Information as a Source of Distraction

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FOREWORD

In the past, communicating messages legibly on electronic changeable message highway signs (CMS) was limited by older CMS technology to textual information, using just a few fonts. Today, CMS technology has advanced to the point where messages can display graphical information, including exact replicas of standard highway signs, and Federal Highway Administration fonts. Although what can be displayed on CMSs intended for highway applications is limited, the technology is capable of producing full color, animation, and video, and can display these images in bright daylight. This project examined the distraction potential of information sources in the right-of-way, with a focus on the latest generation of CMS technology that is capable of displaying any type of message—large or small letters, graphics, and symbols. In one of the experiments, drivers did not look at the salient images (faces on brightly colored backgrounds) more often or longer than they looked at travel-time messages.

In addition to CMSs, the project evaluated the distraction potential of increasing the number of supplemental guide signs associated with a single interchange and potential information overload effects on drivers, from the frequency and spacing of guide signs. The results of that study supported retaining current *Manual of Uniform Traffic Control Devices for Streets and Highways* standards and recommendations for guide signs and suggested further research on the design of specific-service logo signs. The research should be useful to engineers interested in standards for highway signing, to Transportation Management Center operators interested in conveying messages that complement driver behavior and to researchers interested in assessing driver visual attention.

Monique R. Evans
Director, Office of Safety
Research and Development

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16. Abstract

The overall goal of the Information as a Source of Distraction project was to further the scientific basis for decisions about the types of information that can be displayed within the right-of-way without adversely affecting drivers' attention to their primary task—safe driving. There were two focus areas: electronic changeable message highway signs (CMS) and guide signs. Six studies were conducted. The first study examined the perceived similarity between messages on a full-color, full-matrix, light-emitting diode CMS display with 0.79-inch (20-mm) pixel pitch and the same messages on a liquid crystal display. The purpose of that study was to derive requirements for laboratory and driving simulation studies of CMS messaging. The second study examined the legibility distance for text message on the CMS display used in the first study. It was determined that, assuming 20/40 vision, legibility distance could be estimated using a letter height of 1 inch (2.54 cm) per 20 ft (6.1 m) of viewing distance. In the third study, drivers read the CMS display as they approached it on a closed course that required them to simultaneously navigate a curved path. The effects of CMS message properties such as flashing, phasing, abbreviations, and use of symbols versus text were examined. The fourth and fifth studies simulated overhead CMS messages on a freeway on which there was a CMS every 0.5 mi (0.8 km). By displaying highly salient images (faces on brightly colored backgrounds) that changed every 3 s, an attempt was made to distract drivers. Drivers did not look at the salient images more often or longer than they looked at travel-time messages. When headways were short, the salient signs had a 0.2 probability of receiving a brief look. None of the signs caused drivers to miss safety-critical messages encountered later in the drive. None of the signs caused drivers to fail to detect a roadway hazard (spilled logs). The final study examined the effects of the frequency and spacing of guide signs on navigation performance and eye-glance behavior. That study supported retaining current *Manual of Uniform Traffic Control Devices for Streets and Highways* standards and recommendations for guide signs and suggested further research on the design of specific service logo signs.

17. Key Words
Distraction, Changeable message sign, CMS, Supplemental guide sign, Specific service sign, Sign spacing, Sign frequency, Sign content

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway Transportation Officials
CIE	Commission Internationale de l'Eclairage (International Commission on Illumination
CMS	Electronic Changeable Message Highway Sign
FHWA	Federal Highway Administration
GEE	Generalize Estimating Equation
ITS	Intelligent Transportation System
LCD	Liquid Crystal Display
LED	Light-Emitting Diode
M	Mean
MUTCD	*Manual on Uniform Traffic Control Devices for Streets and Highways*
NCHRP	National Cooperative Highway Research Program
NEMA	National Electrical Manufacturers Association
NTCIP	National Transportation Communications for Intelligent Transportation System Protocol
PRC	Percent of Road Center
RGB	Red, Blue, Green
ROI	Region of Interest
SE	Standard Error of the Mean
SDG	Standard Deviation of Gaze Angle
TCD	Traffic Control Device

EXECUTIVE SUMMARY

The overall goal of the Information as a Source of Distraction project was to further the scientific basis for decisions about the types of information that can be safely displayed within the right-of-way without adversely affecting drivers' attention to their primary task—safe driving. There were two focus areas: electronic changeable message highway signs (CMSs) and guide signs.

This study had the following objectives:

- Determine the distraction potential of non-traffic-related messages.
- Determine the distraction potential of guide signs that are more closely spaced or more frequent than current guidelines permit.
- Perform both on-road and driving simulator evaluations of distraction.
- Create a report and present recommendations that provide a scientific basis for practitioners to assess the informational load imposed on road users by information sources within the highway right-of-way.

CHAPTER SUMMARY

Chapter 1, the report's introduction, discusses the definition of distraction, the properties of modern light-emitting diode (LED) based CMSs, and the specific issues addressed in the subsequent chapters.

Chapter 2 presents some laboratory assessments of a full-color, full-matrix, LED display with 0.79-inch (20-mm) pixels. The display represents capabilities of the current generation of CMSs that are compliant with intelligent transportation system (ITS) standards. In one experiment, observers rated the visual similarity of messages on the CMS with the same messages displayed on a 60-inch (152-cm) liquid crystal display. The results of that experiment suggest that it is not necessary to emulate individual pixels of the CMS display to generate images that observers rate as reasonably similar to the CMS images. The results will have significance for future CMS research in either the Federal Highway Administration's (FHWA) sign laboratory or the FHWA highway driving simulator.

Chapter 3 presents a study of the legibility of the CMS described in chapter 2. These results suggest that the legibility distance of the 0.79-inch (20-mm) pixel-pitch full-color display used in this test provides a longer legibility distance than the previous generation of CMS displays that used a 1.6-inch (40-mm) pixel pitch with amber LEDs.(1) They also suggest that for the display type used and drivers with approximately 20/20 vision, the 90- to 100-percentile legibility distance can be estimated using a factor of 40 to 45 ft/inch (4.8 to 5.4 m/cm) of letter height. This equates to a somewhat lower legibility distance for 0.79-inch (20-mm) pixel pitch CMS display than that provided by the 30 ft/inch (3.6 m/cm) legibility distance criterion in the *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD), assuming a 20/40 visual acuity.(2) (Because the relationship between letter height and visual acuity is linear, the MUTCD criterion would yield a 60-ft/inch (7.2-m/cm) legibility distance for individuals with 20/20 visual acuity.)

Chapter 4 examines the legibility of CMS messages in a dynamic roadway environment. In this study, observers drove toward the CMS on a winding path at 25 mi/h (40 km/h) and read the messages on the sign as soon as possible. An eye-tracker was used to assess when the observers were looking at the signs. The time and distance for the beginning and ending of response were recorded. The following properties of the messages on the sign were assessed for their effect on gaze behavior and message reading:

- **Message length.** The amount of time required to read messages of up to five words was fairly constant. Six- and seven-word lists took considerably longer to read. It is recommended that text messages be limited to five or fewer words whenever possible.

- **Flashing.** The MUTCD standard is not to flash messages.(2) When the first line of a message was flashed, the duration of observers' responses was longer than for either static messages or all-lines-flashing messages. The delay before participants began responding was longest for all-lines-flashing messages. The findings support the current MUTCD standard.

- **Symbols versus text.** The symbol versions of messages (e.g., an electronic version of the signal ahead symbol sign) that filled the same display area as their text equivalents were legible or recognizable from a greater distance than their equivalents. The exception to this finding was the road workers ahead symbol sign, which was unfamiliar to the majority of observers. It is recommended that a familiar symbol be used in place of a text message when: (1) the high-resolution CMS can accurate portray the symbol, and (2) the symbol is recognizable at the same or greater distance as the equivalent text message.

- **Abbreviations.** It was found that use of the abbreviations approved in the MUTCD had no adverse effects compared with the spelled out versions of the abbreviated words.(2)

Chapter 5 presents an experiment conducted in the FHWA highway driving simulator to evaluate whether frequently changing overhead freeway CMS displays with human faces and colorful backgrounds would distract drivers more than static travel-time-related messages or a blank CMS. Another purpose of the experiment was to evaluate whether noncritical information presented on frequently occurring CMSs (i.e., a CMS every 0.5 mi (.8 km)) would cause drivers on a 48-min trip to lose respect for or habituate to the CMS messaging and result in drivers missing a safety-critical CMS message. The results showed that gaze behavior (i.e., number of looks, duration of looks) did not differ between signs with rapidly changing faces and static text messages. Drivers briefly looked at signs with changing faces and travel times about 40 percent of the time (40 percent of the signs) when headway to the car ahead was greater than 1.5 s. When headways were shorter than 1.5 s, the probability of briefly looking at a non-blank sign was about 0.15. Regardless of what was displayed on the CMS, the mean duration of individual looks was 0.2 s or less.

For the simulated trip, in which the drivers passed under 96 noncritical CMS message signs, there was no indication of habituation. The 97th CMS carried the message "ACCIDENT

AHEAD ALL LANES BLOCKED USE NEXT EXIT." Of the 32 participants, 9 failed to exit after passing under that sign. However, only one of the nine participants claimed to be unaware of the critical message. The majority of the remaining participants tried to exit but were unable to find a safe gap to change lanes.

Chapter 6 presents another experiment in the FHWA highway driving simulator similar to the experiment described in chapter 5. However, in this experiment, a spilled load of logs was in the participant's lane, and the primary dependent measure was whether the participant avoided hitting the spilled load. There were 72 CMSs—1 every 0.5 mi (0.8 km), the 3 sign types (changing faces, travel-time messages, and blank) occurred in cycles of 3. The 72d sign was blank for a third of the participants, had a travel-time message for another third, and had changing faces for the final third. The spilled load came early in the trip (just before the third CMS) for half the participants and late in the trip (just before the last CMS) for the other half. Of 80 participants, 21 hit the logs. There was no significant relationship between the content of the CMS at the spill site and the probability of hitting the spilled load.

Chapter 7 examined the effect of the frequency and spacing of guide signs on navigation, eye glance behavior, and driving performance. The primary focus was the frequency and spacing of specific-service signs and supplemental guide signs. The number of supplemental guide signs varied between zero and three as did the number of specific service signs. The number of destinations on guide signs varied between one and two. The distance between the three types of guide signs also varied. In most conditions, the spacing minimum was 800 ft (244 m), which is the current standard. In the remaining two conditions, the spacing was 400 and 200 ft (122 and 61 m). Overall, the results support the current MUTCD standard of 800 ft (244 m) spacing between signs and up to two destinations on advance and supplemental guide signs. There was some evidence that the specific-service six-panel logo signs used in this study required too much visual attention, especially when there was more than one specific-service sign. Participants appeared to scan food and gas service signs in search of a lodging destination and thus did not appear to use the sign legends in their search strategy.

SUMMARY OF FINDINGS AND RECOMMENDATIONS

The overall goal of the project was to further the scientific basis for decisions about the types of information that can be displayed within the right-of-way without adversely affecting drivers' attention to their primary task—safe driving. There were two focus areas: electronic CMSs and guide signs. Findings and recommendations include the following:

- Research on messaging can be done on laboratory and driving simulator displays without precisely emulating the pixel spacing or color properties of CMS devices. It is sufficient to emulate legibility distance and approximate color and contrast.

- The daytime legibility distance of 0.79-inch (20-mm), full-color, full-matrix CMS text can be estimated using a letter height of 1 inch (2.4 cm) per 20 ft (6.09 m).

- Large symbols that motorists easily recognize have greater legibility distance and require less visual attention than equivalent word messages that require the same display area.

- CMS messages should be limited to five words or fewer whenever possible, especially if the messages contain rarely used elements (e.g., evacuation routing or atypical lane closures).

- Visually salient CMS images (faces) that change every 3 s attracted no more attention than static travel-time text messages. Blank signs attract less attention than populated signs.

- Drivers attend to CMSs when driving demands are manageable.

- The frequently occurring and driving irrelevant CMS messaging used in this study did not appear to cause drivers to rapidly habituate to or lose respect for CMSs such that safety-critical messaging would be ignored. This study did not examine whether long-term habituation might occur over many trips. It is possible that messaging that cannot be easily recognized as driving irrelevant (e.g., messages that must be fully read to determine irrelevance) might result in loss of respect if encountered frequently.

- CMS messages that were theoretically highly visually salient did not distract drivers from detecting roadway hazards. It appears that drivers have learned to regulate their visual attention in a way that minimizes susceptibility to visual distractions. This finding does not imply that drivers cannot be distracted by CMS messages but rather that visual salience alone is not sufficient to distract.

- The MUTCD criteria for the frequency and spacing of guide signs, including supplemental and specific-service signs, were supported by the current findings.(2)

- Further research is recommended to address why participants in this study searched fuel- and food-specific service signs when their task was to search for a specific lodging business.

CHAPTER 1. INTRODUCTION TO THE INFORMATION AS A SOURCE OF DISTRACTION PROJECT

The overall goal of the Information as a Source of Distraction project was to further the scientific basis for decisions about the types of information that can be displayed within the right-of-way without adversely affecting drivers' attention to their primary task—safe driving. The goal was to be accomplished by evaluating the distraction potential of various types of information when displayed on electronic changeable message highway signs (CMSs), especially non-traffic-related messages displayed within the right-of-way. In addition to CMS messaging, the distraction potential of frequent and closely spaced freeway navigation guide signs was to be considered.

OBJECTIVES

The objectives of this project were to determine the distraction potential of various types of information when displayed within the right-of-way. In particular, the studies were to determine the potential of CMS depictions of road signs and non-traffic-related messages and other information sources and to determine the distraction potential of guide signs that are more closely spaced or more frequent than current criteria permit. The objectives were to be achieved through performance of both on-road and driving simulator evaluations. The researchers were to create a report and present recommendations with a scientific basis to enable practitioners to assess the informational load imposed on road users by information sources within the highway right-of-way.

BACKGROUND

CMSs are used by highway agencies to communicate current information to drivers.[1] Information displayed on these signs may include travel times, incident information, temporary lane restrictions, and alternate route suggestions. CMSs are intended to aid motorists, transportation agencies, and the general public.(2) The signs are thought to benefit motorists by increasing safety and reducing travel delays. Transportation agencies are thought to benefit from improvements in network operational efficiencies. The general public is thought to benefit from reductions in pollution that result from network efficiencies.

Because CMS display technology continues to evolve and improve, the potential for the development of novel CMS uses is likely to continue. It is also conceivable that some of the extensive guidance for CMS operations and policy may become obsolete as technology continues to evolve.(3–5) The FHWA has requested additional research to assist future decision making, and guide validation or update of CMS standards and guidelines contained in the *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD).(2) The present project is intended to serve that role, with an emphasis on guidance to avoid unnecessary driver distraction by CMS content. This literature review is intended to summarize the current knowledge base regarding CMS information display and its relation to driver distraction.

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[1] Changeable message signs are also referred to as variable message signs and dynamic message signs. This report uses CMS throughout.

Distraction is a construct that is related to attention and stimuli that inappropriately divert or attract attention. Before distraction can be studied in a scientific manner, an operational definition is required.

Operational Definition of Distraction

In their book on driver distraction, Regan, Lee, and Young define distraction as "…a diversion of attention away from activities critical for safe driving toward a competing activity."(6) They go on to say the following:

> …[D]riving is a complex, multitask activity, making it likely that the demands of one element of driving will interfere with another element. Considering driving as a single activity in defining distraction oversimplifies a complex activity and neglects important driving-related distractions that drivers must manage. (p. 35)

Because driving involves the management of multiple tasks, such as monitoring the road ahead, monitoring the speedometer, monitoring the review mirrors, and perhaps reading safety-critical messages on a CMS, Regan et al. qualify distractions as an "inappropriate" distribution of attention.(6)

The US-EU Bilateral ITS Technical Force working group on driver distraction provided a similar definition of driver distraction to that provided by Regan, Lee, and Young.(7) The members of the working group also distinguished between appropriate and inappropriate attention. They acknowledge a rear-end collision with a suddenly braking vehicle would not be caused by distraction if the driver of the following vehicle was performing a shoulder check while merging with mainline freeway traffic. That is, when two safety-critical demands for attention are simultaneous, workload—not distraction—would be the main causative factor for a collision. The working group defined *critical for safe driving* tasks as those that *allow the driver to avoid or not cause a crash*. The working group acknowledged that safety-critical tasks may be situation dependent and liable to interpretation. They caution against using hindsight (i.e., whether a crash actually occurred) as a criterion for determining safe driving. As yet, however, there are no universally accepted metrics for assessing safe driving in the absence of a crash.

Horberry and Edquist discuss distraction from elements outside of the vehicle.(8) Their analysis focuses on billboards and the potential for billboards to attract driver attention from the built roadway, which they define as roadway geometry, the roadway surface, and traffic signs and markings. Despite this narrow scope, they conclude that although it seems intuitively obvious that billboards are a distraction to drivers, there is little research to support or refute this view. Their analysis provides little guidance on an approach to the distraction potential for CMSs that are part of the built roadway. However, their analysis does provide suggestions for the direction of future research. They identify the following three types of distracting stimuli:(8)

- Visual distraction of attention capture.
- Cognitive distraction.
- Secondary activity.

Visual distraction occurs when a strong visual stimulus causes an involuntary glance, as might occur in response to a bright flash of light. Cognitive distraction occurs when a stimulus causes the driver to inappropriately devote mental attention to a matter not immediately necessary to safe driving, such as engaging in a conversation. Secondary activities are non-driving-related activities in which drivers voluntarily engage, such as searching for a vehicle identified in an AMBER alert that was posted on a CMS.

Thus, in the study of the relationship between CMS content and driver distraction, it is suggested that researchers are looking at the content of CMS that results in inappropriate diversion of attention away from activity critical for safe driving to CMS stimuli that do any of the following:

- Capture drivers' attention involuntarily.
- Capture drivers' visual or mental attention for longer than is appropriate.
- Prompt additional activities that inappropriately draw resources away from safe-driving-related tasks, e.g., tuning the radio or writing down the license number from an AMBER alert while negotiating a lane change in traffic.

There are several challenges to successfully addressing the information distraction issue. CMSs on freeways are primarily, if not exclusively, traffic control devices (TCDs). Thus by definition, CMSs are part of the roadway, and reading them is part of the driving task. In some cases, CMSs contain information critical to safe driving. This implies that a CMS, when used as a TCD, can only be distracting if it causes an inappropriate diversion of attention (i.e., when the information on the CMS is not more critical to safe driving than other roadway visual stimuli). When used to display non-traffic-related messages, e.g., advertising, AMBER alerts, or public service announcements (e.g., click it or ticket), the bar for distraction is lower (i.e., this information is not safety critical) and any attention that would otherwise be devoted to safety critical tasks would then constitute distraction. Even in the case of non-traffic-related messages however, there is room for diversion of driver attention, if that diversion does not detract from safety-critical activity.

The amount of driver mental capacity available for safety-critical driving tasks can vary from time to time, person to person, and place to place. For instance, required capacity can vary in time with the level of traffic. Persons who are fatigued may have less available capacity.(8) Freeway sections with sharp curves, narrow lanes, or frequent weaving generally require more attention than straight, wide, uninterrupted sections. Therefore, assessing the distraction effects of CMS information requires either methods of measuring attention requirements and available driver attention capacity or the use of some putative surrogate measure of distraction.

