from the analyses indicated that speed variance generally decreased on horizontal curves compared with the upstream tangent. Given this finding, it is inappropriate to consider speed variance as a design consistency measure for horizontal curvature.

Driver workload is a measure of the information processing demands imposed by roadway geometry on a driver. The efforts for this study used both objective and subjective measures to model geometric features and combinations of features in terms of the difficulty that they pose to drivers. Vision occlusion, subjective difficulty ratings, a driving simulator, and a eye-mark system were used during the research.

FINDINGS

The findings from the Phase II efforts are subdivided into alinement indices, spot speed variability, and driver workload. Following are the list of findings within each of these categories.

Alinement Indices

The alinement indices task produced the following findings:

- Several alinement indices were identified as possible measures in rating the design consistency of rural two-lane highways. Some of the indices were not considered during this research because of limitations in determining available sight distance from roadway plans and the desire to have indices that provide information on individual features rather than on the general character of the roadway.

- The alinement indices recommended for preliminary use as measures of design consistency from this study included:

    Horizontal Alinement Indices
    1. Radii Measures
        - Average Radius
        - Maximum Radius / Minimum Radius
    2. Tangent Length
        - Average Tangent Length

    Vertical Alinement Indices
    1. Angular Change in Direction
        - Average Rate of Vertical Curvature

- An analysis of safety data was conducted to test the relationship to safety of several forms of the alinement indices identified above as preliminary design consistency measures. The alinement indices that appeared to have the strongest and most sensitive relationship to accident frequency are:

    - Ratio of an individual curve radius to the average radius for the roadway section as a whole.
    - Average rate of vertical curvature for a roadway section.
    - Average radius of curvature for a roadway section.

- However, none of these alinement indices has a relationship to safety as strong as the speed reduction of a horizontal curve relative to the preceding curve or tangent, which was developed as a design consistency measure by Fitzpatrick et al.[8]

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Speed Distribution Measures

The spot speed variability measures task produced the following findings:

- Several previous research efforts have indicated that higher speed variability suggests a higher accident potential.

- For horizontal curves, standard deviation of speeds varied from 6 to 12 km/h.

- The graphical analysis of the effects of roadway geometry on speed distribution measures presented no clear indication of a relationship between any of the measures (variance, standard deviation, coefficient of variation, coefficient of skewness, coefficient of kurtosis) and geometric elements (tangent length, horizontal curve radius, horizontal or vertical curve length, deflection angle, superelevation, lane/pavement width, rate of vertical curvature, approach grade, departure grade) with one exception. For radii 100 m and less, standard deviation was lower than for larger radii.

- The analyses conducted to examine the relationship between standard deviation of speeds and design or posted speed did not produce any significant relationships. Expected trends in the data were found that related speed measures to these two speed components, but the variation of the data suggested that design and posted speed were not accurate predictors of speed distribution measures.

- Linear relationships between speed distribution measures of successive features existed because the same sample of drivers was being measured. Extreme differences existed for some locations where the horizontal distribution measures did not fit the linear trend with respect to the tangent measures. These locations may be locations where inconsistencies are present, but without accident data, no inferences can be made regarding the design inconsistencies at these locations.

- The evaluation of speed distribution measures did not find significant relationships with roadway geometry. The range of standard deviations of speeds was wider for large radius horizontal curves. Small radius curves (less than 100-m radii) had lower standard deviations of speeds. These findings are contrary to the original hypothesis, but the limited number of observations of small-radii horizontal curves does not allow for sound conclusions to be made. The lower standard deviation of speeds for small radii conflicts with findings from previous studies, which showed that high speed variance locations have the potential for high accident rates.

Driver Workload

The driver workload tasks produced the following findings:

- Several driver workload studies have indicated that high driver workload and large changes in driver workload result in an increased potential for accidents.

- The use of multiple measures of driver workload (e.g., visual demand, subjective ratings) provided an enhanced understanding of the effects of changes in roadway geometry.

- Studies of driver responses in a wide variety of driving environments found that driver workload is significantly affected by the geometric properties of roadway curves.

- The general pattern was for the visual demand to begin to rise about 90 m from the beginning of the curve, peak near the beginning, remain level or slightly drop through the curve, and then gradually return to the baseline level after the end of the curve.