Measuring Attention and Distraction

Young, Regan, and Lee discuss various driving performance measures to assess the distraction effects.(9) They mention lateral (lane) tracking performance, longitudinal (following headway) performance, gap acceptance, steering entropy, reaction time, and speed maintenance as potential driving performance measures that have been shown to vary with putative levels of distraction. They caution that these measures are not interchangeable.

Visual distractions (tasks that require looking away from the roadway) have been shown to affect lateral tracking performance, whereas tasks with moderate levels of cognitive distraction are associated with improved lateral control (measured by lane tracking and steering entropy). Reaction times to traffic events have been shown to be degraded by cognitive distraction. Young, Regan, and Lee also reported that in many cases driving simulations are more sensitive to driving performance degradation than are on road and test track assessments.(9) However, they caution that this greater sensitivity in driving simulations may be the result of shifts in drivers' criterion for attending to the driving and distraction tasks (i.e., in simulators drivers may give higher priority to attending to the distraction and lower priority in attending to the driving task). How this shift in priorities relates to driving safety in the real world is unknown. However, this phenomenon points to the importance of measuring both primary (driving) and secondary (cognitive) task performance to assess how drivers are trading off performance in the two tasks.

Where drivers look can also be a clue to where their attention is directed.(10) Although it is possible to attend to locations on which the eyes are not focused and the level of attention to the location where the gaze is fixed can vary because of cognitive distraction, the center of gaze is generally a good indication of where drivers are attending.(11,12) Furthermore, there is a long history of using eye-tracking technology in the study of how drivers attend to traffic signs.(13,14)

The fovea is the area of the retina that has the highest resolution and is used for reading normal text. The fovea covers about 2 degrees of visual angle. To capture fine detail, the direction of gaze must change to place the detail within the fovea. Assuming good contrast, an individual with 20/20 visual acuity can read a highway sign with letters 18 inches (46 cm) high from 1,000 ft (305 m) away. At 1,000 ft (305 m), a 2-degree cone of vision would encompass a diameter of 36 ft (11 m). A CMS of 8 ft (2.4 m) in height (typical of a gantry-mounted overhead CMS on freeways) with the bottom of the sign at 20 ft (6.1 m) above the roadway would fall within this 2-degree cone, even if the driver is focused on a vehicle on the roadway below the sign. Furthermore, when deployed in a moving vehicle, well-calibrated eye trackers are limited to about 1.5 degrees of resolution.(15) As a result, a field study with an eye tracker may not be able to establish with certainty when a driver first begins reading an overhead freeway sign or when the first glance at the sign occurs. At 500 ft (152 m), the 2-degree cone of fine vision has an 18-ft (5.2-m) diameter, so at that distance, it should be possible to determine with reasonable certainty whether a driver's eyes are directed toward an overhead sign or to the roadway ahead. However, at 500 ft (152 m), another complication arises. The 18-inch (46-cm) letter will subtend 10 min of arc or about twice the angle required for legibility. Text of this size, especially if it is expected, such as a route number or speed limit, would be legible in near peripheral vision (2 to 10 degrees from the center gaze). This means that a driver may comprehend a CMS message without the necessity for the direction of gaze falling on the text. Three information unit text messages (what, where, and action) suggested for CMS messages by Dudek are probably too complex to be read quickly with near-peripheral vision.(3,5) However, the new technology CMSs (see the next section, New CMS Capabilities) are capable of displaying symbols that constitute a single item of information and might be recognizable in near-peripheral vision. Also, drivers might be able to detect single high-priority words, such as "ACCIDENT," in near-peripheral vision.

The use of percent of time gazing at the forward roadway (i.e., percent road center (PRC)) has been proposed as an inverse measure of driver visual distraction to in-vehicle devices.(16) PRC would typically not be appropriate for assessment of distraction caused by CMS content because at least portions of the signs can be read without taking the driver's gaze away from the forward roadway, which these authors defined as a 16-degree cone about the forward path. As noted in the previous paragraph, a cone that large would include obstacles on the road and an overhead CMS for at least 500 ft (152 m) of travel distance.

The standard deviation of gaze angle (SDG) (computed as the sum of the square root of x^2 plus y^2, where x is the difference between the previous horizontal gaze angle and the current gaze angle, and y is the analogous difference in the vertical plane) is reported to be sensitive to cognitive workload (mental distraction not caused by a competing visual task).(12) Therefore, SDG might be an appropriate indicator of distraction by CMS content if that content increases driver cognitive distraction. Victor et al. found that cognitive distraction decreased the standard deviation in gaze angle compared with a no distraction baseline.(16) However, they could not show that SDG varied with the other levels of cognitive distraction they employed (i.e., levels of distraction other than the no distraction baseline). They speculated that the easiest cognitive distraction task maximized workload so that more difficult tasks could not show additional decrements. The distracter task they used was to count the number of times a target tone occurred within a string of 15 tones. The difficulty was manipulated by varying the number of different target frequencies (two, three, or four) for which the participant had to listen.

Lane tracking, whether measured by steering entropy or lane deviations, would also not be a suitable measure of attention devoted to CMS content for the following reasons: (1) although lane tracking has been found to be sensitive to visual distraction by in-vehicle devices, gazes at CMSs would still allow monitoring of lane position with near peripheral vision, and (2) lane tracking has not been found to be sensitive to degradation from cognitive distraction.(12)

Reaction time to traffic events has been shown to be degraded by cognitive distraction as defined by increased mental workload. Thus, to the extent that CMS content is suspected of increasing mental effort, reaction time to events in the roadway might be used to test the presence of this distraction effect.

Time headway appears to be a weak predictor of distraction.(17) In an extensive series of on-road and driving study tests, there was some suggestion that visual distraction (attention to an in-vehicle device) results in slower speeds and longer headways, whereas cognitive distraction results in somewhat shorter headway in some studies, but not others.

New CMS Capabilities

Currently, CMS vendors are marketing ITS grade (National Transportation Communications for ITS Protocol (NTCIP) and National Electrical Manufacturers Association (NEMA) compliant) light-emitting diode (LED) CMSs for freeways with pixels as small as 0.47 inches (12 mm). Each pixel of a full-color CMS is made up of red, green, and blue LEDs. Such signs can display color images with symbols that closely match the MUTCD color specifications.(18) Although the ITS grade signs cannot display full-motion video or rapidly refreshed animations, commercial LED signs (often supplied by the same vendors that market ITS signs) can.

Current CMS Guidelines and Knowledge Gaps

This section provides an overview of the current state of knowledge concerning the human factors aspects of CMS content.

The following distraction effects are discussed in this section:

- **Attraction**. CMS stimuli that capture attention involuntarily.
- **Information overload**. CMS stimuli that capture drivers' visual or mental attention for longer than is appropriate.
- **Unintended driver reactions**. CMS stimuli that prompt secondary activities that inappropriately draw resources away from safe-driving-related tasks.

Attraction

The idea that distraction can be the result of an involuntary capture of attention is related to the orienting response in the classical conditioning paradigm. A bright light that suddenly and unexpectedly illuminates may cause an orienting response—a response in which the individual involuntarily shifts attention and gaze to the stimulus. Whether a CMS could cause an orienting response is questionable. Orienting responses are easily extinguished.(19) That is, if exposure to the stimulus is repeated and the stimulus is not related to current priority goals—in this case driving—then the orienting response to the stimulus will stop occurring. Thus, even if the sudden onset of a CMS image or message would cause an orienting response on first occurrence, drivers would soon learn not to orient to such changes unless those changes reliably predicted an event that has priority over watching the road and monitoring the vehicle state.

Information Overload

The construct of information overload was aptly described in National Cooperative Highway Research Program (NCHRP) Report 488:(20)

> "Driver information overload" results from providing too much information, through devices or conditions, for a driver to perceive and respond properly. Therefore, the information load on a driver is a property not only of the specific sign they are encountering, but also of the roadway context in which the sign occurs, the information context in which the sign occurs, the behavior characteristics of the driver, and the particular navigational task. Where drivers are confronted with more information than they can process, they may decelerate severely or drive unduly slowly, make late or erratic maneuvers, take an improper route alternative, ignore critical information, fail to monitor other traffic, or have excessive eyes-off-the-road episodes. These behaviors have obvious safety and operational consequences. (Foreword)

Information overload might occur if a driver perceives the need for the information on a TCD but extraction of the information requires more attention resources than the driver can devote to the message without risking degradation of driving performance.

Unintended Driver Reactions

Information overload may be possible when drivers either have to gaze at a CMS too long, or drivers have to devote too much attention (mental effort) to extracting meaning from a CMS. Two studies that appear to provide direct evidence of the distracting effect of information overload from CMS messages are cited here.

Erke, Sageberg, and Hagman conducted a study of driver responses to route diversion messages of CMS in Oslo, Norway.(21) At one site, the messages displayed indicated that a tunnel ahead was closed and suggested a ring road diversion. In fact, the tunnel was not closed. They found an increase of about 25 percent in the proportion of drivers exiting at the suggested ring road. Virtually all traffic left the freeway before reaching the tunnel. Thus, it appeared that the messages were nearly 100-percent effective in communicating that the tunnel was closed. However, there were unintended consequences. Mean speed was reduced in the proximity of the sign by about 5 mi/h (8 km/h). There was also a significant increase in speed variance and a significant increase in the number of brake light illuminations within reading distance of the sign. Video recordings suggested that part of the decrease in speed and braking events resulted when the lead vehicle in a platoon braked thereby requiring braking by closely following vehicles. Unfortunately, the authors did not measure legibility distance nor do they report the size of the text on the signs, which used amber LEDs. The text messages on the signs consisted of four lines but only three units of information (location, event, and action). The authors imply that the signs were legible from about 500 ft (150 m). At the posted speed of 50 mi/h (80 km/h), drivers would have had about 5.5 s to read the sign, or slightly less than the 2 s per information unit suggested by Dudek.(3) The Erke et al. study demonstrates that CMS can adversely affect driving performance and potentially affect safety. However, because the signs in this study appear to fall short in legibility distance and perhaps because the messages had more lines than are typical, it should not be concluded that these effects would be observed with messages that fully comply with the guidance provided by Dudek.

A similar slowing for four-line CMSs was reported for a simulator study that primarily focused on the effect of bilingual CMS messages on driver performance.(22) In that study, drivers slowed for four-line message signs, whether monolingual or bilingual, but did not slow for one- or two-line messages. A significant reduction in time headway was also observed only for four-line message signs when the vehicle ahead varied its speed on approach to the signs. For bilingual four-line messages, the investigators tried to mitigate the performance changes by placing a blank line between the English and Welsh messages (two lines each). This mitigation strategy had no effect. However, the number of trials in which the blank line was present was small, and participants were not told ahead of time what the line indicated (English above, Welsh below). Thus, in locations where bilingual CMSs may be desirable in the United States (e.g., States that border Mexico and Quebec), strategies such as visual separation of message lines might still be effective if drivers know what the visual separation means and also have more than minimal exposure to the visual separation. Because Welsh, English, Spanish, and French use nearly identical alphabets, drivers need to process all the lines of a bilingual message to extract the part of the message that is meaningful to them. It is reported that when the characters are distinctly different (e.g., Japanese and English or Greek and English), four-line bilingual signs do not hinder driver performance.(22)

The studies described in this section suggest that speed and headway changes in the vicinity of a CMS are potentially useful driving performance measures for assessing the distraction effect of CMSs because erratic control of speed and headway could indicate a diminution of attention to the driving task. Note that if a driver slows to allow more time to read a CMS, the headway of the driver who slows will increase, but that will cause the headway of following drivers to decrease.

CMS Properties

This section reviews some of the CMS properties that, depending on implementation and operational variations, may be related to the human factors that may result in reduced or increased driver distraction.

Pixel Size (Dot Pitch)

Currently, NTCIP- and NEMA-compliant, full-matrix, full-color CMSs for freeway implementations have pixel sizes that range from 0.79 to 2.36 inches (20 to 60 mm).(23,24) Each pixel consists of red, green, and blue LEDs. In some cases, the two red LEDs are used in combination with one blue and one green. Although the pixels, even those of 0.79 inches (2 cm) in diameter, would seem to be large, at the viewing distances of 100 to 1,000 ft (30.5 to 300.5 m), the individual pixels can appear to form fairly smooth continuous lines and curves.

Font Issues

Previous research on the legibility of text on CMSs does not necessarily apply to CMSs with 0.79- or 1.33-inch (20- or 34-mm) CMS displays. Early research found that the number of matrix elements did not affect legibility distance.(25) Although Garvey and Mace tested a font that consisted of 0.79-inch (20-mm) pixels, they did not attempt to replicate FHWA fonts, which can be approximated with 0.79-inch (20-mm) pixels and 18-inch (46-cm) letters. They also did not test uppercase/lowercase lettering with 0.79-inch (20-mm) pixels.

Much of Europe is in the process of adopting the TERN font for CMS.(26) The TERN font is used on conventional European traffic signs, so in that sense, it is comparable to the FHWA standard fonts.

Garvey, Pietrucha, and Meeker reported that recognition distance (i.e., the distance at which destination names could be distinguished from each other) was greater when uppercase/lowercase lettering (i.e., first letter capitalized and the remaining letters in lowercase) than all uppercase lettering.(27) Their stimuli were all positive-contrast white letters on a green (guide sign) background. Garvey et al. suggest that the uppercase/lowercase benefit derives from participants' ability to distinguish word shapes from the configuration of risers and descenders in uppercase/lowercase text. In their study, participants were given a destination name to look for, and the participants responded by indicating whether the target destination was on the first, second, or third line of a sign. With no expectation regarding what words to anticipate, shape was of less benefit. Indeed, the investigators found that legibility distance did not vary between uppercase/lowercase and all uppercase destination names when the participants had no expectation of what destinations would be shown on the sign. Apparently on the basis of this finding, the 2009 MUTCD was amended to specify street name and destination names be in uppercase/lowercase font. Other text on guide signs is to remain all upper case.(2) This study's research team was unable to identify research that examines whether case has an effect on recognition or legibility distance on high-resolution CMS displays. At least for positive contrast, similar effects may be true for CMSs. In tests with negative contrast text, Holick, Chrysler, and Park found no advantage for uppercase/lowercase text over upper case test.(28) However, this seemingly contrary finding may be because participants in the study had no expectation regarding the message content. For CMSs with a limited vocabulary and where location names are used, uppercase/lowercase text may provide a recognition distance benefit. This hypothesis is testable.

Symbols

McDougall, Tyrer, and Folkard reported search times for icons are faster when the icons possess a quality they refer to as "objectness."(29) Quickly recognized icons are not necessarily the least complex (although complexity may affect legibility). Thus the I-10 route shield may be reacted to more quickly than the I-10 text if the text is treated perceptually as two objects and the route shield as one. This prediction is easily testable.

Icons that have good legibility distance, that are recognized in context by most drivers, and that are familiar are likely to speed sign comprehension. The only study this research could identify that appears to confirm this conjecture was difficult to evaluate. Wang, Collyer, and Clark reported that recognition of CMS messages with icons was slightly faster than text-only messages.(30) However, the generalizability of their findings is doubtful. Participants had to decide which of two messages was being displayed. In this situation, recognition of either the text or the icon was sufficient to support a response. Icons were used to communicate incident type (e.g., crash, congestion, and slippery wet pavement), and text provided the location and recommended action. Only the icon or first line of all text messages needed to be recognized. Had participants needed to read the entire text or icon plus text message, the results may have been different. Also, there were hints in the data of speed/accuracy tradeoffs. Although the correlation between speed and accuracy was not significant, accuracy was not analyzed as a dependent measure. Thus, the possibility that the use of familiar icons or symbols could speed sign comprehension or increase legibility distance has not been fully and unambiguously evaluated.

Motion

Motion or animation and flashing are not allowed by the MUTCD. Lane closure portable arrow boards, which are included in the MUTCD, use a sequence of chevrons to imply motion; however, these boards do not create true apparent motion and do not qualify as animation (see section 6F.61 of the MUTCD).(2) These boards are currently only approved for temporary lane closures in conjunction with other TCDs such as channelizing devices and static signs. With the advent of active traffic management, which includes lane closures using permanent overhead CMS, the evaluation of effectiveness of similar sequenced symbols seems warranted.

Luminance

The MUTCD does not specify the required luminance for CMSs other than dictating that it meets industry standards for day and night-time illumination.(2) The current industry standard is NEMA TS 4.(23) The MUTCD specifies that the luminance automatically adjust to ambient light and recommends that the contrast ratio between lit and unlit portions of the sign remains between 8 and 12 (see section 2L.03, paragraphs 10 and 11 of the MUTCD).(2)

Contrast

As indicated in the previous paragraph, it is recommended that the contrast ratio between lit and unlit elements of CMSs be between 8 and 12.

The contrast ratio C is defined by the formula shown in figure 1.

$$C = (L_{on} - L_{off})/L_{off}$$

Figure 1. Formula. Contrast ratio.

Where:

L_{on} = luminance of an area of the display with pixels on.
L_{off} = luminance of the same area with pixels off.

Sun position is an important element of CMS legibility. When the Sun is shining from behind the driver onto the face of the sign, contrast can be considerably reduced. The amount of reduction depends on the maintenance of the sign and on the design of the sign face. NEMA TS 4 specifies the test procedure for verifying standard conformance when the Sun is 10 degrees above a perpendicular to the sign face.(23) When the Sun is shining from behind the sign into the driver's face, apparent contrast will depend on the amount of shielding around the sign. Standards for shielding the sign or illuminating sign elements in this adverse lighting condition were not identified.

Messaging

The most complete guide to CMS message construction is probably the guide prepared for the New Jersey Department of Transportation.(5) That document provides guidance on message structure, vocabulary, length, flashing, and paging of messages. Although it provides thorough and apparently sound advice for CMS operators, the empirical foundations for that advice are not cited. These foundations may be found in earlier publications, many of which are cited in the following sections.

Flashing

Currently, the MUTCD does not allow flashing any part of a message on a CMS (see section 2L.05, paragraph 5).(2) Numerous studies have looked at the effects of flashing messages on CMS. Flashing is generally intended to increase the conspicuity or attention capturing of important CMS messages.(31) However, few evaluations examine the effects of flashing on attention capture. One study that did look at the effect of flashing on conspicuity was reported by Charlton.(32) In that study, the effects on conspicuity were mixed. A flashing school warning sign increased search conspicuity and memory for that warning compared with a static school warning sign. A flashing road work ahead sign also proved more conspicuous than a static road work ahead sign of the same size, but was not more conspicuous or memorable than an oversized static version of the same sign. Charlton concluded that the effectiveness of flashing for attracting attention and improving memory for CMS messages may vary with the message.

However, the Charlton study looked at only a small subset of CMS symbols and no text messages. The overall effectiveness of flashing as a conspicuity enhancement deserves further research.

A number of studies have shown that flashing may make CMS text messages harder to read. These studies examined reading time and comprehension for flashing messages and did not weigh the benefits of faster reading time or better comprehension against the potential for more drivers to attend to the sign or the likelihood that the sign would affect driver behavior in the desired manner.(33–35) One study in which messages were presented on a laptop computer found that reading times were increased by about 20 percent if any part of a message was flashed.(34) This finding seems reasonable because the amount of time the message is exposed is decreased when it flashes. Nonetheless, the Dudek 2006 study failed to replicate the reading time effect in a driving simulator.(33) Comprehension was not affected when an entire three-line message was flashed.(34) However, recall of the third line of simulated CMS messages was depressed when only the first line of the message flashed.

No research was identified that looks specifically at whether flashing on a CMS distracts drivers in a manner that would adversely affect safety. Dudek et al. did not find effects on driving performance in a simulator as a result of flashing.(34) In that study, the roadway was straight, and drivers had to monitor the forward roadway to maintain a safe following distance behind a simulated vehicle that braked unpredictably.

Flashing is used by some agencies to increase the conspicuity and apparent importance of CMS messages. There is a dearth of research showing that flashing accomplishes its intended purpose and little research that shows negative effects on reading time or comprehension that would outweigh the putative conspicuity benefits. Although the current body of research does not support elimination of the ban on flashing, neither is there evidence that either operational effectiveness or safety is adversely affected by the ban. Research in this area might clarify these issues.

Vocabulary

The appropriate vocabulary and syntax for text-based messages was one of the earliest areas of human factors CMS research and analysis. (See references 36 through 40.) More recently, research has focused on methods of presenting travel times on CMS.(41,42) The research in this area seems adequate to meet user needs for permanent full-matrix color CMSs.

Message Length

CMS technology (e.g., the number of characters that can be displayed) and the amount of time CMS messages are legible to drivers constrain the amount of information that can be displayed. When approaching drivers are traveling at freeway speeds, CMS text with 18-inch (46-cm) characters is legible for a maximum of about 8 s. The MUTCD specifies 18 inches (46 cm) as the minimum letter height for CMSs on freeways (see section 2L.04, paragraph 6 of the MUTCD).(2) Because CMS legibility distance has been found not to increase much beyond that afforded by an 18-inch (46-cm) letter height, this height has tended to become the standard height. Obstructions, such as other vehicles, horizontal of vertical curves, and adverse atmospheric conditions (e.g., rain), can further reduce the amount of time that drivers are exposed to legible messages.

Furthermore, early research in driver glance behavior showed that drivers do not look at signs in single long glances.(13) Rather, drivers make multiple short glances interspersed with glances to the roadway and other vehicles. Thus, for a static sign that is legible for 8 s, the total time a driver may glance to areas where the sign text can be read will sum to only about 2 s on average but may be as much as 6 s.(13) Dudek has estimated that each "unit" of information on a CMS can be read in about 2 s.(3) He recommends that CMS messages be limited to three or at most four units of information. Dudek defines a unit of information as the answer to a simple question. For CMS these questions are usually what (e.g., crash), where (e.g., ahead), and what action should be taken (e.g., use frontage road).

In the section on unintended driver responses, this report noted that some studies with messages that probably violate the Dudek guidance on message length resulted in drivers slowing or braking. There is also some evidence that at least some drivers slow in response to CMS messaging even when the messages are properly formatted.(43) It is unlikely that improvements in CMS technology could justify text-only messages longer than those currently recommended.

Abbreviations

No research was identified that showed that abbreviations that are understood by more than 85 percent of drivers take longer to comprehend than the complete words that would be used in their stead. Huchingson and Dudek and Hustad and Dudek reported many of the abbreviations specific to portable CMSs are almost universally understood when shown with a prompt—a word with which the abbreviation would always appear (e.g., New Jersey TRNPK).(44,45) To date, the study of highway sign abbreviations has only considered comprehension. The effect of abbreviations on reading and comprehension time and effort should be considered in addition to simple comprehension measures because the time available for drivers to view CMS messages can be short.

Phasing

Of all the currently allowed approaches to displaying messages on CMSs, phasing is probably the most problematic in terms of the potential for driver distraction. Phasing, or paging, breaks a message into two or more parts, with each part displayed in sequence on the same sign. Phasing is used to overcome space limitations. The MUTCD limits phasing to two parts, with each part having no more than three lines (see section 2L.05, paragraph 4).(2) The minimum duration of a phase is 1 s per word or 2 s per information unit. The maximum cycle time is 8 s, which would mean that at freeway speeds, a driver would be exposed to only one cycle during the time that the message is legible. The MUTCD also requires that the intelligibility of the message not depend on the order in which the two phases are read.

The distraction potential of phasing is high because drivers typically make multiple short glances to signs rather than single long glances. The first glance could come at any time during either phase. If more than one glance is required to extract the information from a phase, there is no guarantee that the same phase will be present when the driver returns for a second glance. If the second glance arrives during a new phase, the driver will need to reorient attention to the new message phase. Once oriented, a third glance may be necessary to begin processing the second phase. A fourth glance might be needed to complete processing of the second phase, but this glance could potentially land not on the second but on the first phase, which would again call for a reorientation of attention. All this would be done while the driver continues to monitor the roadway, so that timing of glances to the sign would depend on what the surrounding traffic is doing. Furthermore, the MUTCD allows for a blank interval between phases of up to 0.3 s. Research has suggested that readability, measured by recall, is improved by the insertion of a 0.3 s blank interval between phases. A blank phase may prevent masking of one message by another, or it may just allow drivers time to prepare to attend to a new phase, e.g., shift attention to the upper left portion of the display. However, a driver's glance might arrive during a blank interval, which could either cause a driver to linger on the display until a message appears or return attention to the road and delay reading the sign. In any case, phasing increases the effort and time required to read a CMS and thus will increase the probability that attention will be on the sign when a safety-critical event occurs.

No previous studies were identified that examined the effects of CMS phasing on driver behavior in the field or employed eye tracking to quantify how drivers manage CMS messaging with the other visual requirements of the driving task. The effects of phasing on reading time are reported in chapter 4 of this report.

Supplemental Guide Signs

The MUTCD describes the use of supplemental guide signs (see figure 2) as follows:(2)

> Supplemental Guide signs can be used to provide information regarding destinations accessible from an interchange, other than places displayed on the standard interchange signing. However, such Supplemental Guide signing can reduce the effectiveness of other more important guide signing because of the possibility of overloading the road user's capacity to receive visual messages and make appropriate decisions. (Section 2E.35)

Figure 2. Photo. A series of four consecutive supplemental guide signs at a Virginia interchange.

Supplemental guide signs are approved for guiding unfamiliar travelers to certain types of destinations. Destinations specifically approved for supplemental signing are major colleges and universities, large military bases, major event facilities (e.g., sports arenas and stadiums), State and national parks, monuments, and major recreational areas.(46) For each of these destination types, the American Association of State Highway and Transportation Officials (AASHTO) has provided specific minimum traffic generation criteria. Among the destinations for which supplemental guide signs are deemed inappropriate are businesses, churches, government research centers, driver’s license centers, any schools not qualified as major colleges or universities, and medical facilities.

The MUTCD recommends that no more than one supplemental guide sign be installed per interchange and not more than two destinations be listed on a supplemental guide sign. AASHTO also provides specific maximum distance from interchange criteria that should be met. The AASHTO guidelines are incorporated into the MUTCD by reference (see section 2E.35).(2) If a supplemental guide sign is used, it is to be placed approximately midway between advance guide signs for an interchange where two advance guide signs are used or 800 ft (244 m) after a lone advance guide sign.

The recommended limit of one supplemental guide sign per interchange and the spacing of supplemental guide signs at least 800 ft (244 m) from other signs is intended to avoid possible driver information overload. However, there appears to be no direct empirical evidence that this amount of signing will mitigate information overload or that more signing than is currently permitted would result in information overload. Therefore a priority for the data collection portion of this project was to measure driver performance as a function of the frequency and spacing of guide signs, specific-service signs, and permanent overhead CMSs. In conducting this research, it was assumed that the driver is unfamiliar with the roadway and adjacent facilities and is seeking specific destinations.

APPROACH

The objectives were addressed through a series of studies. Each of these studies is the subject of a separate chapter.

Chapter 2 briefly describes a laboratory study to obtain psychophysical measurements with a state-of-the-art NTCIP- and NEMA-compliant CMS. This effort included asking observers to judge the similarity of symbols and messages displayed on an actual CMS with variations of the same symbols and messages on a liquid crystal display (LCD). The purpose of collecting the similarity comparison judgments was to assess the requirements for conducting CMS messaging research with simulated CMS displays.

Chapter 3 examines the legibility distance of CMS messages in relation to letter height and the observer's visual acuity.

Chapter 4 describes a field test with the state-of-the-art CMS in which drivers read CMS messages in a controlled driving environment. Reading time, reading distance, and eye glance behavior were recorded as drivers approached the CMS while maneuvering an instrumented vehicle at a constant speed. The results are reported for phased messages, flashing messages, messages with abbreviations, messages of varying length, and text versus symbol messages.

Chapter 5 describes a driving simulator study that examined the following issues:

- Would drivers habituate to or lose respect for CMS messages such that a critical CMS message is missed, if, on a long trip (48 min), they encountered a CMS containing irrelevant information every 0.5 mi (0.81 km)?
- Would salient and frequently changing (every 3 s) images on a CMS compel drivers to look at the CMS (i.e., cause attention capture)?
- Would following distance influence glance behavior to a CMS?

Chapter 6 describes a study that is very similar to that of chapter 4. However, this chapter examines whether the content on the CMS changes the probability that the driver will detect a hazard in the roadway.

Chapter 7 examines how the frequency and spacing of freeway guide signs affects driver behavior and the ability to detect guide sign information.

CHAPTER 2. LABORATORY EVALUATION OF CMS

INTRODUCTION

Laboratory comparisons were made between messages displayed on a CMS and the same messages displayed on a 60-inch (1.5-m) LED/LCD monitor. The purpose of the comparisons was to determine which display properties of CMS messages were most important when emulating messages on other types of displays. There were two immediate applications for the findings: (1) to guide the display of CMS messages in the FHWA sign laboratory, which uses the LED/LCD display used in these comparisons, and (2) to guide the display of CMS messages in the FHWA highway driving simulator.

The FHWA Human Factors Team often evaluates new sign formats in its sign laboratory. In the past, these formats have been for static highway signs. In those evaluations, red, green, and blue color values and visual angle subtended were the primary concerns in emulating the highway signs. This seemed reasonable given that in the real world, the actual color values of the signs would vary with the available lighting, and visual angle would vary with viewer distance. However, modern CMSs use LEDs to emit light so available light will primarily affect contrast and not color. The LEDs on the Daktronics® CMS used in this study consist of one red, one blue, and one green LED in each pixel, and the pixels are spaced 0.79 inches (20 mm) apart, center to center. At sufficiently long distances, the light emitted from individual LEDs is perceived as coming from a single source, and the individual pixels are perceived to blend together, much as individual color television pixels, when viewed from an appropriate distance, are not perceived. The present study examined whether it would be necessary to emulate the individual LED elements or pixels of the CMS when presenting alternative CMS message formats in the sign laboratory or the driving simulator.

METHOD

Materials

The CMS was a Daktronics® VF-2320 full-color (red, green, blue (RGB)) matrix display with 0.79-inch (20-mm) pixel pitch. The display surface was 4 by 4 ft (1.2 by 1.2 m), which accommodated a 64- by 64-pixel display. The display is shown in figure 19 in chapter 3.

Some messages for the CMS were developed using the Daktronics® Vanguard V4 Professional software. Other messages for the CMS were images of static signs adapted from the MUTCD and supplied by Daktronics®. Bitmaps were exported from the Daktronics® software and then imported into graphics software to develop messages to be displayed on the LCD/LED monitor.

The graphics software was used to modify the imported bitmaps so that alternative methods of emulating the CMS display could be compared. In some cases, an image was intended to come as close as possible to a literal replication of the CMS display—where each pixel consisted of three circular RGB elements and pixels were 0.79 inches (20 mm) apart, center-to-center. In other cases, the emulated images were made up of circular or rectangular pixels of a uniform color. Finally, some images were made of filled in tracings of the imported images—that is, individual pixels were not emulated in those images.

The 60-inch (152-cm) LED/LCD display was shorter and wider (29 by 52 inches (73.6 by 132 cm)) than the CMS. To display images on the CMS that were the same size as those on the LCD, the CMS images were cropped to the LCD height.

Procedure

Display comparisons were made in the FHWA photometric and visibility laboratory, which has flat black interior walls and no windows and is sealed so that outside light is not admitted. During the comparisons, the only light inside the laboratory came from the two display devices, the CMS controller, and a laptop computer used to control the LCD.

The intensity of the CMS was set to the lowest available setting (1 percent). At that setting, a white circular area with a 12-inch (30.5-cm) diameter emitted about 52.5 fl (180 cd/m^2). A circular area consisting of only red LEDs emitted about 14.6 fl (50 cd/m^2), a blue circular area emitted about 4.4 fl (15 cd/m^2), and a green circular area emitted about 36.5 fl (125 cd/m^2). Table 1 shows the photometric measurements of the X and Y Commission Internationale de l'Eclairage (CIE) color coordinates of stimuli displayed on the CMS.(47) The table also shows the specified RGB settings that were used to generate the measured colors.

Table 1. Measured CIE color coordinates for colors displayed on the CMS and the RGB settings used to generate those colors.

	Coordinates		RGB Settings		
Color	**X**	**Y**	**Red**	**Green**	**Blue**
Red	0.70	0.30	255	0	0
Green	0.17	0.73	0	255	0
Blue	0.13	0.07	0	0	255
White	0.29	0.29	255	255	255
Yellow	0.43	0.52	255	255	0
Orange	0.59	0.49	255	128	0

On the LCD, a white circular area with a 12-inch (30.5-cm) diameter measured 32.4 fl (111 cd/m^2); a red circular area emitted 7.4 fl (25.2 cd/m^2), green emitted 23.5 fl (80.4 cd/m^2), and blue emitted 2.3 fl (8.0 cd/m^2). Table 2 shows the photometric measurements of the X and Y CIE color coordinates of colors displayed on the LED/LCD monitor.

Table 2. Measured CIE color coordinates for colors displayed on the LED/LCD and the RGB settings used to generate those colors.

	Coordinates		RGB Settings		
Color	**X**	**Y**	**Red**	**Green**	**Blue**
Red	0.65	0.33	255	0	0
Green	0.29	0.63	0	255	0
Blue	0.15	0.06	0	0	255
White	0.28	0.28	255	255	255
Yellow	0.44	0.52	255	255	0
Orange	0.6	0.37	233	120	26

For each pair of stimuli presented, one stimulus on the LED/LCD and one on the CMS, participants were instructed to rate similarity, where a rating of 1 indicated that the pair was not at all similar and a rating of 7 indicated that the pair was very similar.

Participants first compared the images on the two displays from a distance of 90 ft (27 m) with the LCD immediately to the left (relative to the observer) of the CMS display. The images on both displays were at the same height above the floor, and subtended the same visual angle.

The comparisons were then repeated with the LCD positioned 15 ft (4.6 m) from the participant and slightly to the participant's left so that the LCD and the CMS, which was still 90 ft (27 m) away, could be viewed at the same time. The images presented at the near distance were sized so that they subtended the same visual angle as the images on the CMS. Except for the reduced size of the near images, they were as similar as possible to the CMS images.

Participants

Nine individuals—FHWA Federal employees and contract staff—served as subjects.

Stimuli

To ease the burden on the reader in relating stimuli to results, the individual stimulus pairs are described in the Results section along with the comparison findings.

RESULTS

The results for the comparisons with the two displays side by side are presented first. These are followed by the same signs with the LCD at 15 ft (4.6 m).

Exit Closed (Side-by-Side)

There were four versions of the sign shown in figure 3. They varied only in RGB values, which are shown in table 3. There were no significant differences in the similarity ratings between versions.

Figure 3. Photo. Message advising that exit is closed.

Table 3. RGB values used in comparisons with message advising that exit is closed.

Version	RGB Settings		
	Red	Green	Blue
A	240	180	10
B	255	172	0
C	255	180	64
D	255	200	20

Exit Closed (LCD Close, CMS Far)

As with the side-by-side comparison, there were four versions of the close comparison stimuli. Unlike the side-by-side stimuli, there was no attempt to emulate individual pixels; all characters were solid. An example of the stimuli as they appeared on the LCD screen is shown in figure 4.

Figure 4. Photo. Exit closed sign example (proportionally scaled and zoomed in).

There were no significant differences in ratings among the four comparisons, which used the same color settings as shown in table 3. Across the four comparison stimuli, the overall mean rating was 4.9.

End (Side-by-Side)

The two versions of this sign are shown in figure 5 and figure 6. Version A consists of white and grey circles intended to simulate the appearance of individual pixels. Version B consists of red, green, and blue circles intended to simulate the three LEDs that make up individual pixels. Both images were based on the same bitmap supplied with the sign vendor's software.

Figure 5. Photo. Version A of the end sign.

Figure 6. Photo. Version B of the end sign.

Version A with a mean similarity rating of 5.0 (with a standard error of the mean (se) = 0.236) was rated significantly more similar to the CMS display of the bitmap than was version B, which was rated 4.2 (se = 0.324), *F* (1, 8) = 12.25, $p = 0.008$. This suggests that at a simulated distance of 90 ft (27 m), it is not necessary to simulate individual LEDs. Use of red, green, and blue circles considerably reduced the perceived brightness of the LCD image, which made the image appear grey in comparison with the nominally white CMS image.

End (LCD Close, CMS Far)

There were three stimuli for this comparison. Two were smaller versions of those shown in figure 5 and figure 6. The additional comparison stimulus eliminated the space between pixels and is shown in figure 7.

Figure 7. Photo. Solid version end sign comparison stimulus.

There were no significant differences in the ratings of the three comparison stimuli. The overall stimuli mean rating was 4.8.

High Wind (Side-by-Side)

There were four versions of the high wind warning sign, one of which is shown in figure 8. Three of the four signs displayed on the monitor were rated reasonably similar to the same sign on the CMS. The difference in mean rating among the four versions was significant, *F*(3, 24,) = 8.67, $p = 0.012$. Post hoc tests showed that version C which had a more orange appearance, was rated lower than the other versions, *F*(1, 8) = 64.0, $p < 0.0001$. The mean and 95-percent confidence limits for the similarity ratings are shown in table 4.

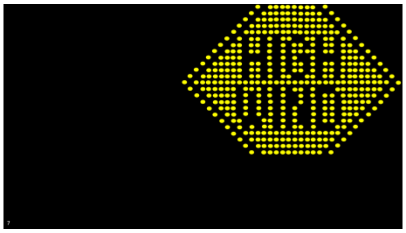


Figure 8. Photo. Emulation of high wind warning sign.

Table 4. RGB values and similarity ratings of four versions of the high-wind warning sign with the CMS standard.