- Driver workload increases linearly with the inverse of radius. That is, as radius becomes smaller, driver workload increases. This finding is supported by the variety of measures and techniques used to evaluate driver workload. Both subjective (Modified Cooper-Harper rating) and objective (visual demand) measures of driver workload indicated similar trends.

- The effect of deflection angle was persistent but small in overall influence and practical significance for driver workload. Analyses examining subjective and objective measures indicated a modest increase in workload with increased deflection angle, although the subjective measure (Modified Cooper-Harper rating) provided a clearer indication of the influence of deflection angle on workload.

- When vision was not occluded in occlusion test sessions, drivers primarily looked ahead searching for points where roads curved and generally ignored edge markings in the near field. The point on which drivers focused depended upon the curve direction (left or right) and how sharp the curve was. The sharper the curve, the more likely drivers were to look at the outside lane line (versus the inside lane line). This may have implications for delineation placement (i.e., providing enhanced outside lane line treatments for sharp curves).

- The examination of paired curves revealed that neither type of curve pair (i.e., broken-back or S-curve) nor curve pair separation greatly influenced VD_L; however, the influence was statistically significant. Somewhat contradictory results were found, indicating different responses depending on the run. An interaction between separation and pair type indicated that closely spaced S-curves resulted in significantly higher workload than closely spaced broken-back curves when run 1 results were examined. Run 2-6 results indicated that widely spaced curves resulted

in higher VD_L than closely spaced curves. Both of these findings were unexpected. It was anticipated that S-curves would be more consistent with driver expectations (and be associated with lower workload) and that more closely spaced curves would impose a greater workload through carryover from the previous curve. The VD_L changes observed were relatively small, however, and further research should be conducted to confirm or extend these results.

- The test track, on-road, and simulator studies all produced generally the same results with regard to changes in workload, as did a previous test track study. Predicting overall workload proved elusive, with significant differences apparent in the various studies; these differences, however, do not diminish the utility of being able to predict the level of workload change between features. Improvements in the roadway markings used on and within 100 m of curves or other test features would be expected to reduce this intercept difference.

CONCLUSIONS

The following general conclusions were developed based upon the findings of the study.

Alinement Indices

Three alinement indices investigated in the study are sensitive to accident frequency. These are the ratio of an individual curve radius to the average radius for the roadway section as a whole, the average rate of vertical curvature for a roadway section, and the average radius of horizontal curvature for a roadway section. However, none of these alinement indices has as strong a relationship to accident frequency as the speed reduction measure developed by Fitzpatrick et al.[8]

Speed Distribution Measures

Based upon the findings from this research, speed variance is inappropriate as a design consistency measure for horizontal curves. The analysis did not provide an acceptable design consistency method.

Driver Workload

- Driver workload has very good potential as a design consistency rating measure. Additional investigation is necessary to develop threshold values indicating limits to driver workload change.

- The vision occlusion method is sensitive to changes in road geometry and is a promising measure of effectiveness. Vision occlusion should be considered for use in

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Speed Distribution Measures

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Driver Workload

- Driver workload has very good potential as a design consistency rating measure. Additional investigation is necessary to develop threshold values indicating limits to driver workload change.

- The vision occlusion method is sensitive to changes in road geometry and is a promising measure of effectiveness. Vision occlusion should be considered for use in future studies when the visual demand/workload of driving situations is to be determined.

- The preferred method of computing vision demand for a horizontal curve is over a relatively short fixed-length portion of roadway after the beginning of the curve to eliminate potential confounding between the summary measures used and the length of the curve. In this study, measures based on the first 30 m of the test curves were used successfully.

- Based on this research, simulator results can provide reasonable estimates of real world estimates of workload and should be considered for use in future studies of visual demand.

RECOMMENDATIONS

The following recommendations are made based upon the findings and conclusions of this project:

Alinement Indices

- Alinement indices do not appear appropriate as primary measures of design consistency because the speed reduction measure developed by Fitzpatrick et al. has a stronger relationship to safety.[8]

- If speed reduction is used as the primary measure of design consistency, the three alinement indices found to be related to safety may have a role as supplementary measures.

Spot Speed Variability Measures

- Analysis of speed distribution measures needs to be further explored to determine the possible relationships with accident potential and roadway geometry. The focus of this analysis was solely on the relationship between speed distribution measures and roadway geometry. Although speed distribution measures do not show promise of

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