Version	RGB Settings			Mean	Lower Confidence Limit	Upper Confidence Limit
	Red	Green	Blue			
A	240	240	13	5.3	4.6	6.1
B	230	246	0	5.4	4.7	6.1
C	255	200	0	4.0	3.5	4.5
D	255	255	0	5.2	4.5	5.9

High Wind (LCD Close, CMS Far)

In reducing the size of the high wind stimuli in which individual pixels were simulated, the brightness was reduced to the point where the LCD stimuli were barely visible. Therefore, the space between pixels was dropped. Version B of the comparison stimuli, as described in table 5, is shown in figure 9. The differences between ratings were significant, by Wilk's Lambda, $F(3, 6) = 5.7$, $p = 0.034$. Versions B and D were rated significantly higher than A and C.

Table 5. RGB values and rating results for the close high wind comparison stimuli.

Version	RGB Settings			Mean	Lower Confidence Limit	Upper Confidence Limit
	Red	Green	Blue			
A	255	246	0	4.2	3.3	5.1
B	230	246	0	5.1	4.2	6.0
C	250	240	20	4.3	3.6	5.1
D	255	255	0	4.8	3.9	5.6

Figure 9. Photo. Version B of the high wind comparison stimuli.

Accident Ahead Merge Left (White, Side-by-Side)

There were three versions of the accident ahead text message that were nominally white. These are shown in figure 10 through figure 12. One version consisted of white pixels (red, green, and blue for each set to 255), the second grey pixels (red, green, blue for each set to 230), and the third in which the space between pixels was filled in with white (red, green, and blue for each set to 255). There was a significant difference in similarity ratings among the three signs, *F* (2, 16) = 7.3, *p* = 0.006. Post hoc comparisons showed that the sign with grey pixels was rated significantly less similar to the CMS image than the two white versions. At a distance, the space between pixels, whether black or white, resulted in images that were judged equally similar. Comparisons were not requested with the close LCD because the small pixelated images appeared too dim to warrant testing.

Figure 10. Photo. Accident ahead merge left sign with white pixels that yielded a mean similarity rating of 5.6 between the CMS and LCD displays.

Figure 11. Photo. Accident ahead merge left sign with grey pixels that yielded a mean similarity rating of 4.7 between the CMS and LCD displays.

Figure 12. Photo. Accident ahead merge left sign with solid white letters that yielded a mean similarity rating of 5.6 between the CMS and the LCD displays.

Accident Ahead Merge Left (Orange)

Four versions of the accident ahead merge left message in various shades of orange or amber were used, one example of which is shown in figure 13. An overall test indicated significant differences in mean similarity ratings, *F*(3, 24) = 15.1, *p* < 0.001. Post hoc tests showed that versions C and D in table 6 were rated significantly more similar to the CMS image than version A. Version B was not significantly different from version A. Interestingly, version B had the same RGB values as the standard displayed on the CMS. It appears that in this case, the Samsung® display required a greater amount of green to approach the perceived color on the CMS.

Figure 13. Photo. Accident ahead merge left example.

Table 6. RGB values for the four orange alternatives to the accident ahead merge left standard.

Version	RGB Settings			Mean	Lower Confidence Limit	Upper Confidence Limit
	Red	Green	Blue			
A	240	180	10	5	4.231	5.769
B[1]	255	180	64	5.111	4.398	5.824
C	255	200	0	5.778	5.137	6.418
D	240	220	56	5.889	5.288	6.49

[1] RGB values also for the CMS standard.

No Pedestrians

There were two LCD versions of the no pedestrians (no peds) text message, which are shown in figure 14 and figure 15. One of the versions was made up of individual white dots aligned in the same manner as the pixels on the CMS. The other version was similar, but the spaces between pixels were filled in so that only the outer edges of characters retained the outline of the CMS pixels. Both versions received equal and relatively low similarity ratings (Mean (M) = 4.8).

Figure 14. Photo. No peds message on LCD with emulated CMS pixels.

Figure 15. Photo. No peds message on LCD with filled-in space between emulated CMS pixels.

Exit 47 B, Route 7 N, Closed

Similar to the no pedestrians sign, the Exit 47 B sign comparison was a pixelated emulation, shown in figure 16, and an emulation with solid letters, shown in figure 17, of the same message on the CMS display. The solid version received a slightly higher rating (5.3) than the pixelated version (5.0), although this difference did not reach statistical significance, $F(1, 8) = 4.0$, $p = 0.08$.

Figure 16. Photo. Exit 47 B message on LCD with emulated CMS pixels.

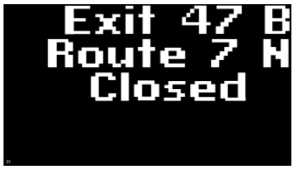


Figure 17. Photo. Exit 47 B message on LCD with filled-in space between emulated CMS pixels.

Shoulder Work

Four versions of a work zone warning (see figure 18) with negative contrast were compared. The RGB values of the LCD images and the CMS image are shown in table 7. There were no significant differences among the four ratings. It appears that the reasonable variation in orange shading of the simulated signs is not critical.

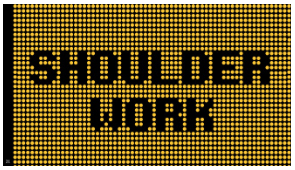


Figure 18. Photo. Shoulder work CMS message emulation on LCD.

Table 7. Ratings for negative contrast orange shoulder work sign.

Version	RGB Settings			Mean Rating	Lower Confidence Limit	Upper Confidence Limit
	Red	Green	Blue			
A	255	120	26	4. 9	4.3	5.5
B[1]	240	133	0	5.3	4.8	5.8
C	255	138	26	4. 9	4.0	5.8
D	233	120	26	5. 3	4.6	6.

[1] Setting on CMS.

DISCUSSION

The ratings suggest that few participants would mistake an LCD image for an image on the CMS. Only one participant gave any ratings of 7. On the other hand, many of the LCD images received mean ratings of 5 or more, which may suggest that the LCD may be a useful tool in addressing human factors issues with CMS messaging.

Overall, the findings suggest that when simulating a CMS display, attempts to emulate individual pixels are counterproductive. This makes sense given that even at its lowest brightness setting, the CMS is brighter than the LCD used in these tests. Emulating CMS pixels reduces the brightness of the LCD even more than when all LCD pixels are used.

Subjective color matches for LCD stimuli are preferable to attempts to match the RGB settings of the CMS. The preference for subjective color matches can be seen in several of the results. For instance, the LCD accident ahead message that was judged most similar to the CMS message had more green in the RGB setting than did the CMS. This also makes sense given the brightness of the LCD color boxes compared with those of the CMS.

When emulating CMS displays, whether in the laboratory or on projected images in a driving simulator, the intended appearance of the CMS should be the primary concern not the absolute color settings on the CMS or the pixel content of the CMS display.

CHAPTER 3. LEGIBILITY TESTING

In addition to the psychometric tests conducted in the laboratory, the CMS was taken outside, and the legibility distance of various messages was tested. The primary interest was the relationship between letter height and legibility distance.

METHODS

Equipment

The CMS was a Daktronics® VF-2320 full-color (RGB) matrix display with 0.79-inch (20-mm) pixel pitch. The display surface was 4 by 4 ft (1.2 by 1.2 m), which accommodated a 64- by 64-pixel display. The display is shown in figure 19.

Figure 19. Photo. Sign used for legibility testing.

Testing was done midday. The stimuli were four-letter words presented individually at a rate of 1.25 words/s with a blank interval of 0.3 s between words.

Procedure

Testing was done during daylight hours between 1 and 3 p.m. The typical ambient illuminance was 2,487.9 fc (26,780 lx). The sign face was oriented to the northwest, with the Sun to the southwest at approximately 60 degrees ±15 degrees elevation. The sign brightness was set to 100 percent. The sign luminance measurement results for white and yellow stimuli are show in table 8. The luminance measures were obtained by illuminating 12-inch (30 cm) squares of the specified color at the specified locations on the display. A Konica Minolta® Chroma Meter CS-100 was used to take the luminance readings. The readings were taken from a distance of 50 ft (15.2 m) with a 1-degree aperture. The luminance of a black (all pixels off) block was 67 fc (229 cd/m^2) which yields a mean contrast ratio of 43 for yellow characters and 46 for white characters.

Table 8. Luminance and CIE color coordinate measures for colors of fonts used in legibility testing.

Color	Units/CIE Coordinates	Upper Left	Upper Right	Center	Lower Left	Lower Right	Mean	Min	Max
Yellow/ Amber	Fl	2,948	2,884	3,153	3,298	3,211	3,099	2,884	3,298
	cd/m^2	10,100	9,880	10,800	11,300	11,000	10,616	9,880	11,300
	X	0.419	0.431	0.423	0.427	0.436	0.4272	0.419	0.436
	Y	0.528	0.518	0.524	0.524	0.517	0.5222	0.517	0.528
White	Fl	3,153	3,065	3,328	3,503	3,444	3,298	3,065	3,503
	cd/m^2	10,800	10,500	11,400	12,000	11,800	11,300	10,500	12,000
	X	0.287	0.298	0.289	0.288	0.298	0.292	0.287	0.298
	Y	0.302	0.303	0.298	0.294	0.301	0.2996	0.294	0.303

Min = Minimum.
Max = Maximum.

The three font sizes used were 7 (height) by 5 (width) pixels, 12 by 8 pixels, and 16 by 8 pixels. All fonts used a 2-pixel stroke width. The actual height of the characters, which were all displayed in uppercase, can be computed by multiplying the pixel size, 0.79 inches (20 mm), by the font height. However, it is common to assume that there will be some apparent blooming of the characters that adds to the apparent font height. Therefore, for the remainder of this section, a bit less than 0.5 inches (12.7 mm) of blooming is assumed so that the three fonts are referred to by their assumed heights: 6, 10, and 13 inches (15, 25, and 33 cm). Each font was tested once with amber letters (red and green LEDs that constitute a character pixel at 100 percent) and once with white letters (all LEDs that constitute a character pixel at 100 percent).

Markers were laid out on the ground on a line perpendicular to the face of the sign at intervals that were multiples of 15 ft (4.6 m). Specific distances where markers were placed were 180, 270, 300, 315, 360, 390, 405, 450, 525, 581, and 600 ft (55, 82, 91, 96, 110, 119, 123, 137, 160, 177, and 183 m). On alternating trials, participants were tested at successively longer distances until they could identify no words, or successively shorter distances until they could identify all words. Each set of trials began with the participant standing at either the closest marker or at the 581-ft (177-m) marker. At the 581-ft (177-m) marker, a wall presented a physical obstruction that prevented testing at a precise multiple of 15 ft (4.6 m). Across participants, the beginning distances were roughly counterbalanced such that particular font sizes and colors were equally distributed between near or far markers.

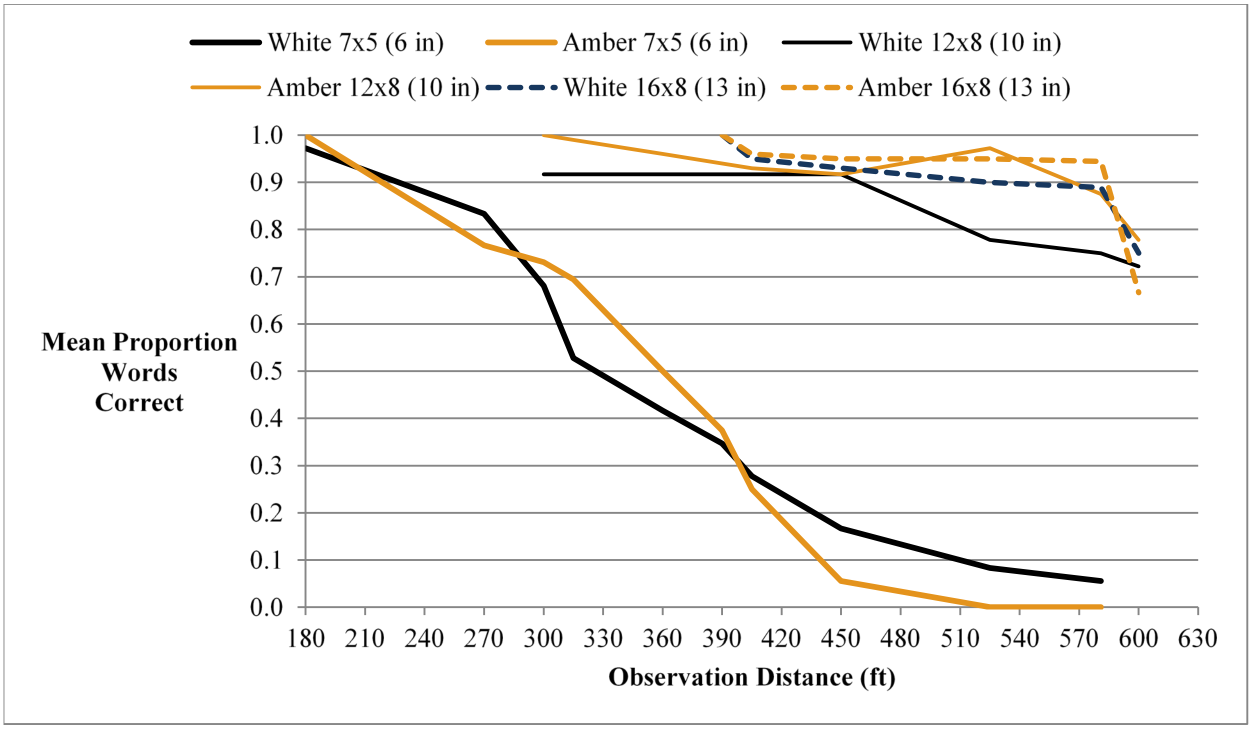
Fifty-nine six-word lists were available. No words were repeated within a list of six words. Each word could appear on up to three lists but not in the same serial order across lists.

Participants

Six individuals, five males and one female, were tested. All were Government or contract personnel who worked at the FHWA Turner-Fairbank Highway Research Center. The mean visual acuity of the participants was 20/17 (range 20/13 to 20/25) as assessed with the Landolt C module of the Freiburg Visual Acuity test.(48)

RESULTS

The mean proportions of six words that were correctly read at each distance are shown in figure 20. The MUTCD criterion for legibility distance for letters on static signs is estimated using 30 ft (9 m) per inch (2.5 cm) of letter height.(2) With 6-inch (15-cm) letter height, nearly all words could be read at 180 ft (55 m). With 10-inch (25-cm) letters, which the MUTCD method suggests should be legible at 300 ft (91 m), 92 percent of white lists and 100 percent of amber lists were read correctly. The MUTCD method suggests 13-inch (33-cm) letters should yield a legibility distance of 390 ft (119 m). At that distance, 100 percent of white lists and amber lists were read correctly. At 581 ft (177 m), 89 percent of 13-inch (33-cm) white character lists were read correctly.



1 inch = 2.54 cm
1 ft = 0.305 m

Figure 20. Graph. Legibility testing results.

Because the visual acuity measure used here is linear, and the relationship between letter height and legibility distance is linear, the CMS results can be easily compared with the MUTCD guidance for estimating legibility distance of standard highway signs of 30 ft/inch of letter height and assumes a minimum visual acuity of 20/40.

Assuming 90-percent correct word identification as the criterion for legibility distance, table 9 shows the results for this study for participants with a mean visual acuity of 20/17 and the linear extrapolation to what the results would have been with individuals having an acuity of 20/40, which is the minimum acuity required for a driver's license in most States.

Table 9. Observed legibility and linear transform of legibility distances for persons with 20/40 visual acuity.

	Observed With Mean 20/17 Acuity		Estimate for 20/40 Vision	
Character Height (inches)	Distance (ft)	Legibility Distance (ft/inch)	Distance (ft)	Legibility Distance (ft/inch)
6	220	37	94	16
10	460	46	196	20
13	590	45	251	19

1 inch = 2.54 cm
1 ft = .305 m;
1 ft/inch = 0.12 m/cm

Because of factors such as small sample size (*n* = 6) and testing a limited number of fixed differences, the results are not perfectly linear. However, they suggest that for persons with normal vision, the CMS characters yield a legibility distance of 40 to 45 ft/inch (4.8 to 5.4 m/cm) of letter height, and for persons with 20/40 vision 20 ft/inch (2.4 m/cm) would yield a reasonable estimate of legibility distance.

DISCUSSION

These results suggest the 0.79-inch (20-mm) pixel pitch full-color display used in this test provides a longer legibility distance than the previous generation of CMS displays that used a 1.6-inch (40-mm) pixel pitch with amber LEDs.(1) They also suggest that for the display type used, drivers with approximately 20/20 vision, the 90- to 100-percentile legibility distance can be conservatively estimated using a factor of 40 ft/inch of letter height (9 m/2.5 cm). It appears that amber characters may have slightly longer legibility distance than white characters, even though the amber characters use one-third fewer LEDs than the white characters.

The test reported in this chapter used participants who were standing still and not looking through a windshield. This would be expected to yield somewhat more accurate and somewhat longer legibility distances than those obtained from observers in a moving vehicle. The next chapter reports on legibility distances for stimuli viewed by drivers of a moving vehicle.

CHAPTER 4. CMS FIELD TEST

INTRODUCTION

The relevant properties of CMSs were reviewed in chapter 1. Chapter 4 describes testing of the effects of those properties on sign comprehension or message-recognition distance while drivers are engaged in navigating a shallow slalom course.

METHODS

The data were collected on a closed course while participants drove an instrumented vehicle that was equipped with a dashboard-mounted eye-tracking system.

Participants

Useable data were obtained from nine participants (six males and three females). The mean age of participants was 39 years old (minimum = 19, maximum = 61). Participants were paid $40/h for 3 to 5 h of participation. All drivers were licensed in Virginia.

Before they were scheduled for testing, participants provided signed permission for the investigators to obtain their records from the Virginia Department of Motor Vehicles. Individuals with more than one moving violation or police-reported crash in the preceding year or a driving while intoxicated violation in the preceding 3 years were excluded from participation. Upon arrival at the test facility, participants read and signed an inform consent form.

Test Facility

Testing was conducted on a 30-ft- (9-m-) wide drag strip. A CMS was placed on the left side of the drag strip 1,250 ft (376 m) from the start line. Traffic cones were placed on the track to form a 12-ft- (3.6-m-) wide lane that curved first from the left to the right side of the track, then back to the left, and ended in the middle of the track at the CMS location. The arrangement of the traffic cones is shown in figure 21. The purpose of the curved path was to require participants to attend to lane keeping in addition to viewing messages displayed on the sign.

Changeable Message Sign

The CMS was the same one used in the laboratory study (see chapter 2) and is shown in figure 22.

Figure 21. Photo. Layout of course on drag strip.

Figure 22. Photo. The CMS used in the study.

The brightness of the sign was set at 100 percent because the tests were conducted in daylight between 9 a.m. and 1 p.m. in fall 2012. At the 100-percent brightness setting, a white stimulus

12 inches (30 cm) in diameter measured between 3,065 and 3,502 fl (10,500 and 12,000 cd/m^2) depending on which location on the display was measured. A red stimulus measured a mean of 1,051 fl (3,600 cd/m^2) and an amber stimulus a mean of 3,094 fl (10,600 cd/m^2). Laboratory testing, reported elsewhere, showed that the display was compliant with NEMA standards for LED color displays intended for highway applications.(23)

Research Vehicle

Participants drove a 5-year-old full-sized sports utility vehicle equipped with a dashboard-mounted, three-camera eye-tracking system.(49) The system sampled eye vectors and head position at 60 Hz. Three scene cameras mounted on the roof of the vehicle, directly over the driver's head, recorded about 80 degrees (horizontal) of the driver's view of the road ahead. In post processing, the scene camera view was merged with the eye-tracking vectors. In addition to the eye-tracking data, direction measuring equipment, Global Positioning System, and accelerometer data were recorded and synchronized.

The sound recording capability of the eye-tracking system was not functional at the time these tests were conducted. Therefore, to capture participants' verbal responses, the experimenter operated a handheld voice recorder during each trial. Recordings were started as the participant maneuvered the research vehicle to the start line and stopped after the participant correctly spoke the message on the sign.

Message Types

Message Length

Current guidance suggests that CMS messages should be limited to three units of information. The unit of information concept is probably appropriate for most drivers, at least in the case where the posted information matches drivers' expectations. If the posted information does not match the typical questions a motorist might have (e.g., What? Where? Action?), then the number of words in the message would be a better metric for message length. In this experiment, the number of words on the CMS was varied from one through seven. Reading time and glance behavior were assessed for all participants with all message lengths. Because of the small size of the CMS that was used, the smallest available font size was used (7 pixels high by 6 pixels wide). The stroke width was 2 pixels and letter height was about 5.5 inches (140 mm). With allowance for some blooming of pixels, the letter height would be equivalent to 6-inch (152-mm) letters on a static sign. Only the first letter of each word was capitalized. Preliminary testing with stationary observers (see chapter 2) showed that these words became legible at 180 ft (55 m) for observers with 20/20 vision. All words displayed were appropriate for traffic-related messages, but the order of words was randomized so that each word represented one information unit. Each word was presented centered on a line. The following is the complete list of words used:

- Accident.
- Ahead.
- Blocked.
- Caution.
- Lane.

- Left.
- Merge.
- Move.
- Slow.
- Traffic.
- Use.

For any particular message, words were selected from the list and ordered randomly. Each participant received a different set of randomized words. To illustrate the font used for all messages, figure 23 shows one of the three-word messages that was used.

Figure 23. Photo. Example of a three-word message.

Flashing

The effects of flashing text were evaluated by displaying the same messages three different ways: (1) static messages (no flashing), (2) first of three lines flashing, or (3) entire message flashing. The flash rate was 1 Hz (on 0.05 s, off 0.5s). The following messages were used with slashes indicating line breaks:

- CRASH/MERGE/LEFT.
- DETOUR/EXIT 67/CLOSED.
- RIGHT/LANE/BLOCKED.
- TIME TO/RESTON/36 MIN.
- TRAFFIC/JAM/BE CALM.
- STOPPED/TRAFFIC/AHEAD.
- CRASH/USE ALT/ROUTE.

The fonts were all 14- by 10-pixel approximations of FHWA type E font. All messages were white (i.e., each illuminated pixel consisted of a fully illuminated red, green, and blue LEDs). Individual participants saw individual messages only once, with the messages randomly assigned to flash mode with the restriction that there was an equal number of trials in each mode.

Symbols Versus Text

This test compared gaze behavior and reading time between pairs of symbol images of traffic signs from the MUTCD and the equivalent text messages for the same signs. Except for the interstate shield text equivalent, all text messages used a 14- by 10-pixel approximation of the FHWA type E font. The text messages were all displayed with positive contrast. The text color was appropriate for the type of message: yellow for warnings, white for the interstate designation, and orange for the work zone sign. The symbol signs and text equivalents are listed in table 10.

Table 10. Signs used for comparisons of symbol- and text-sign reading time and glance behavior.

MUTCD Symbol Sign Designation	Text Alternative
W2-1	intersection ahead
M1-2	interstate shield (I-95)
W2-4R	right lane ends
W3-5	speed reduction (45 mi/h)
W2-6	roundabout ahead
W3-1	stop ahead
W3-3	signal ahead
W21-1a	workers

1 mi/h = 1.6 km/h

Abbreviations

To test the effect of abbreviations on gaze behavior and reading time, MUTCD-approved abbreviations for use on portable message signs were used. The abbreviations used and the phrases in which they were used are shown in table 11.

Table 11. Vocabulary for abbreviations test.

Word	Abbreviation	Message Context
Road	RD	ROAD CLOSED
Avenue	AVE	PARK AVENUE
Center	CNTR	CENTER LANE CLOSED
Normal	NORM	NORMAL TRAFFIC
Feet	FT	100 FEET
South	S	I-495 SOUTH
Mile	MI	NO EXIT NEXT 60 MILES

1 ft = 0.305 m
1 mi = 1.6 km

With one exception, three fonts were used in the abbreviation test: (1) an approximation of FHWA series E that was 14 pixels high by 10 pixels wide, with a stroke width of 2 pixels; (2) an approximation of FHWA series B that was also 14 pixels by 10 pixels with a 2-pixel stroke width; and (3) a manufacturer-supplied 14- by 8-pixel font with a 2-pixel stroke width. Thus, all three fonts were 11 inches high (or 12 inches if a blooming effect is assumed), and all had a 2-pixel stroke width. The choice of font for particular messages was based on the need to use only whole words on a line and the limitation to three lines of text with adequate spacing between lines. The one exception was the abbreviation for south. To approximate the FHWA interstate shield as closely as possible, "I-495 S" and "I-495 SOUTH" were displayed using two fonts: I-495 was in a 16- by 10-pixel font with a 3-pixel stroke width, and SOUTH and S were displayed in a 16- by 8-pixel font with a 2-pixel stroke width.

Phasing or Paging

When a message is too long to fit on one screen, an option is to display the message in a sequence of screens. This is referred to as phasing. The MUTCD limits phasing to two screens or pages.(2) Each screen must be interpretable by itself, and the order in which the two screens are read should not matter. The manual indicates that the legibility distance of messages should be greater (larger text should be used) when messages are phased because it will take drivers more time to read the message. However, the manual provides no guidance on how much larger the text should be and indicates that letter heights greater than 18 inches (46 cm) will not improve legibility distance.

The two-phase messages used in this study were compliant with the manual's regulations and guidance. Only two- and three-line messages were displayed in any single phase. Two phases were used, with each phase displayed for 3 and 0.3 s of blank screen between phases. Each phase was intended to be understandable without reference to the other phase. Only one unit of information was displayed on a line. The messages used in the phasing trials are shown in table 12. Rather than compare the same eight messages in two phases against the same messages presented in one phase, the static messages from the flashing set of trials were used as comparison items. Although not a perfect match, static messages contained a similar number of words and information units (see the bulleted list in the previous section Flashing).

Table 12. Eight two-phase messages used for phasing trials.

Phase	Message Used			
Phase 1	USE EXIT 27	CRASH SR 123	KEEP RIGHT	SLOW TO 25 MPH
Phase 2	CIRCUS TRAFFIC	USE SR 267	DEBRIS IN ROAD	JAM AHEAD
Phase 1	POLICE ACTION	PREPARE TO STOP	ROAD CLOSED	SIGNAL OUT
Phase 2	DO NOT ENTER	ROAD BLOCK	USE EXIT 2	4-WAY STOP

Table 13. Comparison of static message length to phased message length.

Static Message	Number of Words	Information Units	Phased Message	Number of Words	Information Units
Crash Merge Left	3	2	Circus Traffic Use Exit 27	5	2
Detour Exit 67 Closed	4	3	Crash SR 123 Use SR 267	6	3
Right Lane Blocked	3	1	Keep Right Debris in Road	5	2
Road Work Ahead	3	2	Slow to 25 mph Jam Ahead	6	2
Time to Reston 36 Minutes	5	2	Police Action Do Not Enter	5	2
Traffic Jam Be Calm	4	2	Prepare to Stop Road Block	5	2
Stopped Traffic Ahead	3	2	Road Closed Use Exit 2	5	2
Crash Use Alt Route	4	2	Signal Out 4-Way Stop	4	2
Mean	**3.625**	**2**	**Mean**	**5.125**	**2.125**

1 mi/h = 1.6 km/h

Font

When viewed from an appropriately long distance, full-matrix CMSs are capable of emulating FHWA typefaces that include lowercase text. In search tasks, such as looking for a street name on navigation signs, uppercase/lowercase text can result in longer recognition distances, presumably because the shape of words with ascending and descending characters can be recognized before the individual letters become identifiable. Unfortunately, the number of fonts with true ascenders and descenders was limited with the equipment provided for this test. The messages used in the font comparison trials are listed in table 14. Only the uppercase/lowercase "left lane block" and "normal traffic" messages contained true ascenders. None of the messages contained descenders (e.g., the letter "p" in open did not descend below the line of the other characters). Thus, the current test examined the effects of uppercase versus pseudo mixed-case messages.

Table 14. Messages used for comparison of recognition performance between all uppercase messages and messages in pseudo uppercase/lowercase.

Uppercase	Lowercase
HOT LANE OPEN	HOT Lane Open
LEFT LANE BLOCK	Left Lane Block
ROAD WORK NEXT	Road Work Next
SLOW SPEED 1 MI	Slow Speed 1 Mi
NO EXIT NEXT 60 MILES	No Exit Next 60 Miles
NORMAL TRAFFIC	Normal Traffic

Participants were exposed to both uppercase and mixed case versions of each message. The order of mixed case and all uppercase versions was varied across participants, and the different versions of the same message were separated by at least five trials with unrelated messages, which included messages related to other issues (e.g., phasing or message length).

Test Procedures

A total of 146 messages were prepared. Individual participants were each shown about 60 of the messages (range 55 to 70) such that each sign was shown approximately the same number of times across all participants. The order in which signs were shown was randomized for each participant, subject to the constraint that the same message in a different format (e.g., font, case, and abbreviation) did not occur more than once in any series of five messages.

Participants were instructed to begin each trial at the approach to the left start line. There they waited for an experimenter in the backseat to signal that the data recording equipment was ready. At that point, participants were to briskly accelerate to 25 mi/h (40 km/h) and to maintain that speed while they attempted to read the CMS message. Participants were instructed to read the message aloud as soon as practicable while still maintaining 25 mi/h (40 km/h) and staying within the marked lane.

RESULTS

The data recorded by the eye-tracking system were analyzed using software that related regions of interest (ROIs) marked by an analyst on video records of the forward view to gaze vectors determined by the eye-tracking software. For this study, one ROI was marked for each trial. This ROI covered a rectangular area about the sign that subtended approximately 2 degrees of visual angle regardless of the distance from the sign. A representative ROI captured at three locations within a trial is shown in figure 24 through figure 26. Figure 24 is at the beginning of the trial, approximately 1,250 ft (381 m) from the sign. Figure 26 shows the same ROI just before the sign is passed. The 2-degree size of the ROIs was chosen for two reasons: (1) it represents what is generally considered the area subtended by the fovea, the region of the retina used to capture scene details; and (2) it represents the approximate radial accuracy of the dashboard-mounted eye-tracking system.

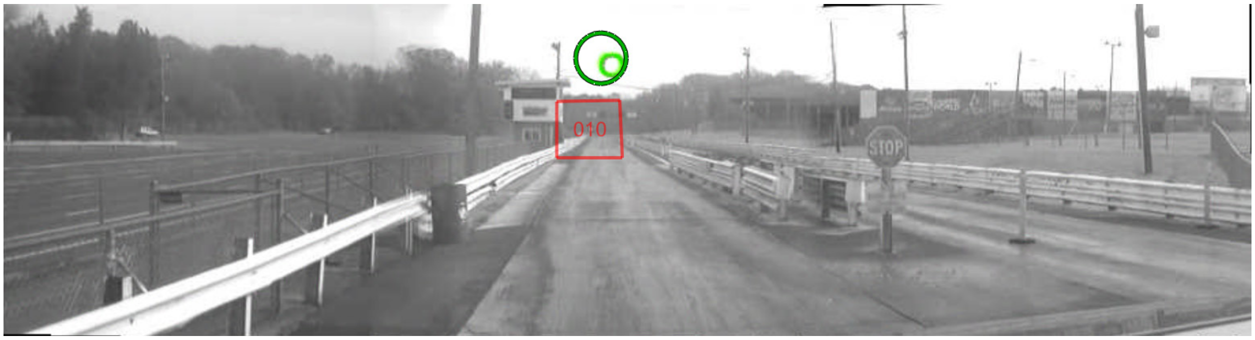


Figure 24. Screen capture. Two-degree ROI for the CMS at a distance of approximately 1,250 ft (381 m).

Figure 25. Screen capture. Two-degree ROI for the CMS approximately halfway down the slalom course.

Figure 26. Screen capture. Two-degree ROI for the CMS toward the end of a run.

The primary measure of eye-movement behavior was the look. A *look* was defined as any accumulation of four or more hits on an ROI within a series of six frames (one frame equals 0.017 s; six frames equals 102 ms). A look began when this criterion was first met and terminated when the number of hits within the preceding six frames dropped below four. The number of looks and the duration of looks were analyzed.

In addition to eye-tracking measurements, two measures were extracted from the voice recordings of participants: (1) trial duration—time from the beginning of a trial until the participant completed correctly reading aloud the message on the sign and (2) response duration—the time between when the participant began repeating the message aloud and when the participant completed reading the message. All measures were to the nearest second.

Response durations of zero length could result when responses were rounded to the nearest second. Trials always began with the vehicle at a full stop. The beginning of trials were marked when the sound of the engine revving was noted in the recordings.

All statistical tests employed General Estimating Equation (GEE) models. Analyses of frequency data assumed a Poisson distribution. Analyses of look durations assumed a gamma distribution. All analyses of vocal response assumed a Poisson distribution.

Note that in evaluating time differences, the vehicle traveled at about 25 mi/h (40 km/h) so each second that elapsed equated to about 37 ft (11 m) traveled.

All error bars shown in the charts below represent 95-percent confidence limits about the expected means.

Message Length

Neither the mean number of looks to the sign nor the average duration of each look varied significantly as a function of message length. As can be seen in table 15, the mean number of looks was surprisingly large, and the mean look duration was brief.

Table 15. Number of looks to messages and look duration as a function of the number of words in the messages.

	Message Length (Number of Words)						
Looks	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Number of looks	30	38	35	28	37	39	51
Mean duration of looks (s)	0.120	0.104	0.123	0.116	0.118	0.135	0.135

Given the large number of looks—far more than would be necessary to read a seven-word message—it appears that many of the looks were made for the purpose of determining whether the sign was near enough to be read. Standard road signs typically get far fewer looks, probably because drivers have far more experience reading standard signs and thus know when they should become legible, but also because drivers are not typically tasked to read standard signs as soon as possible, which was the instruction for reading the CMS.(50) The relatively short mean durations are not concealing single long glances. Across all participants and all message lengths, the longest recorded look was 0.46 s to a six-word message.

There was a significant effect of message length on trial duration, $\chi^2(6) = 92.5$, $p < 0.001$. This effect can be seen in figure 27. Response duration showed a similar significant trend, $\chi^2(6) = 123.9$, $p < 0.001$. Response durations are shown in figure 28. These two measures share the same end-of-response time and are correlated to the extent that the start of reading time is independent of message length. It appears the measures are highly correlated.

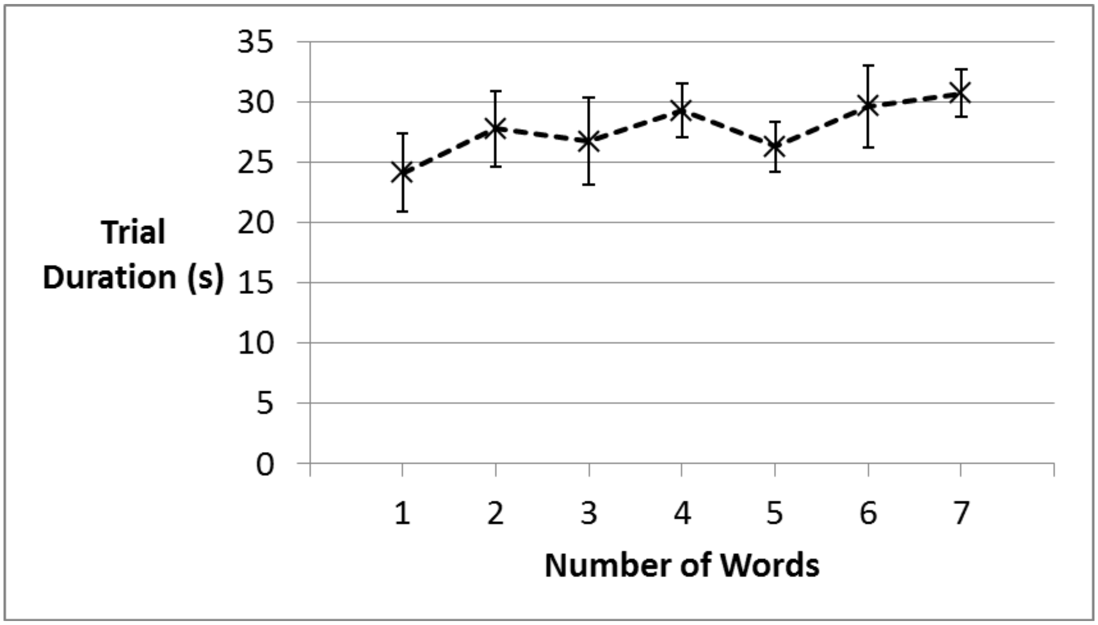


Figure 27. Graph. Expected mean trial duration as a function of the number of words in the CMS message.

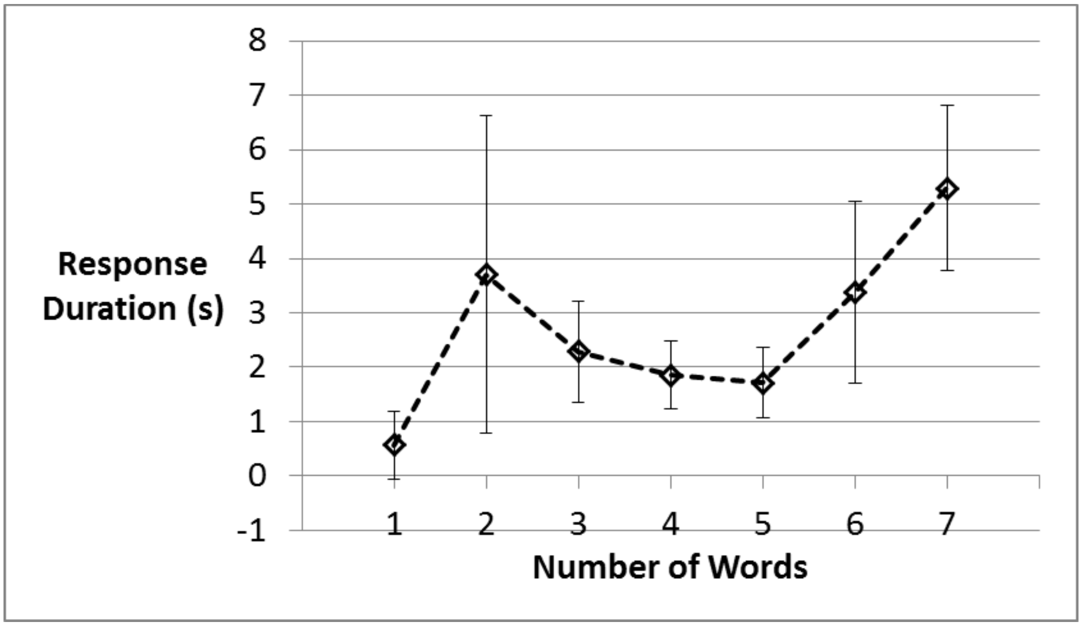


Figure 28. Graph. Expected mean response duration as a function of the number of words in the CMS message.

Flashing

The duration of looks and number of looks did not vary significantly at the $p < 0.05$ level. However, given the small sample size in the study, it may be worth reporting a trend favoring static and all-lines-flashing messages over messages with the first line flashing. The duration of looks to static and all-lines-flashing messages were nearly the same, 0.13 s. The expected mean duration of looks in which the first line flashed and the second and third lines were static was

0.17 s. The test for differences between the means approached significance, $\chi^2(2) = 5.48$, $p = 0.06$. There was also a non-significant trend ($\chi^2(2) = 3.78$, $p = 0.15$) for first-line-flashing messages to receive more looks. The expected mean number of looks is shown in table 16 as a function of message type.

Table 16. Expected mean number looks to messages in the flashing text trials.

Message Type	Expected Mean Number of Looks	Lower .95 Confidence Interval Limit	Upper .95 Confidence Interval Limit
Static	31	24	40
First Line Flashing	36	29	44
All Lines Flashing	27	20	35

The voice response main effects for both trial duration ($\chi^2(2) = 13.2$, $p = 0.001$) and response duration ($\chi^2(2) = 8.5$, $p = 0.015$) were significant, and support the contention that static or all flashing messages result in more efficient message transmission than first-line-flashing messages. Figure 29 shows the expected mean trial duration, and the expected mean response duration. From the start of the trial, responses were completed about 1.5 s later when all lines were flashing than when all lines were static or only the first line flashed. Responses were longest when only the first line flashed.

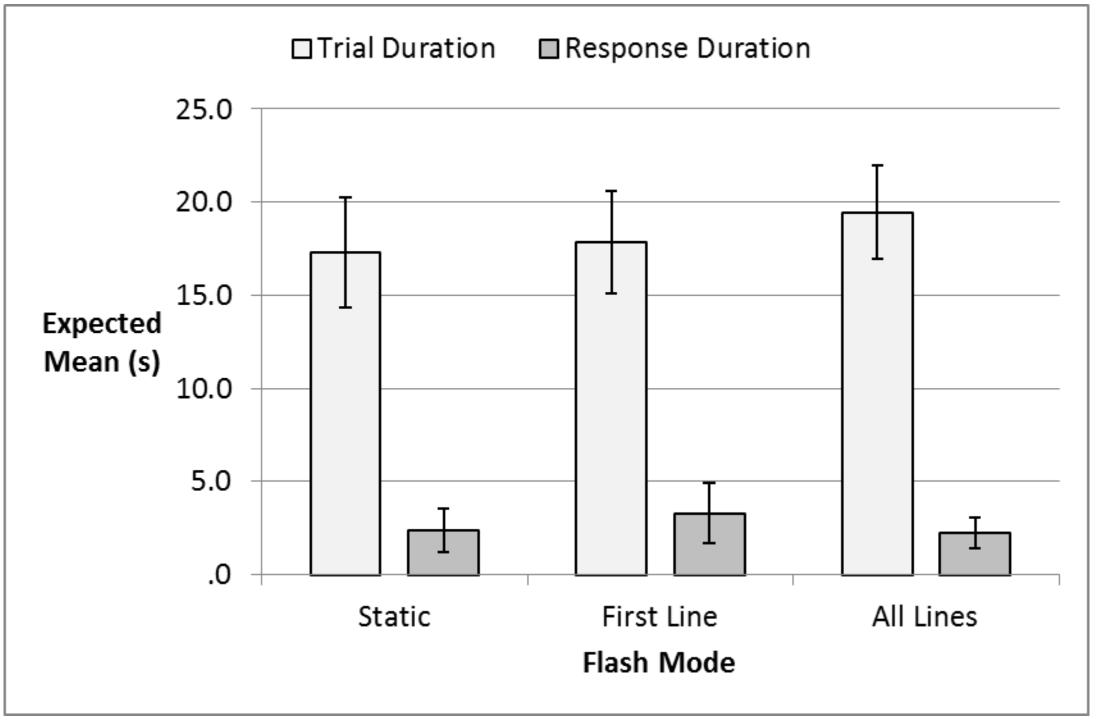


Figure 29. Chart. Trial duration and response duration as a function of flashing mode.

Symbols Versus Text

There were no significant differences in look durations or number of looks between symbol signs and their text equivalents.

Participants responded about 3 s sooner (i.e., trial duration was 3 s shorter) to the symbol signs (expected mean trial duration, 12.1 s ±3.8) than they did to the text-based equivalents of those signs (expected mean, 15.4 s ±3.25), $\chi^2(1) = 6.4$, $p = 0.012$.

Although the symbol signs' meanings were generally recognized sooner, and thus yielded shorter trial durations than the text equivalents, the workers symbol sign was an exception. As can be seen in figure 30, the mean trial duration for the workers symbol sign was more than twice that for the text based version, $\chi^2(1) = 16.4$, $p < 0.001$.

The total number of looks at the workers symbol sign was significantly greater than to its text equivalent, $\chi^2(1) = 13.5$, $p < 0.001$.

Although the workers symbol sign was probably legible from as great or greater distance than the ROAD WORK sign, several participants struggled to interpret the sign and made comments such as "what is that?", and then made several incorrect guesses before generating a plausibly correct response such as "person sweeping." This suggests that the symbol is not easily comprehended.

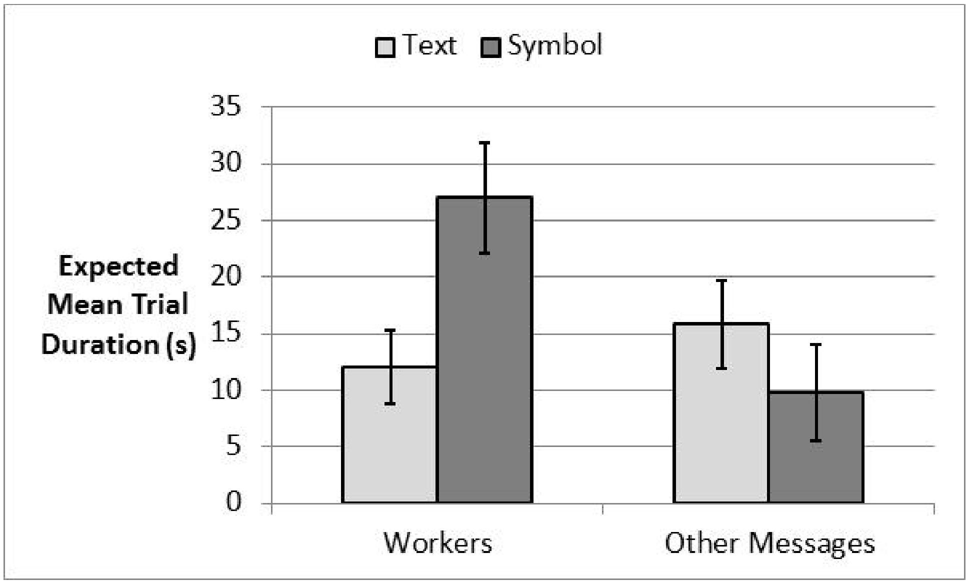


Figure 30. Chart. Comparison of trial durations for workers symbol signs with other text and symbol signs.

Abbreviations

There were no significant differences in look durations or number of looks between messages with FHWA-approved abbreviations and complete word messages. Also, there were no significant differences in either trial duration or response duration.

Phasing or Paging

As shown in figure 31, there were significantly more looks at two-phase messages than one-phase messages, $\chi^2(1) = 8.77$, $p = 0.003$. The duration of these looks did not vary significantly (static message expected mean = 0.136 s, phased message expected mean = 0.151 s).

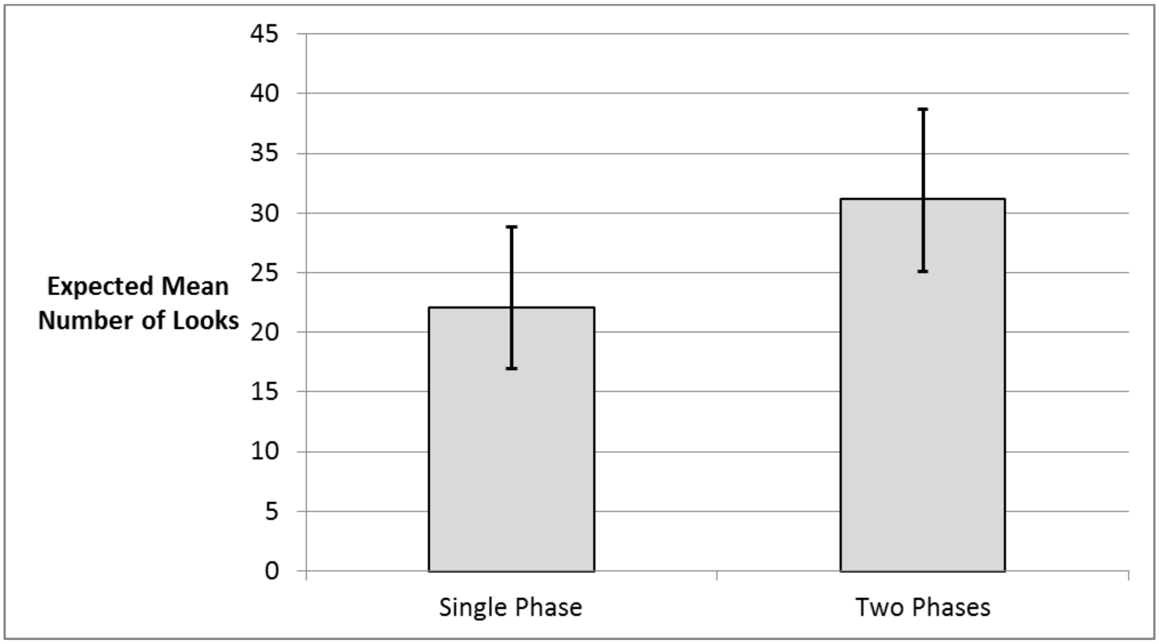


Figure 31. Chart. Expected mean number of looks at CMSs as a function of the number of message phases.

Trial durations were longer by about 3.5 s with phased messages than with static messages, $\chi^2(1) = 12.0, p = 0.001$.

Case

There were no significant effects observed in the font trials—look duration, number of looks, trial duration, and response duration effects were all non-significant.

DISCUSSION AND CONCLUSIONS

In these tests, drivers made a large number of looks to the CMS. Because they were instructed to read aloud the messages as soon as possible, the simplest explanation for this is that participants needed to repeatedly look at the sign to determine when they could begin responding. Whether this finding has any practical significance for CMS applications is uncertain. For static signs, far fewer looks are typically observed. However, drivers presumably have a great deal of experience with static signs, so they may have reasonably good expectations regarding when they should attend to them. Also, the messages on static signs are predictable from context and are fairly standard, so a brief look may be enough to confirm a driver's expectations. CMSs vary more than static signs in legibility distance, partly because the technology used varies and, at least for older CMSs, the legibility distance decreases with the age of the sign. For these reasons, drivers may start looking at CMSs as soon as they are detected. To the extent that CMS messages are less predictable than static sign messages, drivers may need to maximize the distance at which they attend to messages to allow for the extra processing (i.e., reading time) unpredictable messages will require.

On-road eye-tracking observation in which drivers were not instructed to read CMS messages would be needed to clarify whether CMS messages get more looks than static signs. However, in the driving simulation experiments described in the following chapters, large numbers of looks at simulated CMSs were not observed. In fact, there was some evidence that drivers in those studies could read unexpected CMS messages without fixating directly on the signs. In those studies, the messages were in large letters that could be read from at least 800 ft (244 m) away and were positioned over the roadway.

Message Length

The duration of trials increased with the number of words in messages. However, the differences in response duration and trial duration were negligible when messages contained two to five words. Six- and seven-word messages required 4 or 5 s more response time than shorter messages. Although the FHWA guidance on limiting the number of units of information on a CMS to three is valid, the findings of this study suggest that the total number of words is also important and should be limited to five or fewer whenever possible.

Flashing

First-line-flashing messages required more looks than static or all-lines-flashing messages. First-line-flashing messages also had longer response durations than the other two modes. The all-lines-flashing mode had the longest delay before participants completed responses (trial duration). Together these findings support the MUTCD prohibition of flashing messages.(2)

Symbols Versus Text

The present findings support the use of symbols on CMSs, at least in the case where the symbols are already familiar to drivers. The advantage of symbols is that they are recognizable from longer distances than are text messages that require similar display area. The finding that the ROAD WORK symbol sign yielded worse performance than its text-based alternative is important. To provide an advantage, symbols must be familiar or easily comprehended. Symbols that are not quickly comprehended by a large percentage of the population may result in driver distraction while drivers contemplate the symbol's intended meaning. For standard warning signs, placards are sometimes used to familiarize drivers with the meaning of novel symbols. This practice would not be appropriate for symbols on CMSs, because the use of text with symbols would necessitate reducing the size and thus the legibility distance of both text and symbols.

Abbreviations

The present findings support current FHWA policy regarding the use of abbreviations as specified in the MUTCD.(2) Approved abbreviations appear to have no effect on driver performance compared with full-text messages. Abbreviations not approved for use on portable messages signs were not evaluated in the present study, and therefore these findings should not be generalized to abbreviations not in the MUTCD.

Phasing or Paging

Phased messages take longer to read than static messages and should be avoided. In the present tests, all two-phase messages were successfully read. The CMS was within an unobstructed line-of-sight for 1,250 ft (381 m), and the vehicle was traveling at 37 ft/s (11 m/s) so that the drivers had about 30 s to view the messages, although the messages may not have been legible for the entire distance. In real-world driving, other vehicles, roadway geometry, and other TCDs may limit viewing distance more than observed in these tests. If two-phase messages are used, it should not be assumed that drivers will have time to safely read them. Therefore, safety-critical messages should not be phased.

Case

All performance differences between uppercase and proper case (uppercase/lowercase) fonts were non-significant. With all four metrics, the actual differences favored the uppercase messages. These results provide no reason to change the current policy, as specified in the MUTCD, which favors the use of only uppercase messages except when emulating guide signs.(2)

The CMS used in this study, a full-color, full-matrix, LED display with 0.79-inch (20-mm) pixels, is legible from distances approaching those of static highway signs. The capability to display symbols and provide high-contrast messages in text in most lighting conditions, is expected to greatly increase the effectiveness of CMS messaging compared with earlier CMS technologies.

CHAPTER 5. THE EFFECT OF REPEATED IRRELEVANT CMS MESSAGING ON THE DETECTION OF SAFETY-CRITICAL MESSAGING

INTRODUCTION

This experiment was one of a series to determine how signing within the right-of-way affects driver behavior. The focus of this experiment was to examine the potential for driving-irrelevant information on a CMS to cause drivers to lose respect for traffic-related messages on CMSs.

The present study had two purposes: (1) to document how driver gaze behavior would be affected by different information types on CMSs and (2) to evaluate whether drivers might be more inclined to ignore critical safety-related messages if frequently exposed to driving-irrelevant information on CMSs.

METHODS

The FHWA highway driving simulator was used to simulate CMS messaging in a freeway environment. An eight-lane freeway was simulated (four lanes in each direction). An overhead CMS was located every 0.5 mi (0.8 km) over a distance of 48.5 mi (78.1 km). One group of participants was presented with CMSs that displayed frequently changing faces every mile and travel-time messages interspersed between the faces signs. Another group saw blank overhead signs every mile with travel-time messages interspersed between the blank signs. The 97th sign was the same for all drivers. The three-line message on that sign read "ACCIDENT AHEAD/ALL LANES CLOSED/USE NEXT EXIT." Two major hypotheses were tested: (1) whether drivers looked more at signs with frequently changing salient color images than at blank or travel-time signs, which might suggest the salient images distract drivers from their primary task—monitoring the road ahead and (2) whether drivers exposed to visually salient non-traffic-related messages on overhead signs would habituate to or lose respect for the overhead signs and thus fail to detect a critical instruction to exit the freeway. The relationship between following distance and gaze behavior was also examined.

The Simulator

The simulator's screen consisted of a 240-degree portion of a cylinder with a radius of 8.9 ft (2.7 m). Directly in front of the driver, the design eye point of the simulator was 9.5 ft (3 m) from the screen. The stimuli were projected onto the screen by five Barco™ projectors with resolutions of 2,048 pixels horizontally by 1,536 pixels vertically. Participants sat in a late-model compact sedan as shown in figure 32. The simulator's motion base was not enabled in this experiment. The car's instrument panel, steering, brake, and accelerator pedal all functioned in a manner similar to real-world compact cars.

Figure 32. Photo. FHWA highway driving simulator.

The simulated vehicle was equipped with a hidden intercom system to enable communications between the participant and a researcher who ran the experiment from a control room. The researcher in the control room could also view the face video from the eye-tracking system and thereby monitor the participant's wellbeing.

The Simulation Scenario

A 1.5-mi (1.6-km) section of freeway without overhead signs preceded the first CMS. Each CMS spanned all four lanes and approximated the dimensions of a sign 56 ft (17 m) wide by 8.6 ft (2.5 m) high. Because of limitations in the resolution of the simulator's projectors, all signs in the simulator were oversized so that their legibility distance approximated real-world legibility distances. In this experiment, signs were 1.75 times the size of their real-world equivalent. Thus, the simulated overhead signs were sized to approximate the legibility distance of an overhead sign of approximately 32 ft (10 m) wide by 5 ft (2 m) high. A sign of this size with 0.79-inch (20-mm) pixel pitch would enable a display of 488 pixels horizontally and 76 pixels vertically. Before being made oversize, the simulated letter height of the CMS text was 18 inches (46 cm).

Two scenarios defined the between-groups experimental manipulation. One scenario included human faces on every other CMS. The other scenarios simulated no message (blank) on every other CMS. In both scenarios, travel times to a hypothetical destination were displayed between the signs that defined the experimental manipulation. A typical travel-time message is shown in figure 33.

Figure 33. Photo. Travel time to McLean was displayed once per mile.

Thirty-four faces were displayed in sequence on each of the faces signs. Each face was displayed for 3 s, and the entire series of faces repeated throughout the experiment. It has been shown that human faces attract and hold attention as few other stimuli can.(51,52) The face stimuli were captured from two sources: non-copyrighted celebrity photographs from the Internet and selected faces from the International Affective Picture System.(53) On the signs that displayed faces, the backgrounds also varied. Thus, on the approach to any faces sign, the participant might be exposed to four or more faces. The location of the faces on the signs varied, either left, center, or right such that faces photographed from the left side were displayed on the right side of the display, faces photographed straight on were centered on the display, and faces photographed on the right side were displayed on the left side of the display. A representative faces sign is depicted in figure 34.

Figure 34. Photo. Faces serving as salient but driving-irrelevant information.

The 97th sign, with the instruction to exit the freeway, is depicted in figure 35. To make the driving task more realistic and visually demanding, vehicle traffic was simulated. The VISSIM traffic model was used to generate the behavior of vehicles in the traffic stream. Because the random number seed for the traffic model was always the same, all participants were immersed in the same traffic stream. However, because participants controlled their own speed, acceleration, and lane choice, participants could experience different traffic conditions in their immediate surroundings.

Figure 35. Photo. Accident ahead message.

At the beginning of test sessions, 5,000 vehicles/h (1,250 vehicles/h per lane) were generated for 6.7 min. Participants were instructed to begin driving 2.5 min into this period of traffic generation. Thereafter, approximately every 3 mi (4 km), 500 vehicles/h would exit the freeway at off ramps, and 500 vehicles/h would merge into the traffic stream from on ramps. One elderly participant was reluctant to drive at the posted speed limit of 65 mi/h (105 km/h) and eventually was passed by the entire traffic stream. That participant was replaced. There were off and on ramps every 1.5 mi (2 km), although the traffic model populated only half of them with traffic.

Participants were instructed to maintain 65 mi/h and to drive in the second lane from the right, except when they wanted to pass. This instruction resulted in most participants staying within the initially generated traffic flow throughout the experiment. The full instructions were as follows:

> You will be driving on a freeway that has four lanes in the direction you are traveling. There will be other vehicles on the road, although traffic should not be heavy. You should obey the law and drive as you normally would. The posted speed limit is 65 miles per hour. Please drive in the second lane from the right except when you want to pass slower moving vehicles. Your destination is McLean. This is a relatively long trip and may take an hour. We will be recording how you drive and where you look. Please drive as you normally would. However, if you arrive at your destination (McLean) within 3 minutes of the time you would arrive if driving at the posted speed limit, you will receive a $10 bonus. Do you have any questions?

For most of the 51 mi (82 km) of simulated freeway, the speed of other vehicles followed the cumulative probability distribution shown in table 17. However, congestion was simulated beginning 2,081 ft (634 m) upstream of sign 6 and again every 15 signs (upstream of signs 21, 36, 51, 66, and 81). Upon entering congested areas, each simulated vehicle decelerated at a desired rate of 6.6 ft/s (2.0 m/s). After decelerating in these areas, all other vehicles traveled between 30 and 45 mi/h (72 and 48 km/h) according to the desired cumulative probability distribution shown in table 18. Each congestion area continued for 1,200 ft (366 m) and was followed by a 300-ft (91-m) zone in which vehicles accelerated back toward their normal desired speed. Note that the desired speed or acceleration might not have been realized where another leading vehicle provided impedance. In addition, simulated traffic changed lanes to achieve its desired speed or to prepare to exit. The congested areas were included to challenge participants' attention and reduce boredom on the drive, which lasted approximately 45 min.

Table 17. Desired speed cumulative probability distribution of the simulated traffic stream.

Speed (mi/h)	Cumulative Probability
50.0–55.4	0.01
55.5–59.9	0.04
60.0–64.0	0.08
64.1–66.5	0.12
66.6–70.0	0.50
70.1–75.0	0.75
75.1–80.0	1.00

1 mi/h = 1.61 km/h

Table 18. Desired speed cumulative probability distribution at congestion locations.

Speed (mi/h)	Cumulative Probability
30.0–33.6	0.05
33.7–36.1	0.17
36.2–37.6	0.46
37.7–38.5	0.65
38.6–40.0	0.85
40.1–42.5	0.95
42.6–45.0	1.00

1 mi/h = 1.61 km/h

A short practice session preceded the test session. The original purpose of the practice session was to enable the participants to become accustomed to the handling characteristics of the simulated vehicle. However, pilot testing had shown that some participants thought they were supposed to stay on the freeway, regardless of CMS warnings. Therefore, the training session was modified to ensure that participants knew that it was expected that they should follow instructions on the CMSs. The modified training included a minimum of two CMSs that instructed participants to take the next exit. The practice session instructions were as follows:

> You will be driving on a simulated freeway that has no other traffic. The purpose of this five minute drive is to allow you to familiarize yourself with the steering, acceleration and braking of the simulated vehicle. At the start, you will be stopped in the second lane from the right. When we are ready, I will ask you to accelerate slowly to 25 mile per hour and drive within a lane. You will then be asked to brake to a full stop. After that, you will be asked to accelerate to 65 miles per hour

> and continue driving in the second lane from the right. There will be a changeable message sign with a traffic alert about a bridge out on your route. Follow the detour instructions on that sign.

In fact, once on the detour, another CMS was encountered that directed participants back onto the original route. In the practice session, if a participant failed to follow a detour instruction, the researcher would urge the participant to follow the directions on the next CMS that he or she encountered. In this way, all participants saw and followed the instructions of at least two detour messages on CMSs before beginning the main test session. Those who initially failed to follow the CMS directions were presented with three or more dynamic messages with detour instructions. The purpose of this practice was to maximize the probability that participants who read the final message sign in the test session (about 48 min later) would feel obligated to follow its instruction.

Eye-Tracking System

The simulator was equipped with a four-camera dashboard-mounted eye-tracking system that sampled at 120 Hz.(49) The system tracked horizontal gaze direction from approximately the location of the right outside mirror to the left outside mirror and vertical gaze direction from the instrument panel to the top of the windshield. Gaze direction accuracy varied by participant. The mean accuracy of gaze position across participants was 1.6 degrees (radius) with a 0.7-degree standard deviation. The eye-tracking data (e.g., gaze direction of each eye, head position, etc.) were merged with data from the simulator (e.g., vehicle speed, lane position, and steering wheel position) and the current forward view of the simulation visual scene (approximately 60 degrees horizontal by 40 degrees vertical). In addition, a separate dataset was recorded by the driving simulator of the distance between the front bumper of the participant's vehicle and the nearest simulated vehicle in the participant vehicle's forward path.

To quantify when and for how long participants looked at each CMS, a researcher used analysis software to indicate an ROI on individual frames of the recorded video image. An example of an ROI is shown in figure 36 (the halo around the sign). ROIs were created for the first 11 CMSs (signs 0–10), and signs 17–25, 32–40, 47–55, 62–70, 77–85, and 94–96. For each of these CMSs, glances at the ROIs were recorded for the last 10 s before the CMS began to pass out of the driver's view. This resulted in sampling an equal number of travel-time and experimentally manipulated signs at intervals throughout the session so that trends over time in glance behavior could be observed. Note that none of the zones coded with ROIs coincided with the zones that simulated congested traffic.

Figure 36. Photo. ROI indicated on CMS.

Participants

A total of 32 participants—16 males and 16 females—completed the study. All were licensed drivers from the Washington, DC, metropolitan area. The mean age of participants was 47 years (range 20–85). Twenty-four participants provided interpretable eye-tracking data. Otherwise useable data were obtained from eight participants for whom eye tracking was unsuccessful. The mean age of the 24 participants with good eye-tracking data was 45 years (range 20–79 years) and 11 were male. Only one participant reported a mild simulator sickness symptom (headache), and no participant dropped out as a result of simulator sickness.

RESULTS

Throughout this chapter, error bars in the charts and graphs represent 95-percent confidence limits around the means.

Response to the Incident-Related Detour Message

Of the 24 drivers for whom eye-tracking data were also available, 7 failed to respond to the message on the 97th sign by exiting the freeway. These results are shown in table 19. The difference in exit-taking behavior between blank and faces groups was not statistically significant by Fisher's Exact Test. Because there is an apparent trend, even if non-significant, for more drivers to fail to exit in the faces group, a second test was done that included all drivers who completed the study, regardless of the quality of their eye-tracking data. The data for this test are shown in table 20. With the additional participants included, there was no difference between the group presented with faces and that presented with blank signs (apparent or otherwise).

Table 19. Response to warning to take next exit by drivers for whom eye-tracking data were available.

Sign Type	Failed to Exit	Exited	Total
Blank signs	2	10	12
Faces signs	5	7	12
Total	**7**	**17**	**24**

Table 20. Response to warning to take next exit by all drivers who completed the drive.

Sign Type	Failed to Exit	Exited	Total
Blank signs	4	12	16
Faces signs	5	11	16
Total	**9**	**23**	**32**

The eye-tracking evidence for looking at the CMS is summarized in the following subsections. However, most of the participants were also asked during the post-experiment debriefing if they had read the message on the 97th sign. All participants who took the exit said that they had read the message—which seems reasonable given that no participant had taken any of the preceding 48 exits and the 49th exit differed only in that it was preceded by the accident ahead message. Of the nine drivers who failed to exit, seven were asked if they had read the message, and all but one of those also claimed to have read it. The one driver who claimed not to have noticed the warning was in the blank sign group.

Gaze Behavior

Gaze location was measured for the 10 s prior to reaching the point where the sign passed out of the driver's field of view. The areas defined by the 10 s approach are hereafter referred to as "data collection zones."

There are numerous issues to be considered in the analysis of eye-tracking data. The mean accuracy of the gaze location in this study was 1.6 degrees. Because foveal vision is limited to about 2 degrees of visual angle, examination of fine detail requires shifting the gaze to within 2 degrees of the details. At an actual or simulated distance of 1,000 ft (305 m), 2 degrees of visual angle includes an area of about 35 ft (11 m) in diameter. On a flat, level road, a driver whose gaze is centered on a vehicle 1,000 ft (305 m) ahead would also include three travel lanes and any sign within 17 ft (5 m) of the center of gaze within foveal vision. The lower edge of the simulated signs was 17 ft (5 m) above the travel lanes. Traveling at 65 mi/h (105 km/h), as participants were instructed to do in this experiment, 10 s of travel time would traverse 950 ft (290 m) of roadway.

Because the eye tracker sampled at 120 Hz, there was a new estimate of the center of gaze every 0.008 s. Despite the limits in accuracy, precision, and the size of the foveal area subtended at long distances, it can be expected that over time, the average gaze position will fall on the object of visual regard. Therefore the problem is to determine which 120-Hz hits on a target should be counted and which disregarded as noise or error. The analyses that follow employed three different methods for assessing when participants were looking at a CMS. These methods are referred to as glance, look, and fixation. They were defined as follows:

- **Glance.** Any accumulation of 12 (12 × 0.008 s = 100 ms) or more hits on an ROI, where a hit is a single 120-Hz center of gaze estimate that falls on the sign's ROI. This is the least restrictive definition of a gaze at a sign; it maximizes both the probability of correctly detecting a gaze as well as the probability of incorrectly identifying a gaze at something else as a gaze at the sign. For any ROI, this measure was binary; either a glance was recorded or it was not.

- **Look**. Any accumulation of 7 or more hits on an ROI within a series of 12 frames (100 ms). A look began when this criterion was first met and terminated when the number of hits within the preceding 12 frames dropped below 7. This criterion is more conservative than that for a glance but not as restrictive as the definition of a fixation. Also, unlike a fixation, a single look may include more than one gaze at different areas of a sign.

- **Fixation.** Seven consecutive gaze vector hits (60 ms) within a fixation radius of 4 percent of the vertical image height (i.e., 15 pixels on the 372-pixel image) and centered on the first of the 7 gaze positions that designated the start of a fixation. The fixation continued until there were six consecutive hits (50 ms) outside the fixation radius. For a simulated object 500 ft (152 m) ahead, the fixation radius subtended a visual angle of about 2 degrees. A fixation on an ROI was recorded if the center of the fixation was on the ROI. In practice, the fixation criterion is quite conservative in identifying a gaze at an ROI (relatively low probability of correct identification and relatively high probability of a miss) in part because of the restriction that the gaze should remain within a small area and therefore could not capture pursuit movements.

The convergence of the three ROI gaze criteria on the same conclusion should increase confidence in the research findings.

As indicated in the Eye Tracking section, gaze data were analyzed for a subset of 59 signs. Six data collection zones included the final portions of the simulated congestion. Given the proximity of these six zones to simulated congestion, it might be expected that time headways would be shorter there than in the remaining free-flow data collection zones. Because the experimental design includes repeated measurements and the time headways were not normally distributed, a GEE model was used to test for differences in headway as a function of data collection zone type. In this model, a gamma response distribution was assumed, and an identity link function was used. A gamma distribution was used because headways can never be zero or negative. For a discussion of GEE, distribution choices, and link functions, see Stokes, Davis, and Koch.(54) Mean headway in the 52 free-flow data collection zones, not including the zone with the accident ahead sign, was 335 ft (102 m). In the six zones in proximity to congestion, the mean headway was 241 ft (73 m). This difference was statistically significant, $\chi^2(1) = 15.98$, $p < 0.001$. Subsequently, analyses of glance, looks, and fixations were conducted separately for the 6 congestion zones and the remaining 52 free-flow zones. Where differences in gaze patterns were not significantly different between free-flow and congested zones, the data were combined.

Relationship Between Exit Taking and Gaze Behavior

All three measures of gaze behavior were used to assess whether exiting after passing the accident ahead message was related to whether participants directed their gaze to the message. No measure (i.e., glances, glance duration, number of looks, duration of looks, number of fixations, or duration of fixations) was related to whether or not participants took the exit. Table 21 shows the distribution of participants who took the next exit as a function of whether a glance was recorded. Although one participant who did not exit said she did not see the accident ahead sign, the glance data suggested otherwise. The participant who did not take the exit and did not have a recorded glance claimed to have seen the message and, in fact, attempted to exit but decided that traffic in the right lane prevented him from exiting.

Table 22 summarizes the various gaze metrics related to the critical CMS message. Note that the expected mean durations in table 22 include durations of 0.00001 s for participants who did not glance at the critical sign.

Table 21. Relationship between glance to the accident ahead message and taking exit.

Driver Action	Glance Recorded	No Glance Recorded
Took exit	16	3
Did not take exit	4	1

Table 22. Mean counts and mean durations for various gaze metrics to the accident ahead message.

Gaze Metric	Mean	Standard Deviation
Glance duration (s)	0.98	0.98
Number of looks	4.00	4.74
Look duration (s)	0.23	0.30
Number of fixations	2.58	2.47
Fixation duration (s)	0.27	0.29

Glance Results

The entire experimental drive lasted about 45 min. With sessions of this length, there was some concern that glance behavior might vary over time because of fatigue or boredom or because the perceived value of the sign content changed over time. To test these hypotheses, the proportion of signs glanced at in each of the seven groupings of zones described in the eye-tracking system section was examined. GEE models were used because the glance probability data contained repeated measurements and did not appear normally distributed. The order analyses assumed a binomial probability distribution with a logit (log odds) link function. The explanatory variables in the model were order (1, 2, 3, 4, 5, 6, or 7) and order squared (to test for linear and curvilinear order effects). The sign displaying the detour warning was excluded from the analyses. Results indicated that there were no linear or curvilinear trends in probability of glancing at signs as a function of order.

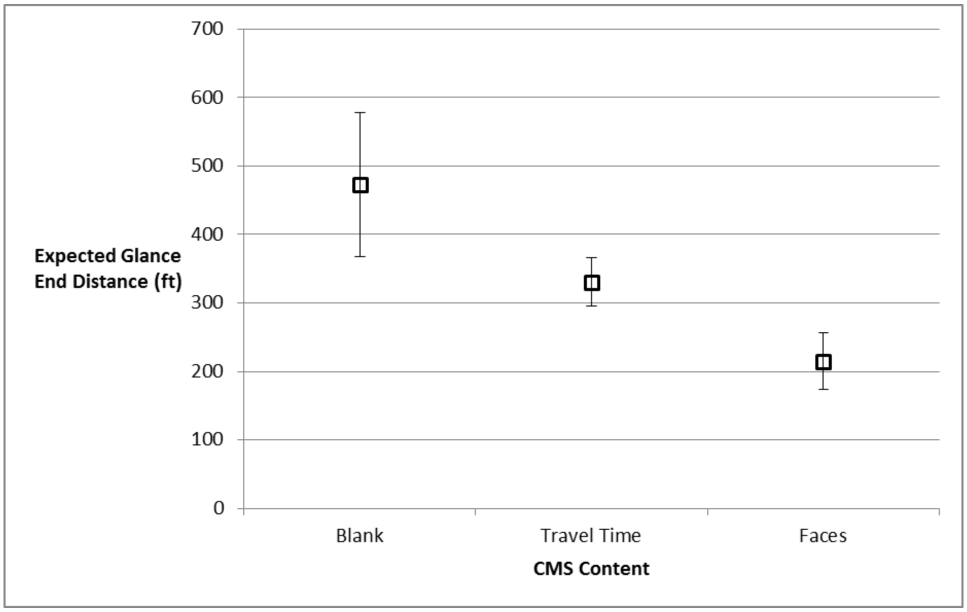
When closely following another vehicle, drivers might have less spare visual capacity for attending to CMSs. Because different individuals adopt different car-following strategies and because traffic conditions could vary along the route, time headway was considered in the analyses of the gaze data. Time headways were considered short if less than 1.5 s and long if greater than that duration. Over all data collection zones and all drivers, 75 percent of headways were greater than or equal to 1.5 s.

Each data collection zone was classified as containing a glance to the CMS in that zone (glance = 1) or not. GEE models were used to test the effects of sign content type, time headway, and their interaction on the probability of a glance. These analyses assumed a binomial response distribution with a logit link function.

Preliminary analysis showed there was no difference in the probability of a glance between faces and travel-time signs in either the 6 congested zones or the 52 free-flow zones. Nor were there glance probability differences between congested and free-flow zones. Therefore, zones with faces and travel-time signs were combined into a non-blank class, and the congestion classification was not used. The GEE analysis included sign type (blank or non-blank), headway (short or long), and the interaction of sign type and headway. The interaction was not significant. Participants had a higher probability of glancing toward the non-blank signs ($P_e = 0.55$) than toward the blank signs (expected probability ($P_e = 0.21$), $\chi^2(1) = 9.11$, $p = 0.003$). Participants had a higher probability of glancing toward a CMS when driving with a long headway ($P_e = 0.49$) than when driving with a short headway ($P_e = 0.38$), χ^2 (1) = 4.07, $p = 0.044$.

Given that a participant glanced at a CMS, the distances at which the glance started and ended were examined. Glance start distance was not significantly affected by sign content, traffic, or time headway. The mean glance start distance was 701 ft (214 m) before the CMS (25th percentile = 555 ft (169 m), 75th percentile = 901 ft (275 m)).

Expected mean glance end distance was related to sign content, $\chi^2(2) = 31.97$, $p < 0.001$. As can be seen in figure 37, expected mean glance endings were farthest from blank signs and occurred closest with faces signs. Post hoc tests showed all three end-distance means were significantly different from each other.



1 ft = 0.305 m

Figure 37. Chart. Expected mean distance from CMS at the last glance.

Beginning and ending glance distances were based on individual 120-Hz gaze samples at signs that received a glance. The location of the beginning and end of a glance did not provide an indication of the amount of time participants were glancing at the signs. To assess the amount of time participants gazed at the signs, the glance duration was computed using only those signs within a content type that received a glance. Recall that glance duration is the sum of all 120-Hz samples for which a gaze at the sign was recorded, regardless of when in the data collection zone these samples were taken. As a result, glance duration could be the sum of one continuous gaze or multiple 1/120-s gazes several seconds apart. A GEE model with gaze duration as the dependent measure and sign content, headway, and the interaction of sign content and headway as predictors were tested. The GEE model assumed a gamma response distribution with an identity link function. Sign content, headway, and the interaction effects were not significant. The estimated mean glance duration was 0.79 s (25th percentile = 0.50 s, 75th percentile = 1.08 s).

Look Results

Within each data collection zone, the number of looks at the CMS was calculated as a function of headway. The analysis included time headway as a grouping variable, where headways greater than 1.5 s were classified as long, and headways less than that were classified as short.

GEE models were used for hypothesis testing because the data contained repeated measurements and did not follow a Gaussian distribution.

Look Probability

The probability of at least one look at each sign was analyzed as a function of headway, sign content, and their interaction. Preliminary analyses showed no significant difference in the probability of looks at faces and travel-time signs, so in the GEE model that is reported, those two zones were combined, and the sign content variable became a comparison of blank signs with non-blank signs. The GEE model assumed a binomial distribution with logit link function. As can be seen in figure 38, both main effects were significant: participants were more likely to look at least once at non-blank signs than blank signs, χ^2 (1) = 4.35, $p = 0.037$, and at either type of sign when headways were long than when headways were short, χ^2 (1) = 31.31, $p < 0.001$.

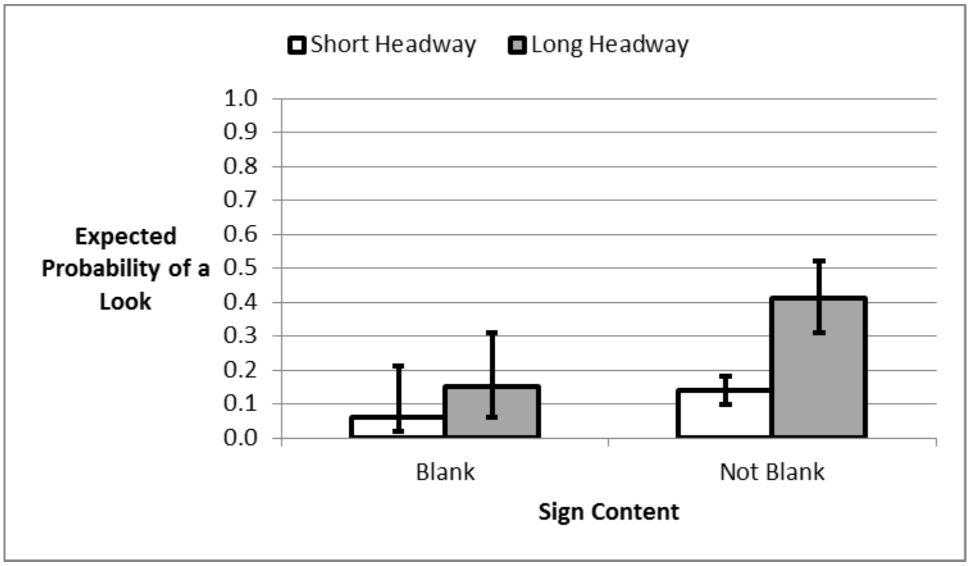


Figure 38. Chart. Expected probability and 95-percent confidence limits of at least one look at a CMS as a function of sign content (blank or not blank) and mean headway.

Number of Looks

The first model examined whether the number of looks at the CMS differed as a function of sign content and headway. This analysis excluded the six data collections zones where congestion was simulated, because the short headways in those zones attenuated the headway effect. As can be seen in figure 39, there was a significant interaction between sign content and headway, $\chi^2(1) = 9.62$, $p = 0.002$. Participants were more likely to take more looks at faces signs when headways were long than when headways were short, and took few looks at blank signs (regardless of headway). Faces and travel-time sign zones were compared in the same manner as blank and faces zones. In that analysis, the interaction of headway with the sign content did not reach statistical significance, χ^2 (1) = 3.24, $p > 0.05$. However, the trend was the same as in the faces zones, with more looks at travel-time messages when headway was long than when it was short.

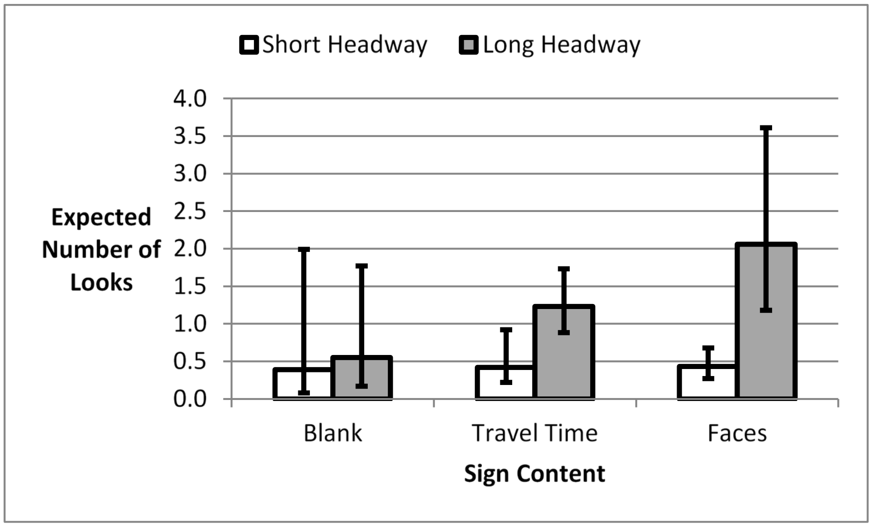


Figure 39. Chart. Estimated mean number of looks and 95-percent confidence limits as a function of sign content and time headway.

Look Duration

The duration of looks at the CMS was computed for all looks. (When the participant did not look at a sign, the duration was coded as missing.) The expected mean look durations computed from GEE models that assumed a gamma distribution with identity link function are shown in figure 40. An unexpected interaction between sign content and headway was found, $\chi^2(1) = 6.34$, $p = 0.012$, in which blank signs received shorter glances with short headways than with long, whereas travel-time and faces signs received longer glances with short headways than with long. All expected mean look durations fell within a narrow range of 160 to 210 ms, so it is not clear that this statistically significant interaction has practical significance, particularly in light of the low probability of looks with short headways.

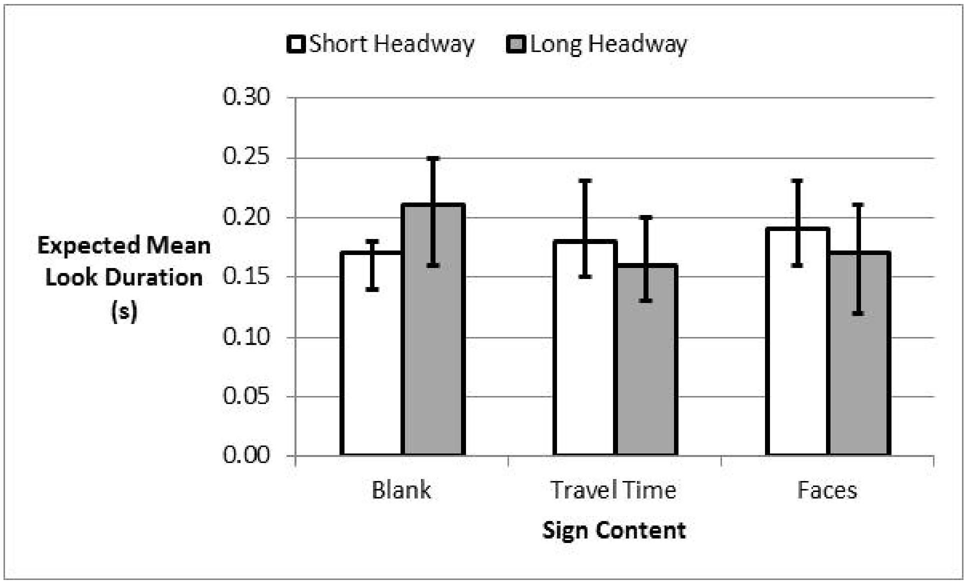


Figure 40. Chart. Expected mean look duration as a function of sign content and time headway.

Fixation Results

Fixation Probability

For each participant, the probability of at least one fixation on each CMS was calculated, and each data collection zone was classified as having either short or long mean time headway. Whether or not at least one fixation had occurred (fixation = 0 or 1) was the predicted variable in a GEE model that assumed a binomial response distribution with a logit link function. Predictor variables were headway, sign content, and the interaction of headway and sign content. Preliminary analyses indicated that congestion was not a significant factor so the analysis included all data collection zones and congestion was not included in the model. The only significant factor in the model was headway, $\chi^2(1) = 37.94$, $p < 0.001$. With headways greater than 1.5 s, the probability of at least one fixation on the CMS approached 0.3, whereas with a shorter headway, the probability of a fixation was about 0.1.

Number of Fixations

A GEE model with headway, sign content, and their interaction was used to analyze the number of fixations on each sign, given that at least one fixation was recorded. The GEE models assumed a Poisson response distribution with a log link function. No significant effects were obtained. Overall, for signs that received at least one fixation, the mean number of fixations was 2.27 (95-percent confidence limits 1.84 to 2.80 fixations).

Fixation Duration

Within each data collection zone, the duration of each fixation was calculated. Headway, sign content, and their interaction served as predictor variables in a GEE model that assumed a gamma response distribution with an identity link function. Only the effect of sign content was statistically significant, $\chi^2(2) = 11.20$, $p = 0.004$. As can be seen in figure 41, mean fixation durations were longest for blank signs and shortest for faces signs. It should be noted that although the software algorithm used to identify fixations was set to detect fixations as short as 60 ms, the shortest fixation captured was 110 ms.

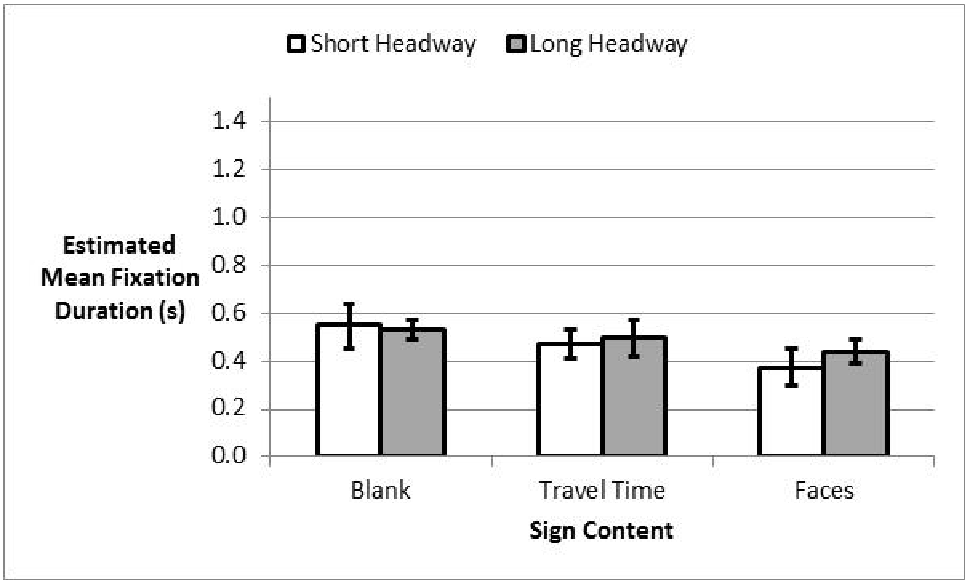


Figure 41. Chart. Expected mean and 95-percent confidence limits for fixation duration as a function of data collection zone and headway.

Mean fixation durations were short, and fixations away from the forward roadway of this duration were generally considered safe. Furthermore, for most of the approach distance, the overhead signs fell within what would generally be considered the forward roadway (i.e., within 2 degrees of the horizon in the direction of travel). A few long, potentially unsafe fixations on CMSs were observed, but the percentage of fixations longer than 2 s was less than 1 percent. Recent analyses by Liang, Lee, and Yekhshatyan suggest that gaze fixations away from the forward roadway greater than 2 s greatly increase the odds of a crash, whereas glances away from the forward roadway, even those between 1.5 and 2 s, may be associated with no increase in crash risk.(55) Whether those recent analyses apply to CMSs above the roadway is unclear, because CMSs might have fallen within what those previous researchers considered the forward roadway or road center. The longest CMS fixation identified was 2.86 s. Table 23 shows the frequency distribution for fixation durations for the current study.

Table 23. Distribution of fixation durations.

Duration	Frequency	Percentage
Less than 1 s	1,153	92.09
Between 1 and 1.5 s	65	5.19
Between 1.5 and 2 s	22	1.76
Greater than 2 s	12	0.96
Total	**1,252**	**100.00**

Table 24 shows the number of fixations with durations greater than 2 s as a function of sign content and time headway.

Table 24. Number of fixations longer than 2 s as a function of time headway and sign content type.

Headway Length	Sign Content				
	Blank	Faces	Time	Warn	Total
Short headway	2	0	0	0	2
Long headway	2	1	6	1	10
Total	**4**	**1**	**6**	**1**	**12**

Driving Performance Measures

The plan for this study included two measures of driving performance that might be affected by sign content—possibly because attending to or avoiding attending to content might increase driver workload. These measures were steering entropy and speed. Unfortunately, an upgrade to the driving simulator to increase the realism of the steering wheel feel resulted in a loss of the data channel used to measure steering angle and therefore entropy. Speed was examined to detect either decreases or variability in speed to enable greater attention to sign content.

There were no significant effects of mean speed or standard deviation of speed as a function of either sign group (blank versus faces) or sign content (travel time versus other), or the interaction of these variables.

DISCUSSION

Respect for CMS as TCDs

The majority of drivers heeded the accident ahead message that directed them to take the next exit. Only one of the drivers who failed to take the exit claimed to be unaware of the message. Indeed, several of the drivers who did not take the exit were observed trying to change into the exit lane. This suggests that placing non-traffic-related messages on overhead signs will not necessarily lead drivers to ignore these signs. Likewise, the frequently occurring travel-time messages did not show evidence of leading drivers to ignore more safety or operationally critical messages.

No evidence of habituation or loss of respect for CMS messaging was evidenced in this 45 min drive with CMSs recurring every 0.5 mi (0.8 km). The following two caveats to generalization of this finding are warranted: (1) the base case did not include a 45-min drive in which there was no CMS preceding the warning, and (2) these results apply to a single drive, not weeks, months, or years of driving under signs with irrelevant messages.

Overall, 28 percent of participants who were exposed to 96 CMSs failed to exit. Only one participant claimed not to have read the message, and the glance data indicated that that participant had gazed at the message, although this does not imply the she read it.

Although this study cannot address long-term habituation, it did look for changes in glance behavior over the 45-min drive and did not detect evidence of the beginning of such a change. The study should be taken as positive evidence that frequently occurring CMSs that meet a traffic operations and safety need, such as CMSs for active traffic management, should not induce habituation or loss of respect for TCDs.

Gaze Behavior

Three measures of gaze behavior were used because it was uncertain whether any single measure would unambiguously characterize gaze behavior in the presence of CMSs.

The glance and look measures suggested that drivers are more likely to look at non-blank signs, a finding that makes intuitive sense. All three measures showed a strong effect of headway—when headways are short, drivers are less likely to divert their gaze from the roadway to a CMS. Drivers seem to regulate their gaze behavior according to the demands of the driving situation. Even the frequently changing faces signs did not compel drivers to divert their attention away from the driving task.

The look measure suggested that the faces signs were more likely to receive visual attention when the roadway demands for attention were low (i.e., time headway was greater than 1.5 s). Given that change and that faces are generally considered to have high saliency, the look finding was not unexpected. However, the glance and fixation measures did not reinforce the suggestion that changing faces attract visual attention more than static travel-time messages.

The fixation measure is probably the most conservative of the three gaze criteria. That is, it is less likely to incorrectly identify the focus of visual attention and most likely to miss short gazes at moving objects. Nonetheless, it was surprising to find that the longest fixations were to blank signs and the shortest to faces signs. This effect was small and probably not worth interpreting in the absence of additional replications. In addition, the total time that blank signs were looked at across all drivers and all blank signs was miniscule compared with the total time spent with gazing on non-blank signs. In this study, the amount of time gazing at the sky, grass, or trees was not recorded. If it had been, it is probable that gazes at them would have exceeded 2 s. Drivers look away from the road ahead for various reasons. This does not imply that they are not attending to the forward roadway. Fixations on the blank signs may have been random fixations to relieve boredom or maintain overall awareness of the environment, and were not necessarily instances of distraction.

Overall, there was little evidence to suggest that CMSs, regardless of the content, are distracting. Participants appear to have attended to the signs primarily when the visual demands of the primary driving task were low. Furthermore, both measures of gaze duration suggest that drivers do not dwell on signs for periods of time that would compromise safety. The next study examines whether the workload imposed by attention to CMSs detracts from detection of safety-critical events in the roadway.

Drivers appear to glance at CMSs when driving demands are low. This is presumably because drivers give priority to attending to safety-critical aspects of the driving task. When the driving demands are high, drivers have little spare capacity to attend to CMS messages. This implies that when a traffic manager posts what is considered a safety-critical message, that message should be tailored to minimize demands on drivers' attention. The more that attention demands of a message increase, the less likely drivers are to have sufficient spare capacity to process the message. Several FHWA publications are available to provide guidance on how to minimize the attention demands of CMS messages.(3,5) Conversely, if drivers expect CMS messages to be noncritical or irrelevant, then the probability that safety-critical messages will be ignored may increase. The experiment described in chapter 6 was intended to test this hypothesis.

CHAPTER 6. THE EFFECT OF CMS INFORMATION ON DETECTION OF SAFETY-CRITICAL EVENTS IN THE ROADWAY

INTRODUCTION

The previous chapter reported on a test of the hypothesis that driving-irrelevant CMS content would cause drivers to lose respect for the signs and then miss important traffic-related messages. The findings did not support that hypothesis. This chapter tests the hypothesis that CMS content distracts drivers from attending to safety-critical information in the roadway. A spilled load of logs was simulated in the roadway 300 ft (91 m) upstream of a CMS. The spilled load was in an area where the previous study showed that glances at the signs were most likely. That is, first glances at a CMS occurred between 901 and 555 ft (275 and 169 m) before reaching the CMS, and last glances occurred in the range 590 ft to 180 ft (180 and 55 m). The primary dependent measure was whether or not the driver avoided hitting the spilled load by changing lanes, braking, or a combination of these responses. As in the previous experiment, glance behavior and speed were also assessed.

To assess whether salient driving-irrelevant content might be more visually distracting than travel-time information or blank CMSs, the sign content that was visible when the logs came into the line-of-sight was varied among participants. To assess whether distraction effects might be greater near the beginning or end of a trip, the location of the spilled load was also varied between groups. There are several reasons that the signs might be more distracting at the beginning or end of the trip. The signs might be more distracting at the beginning of a trip if their novelty attracts attention. None of the drivers in the previous experiment participated in this experiment, so initially the faces signs might be expected to be novel. Signs might be more distracting at the end of the trip because drivers might seek additional stimulation as they begin to feel bored or fatigued. Finding a difference in spilled load response between the beginning and end of the drive would not test the involvement of novelty or fatigue as distraction facilitators, but it might indicate where to look for distraction effects in future studies.

In the experiment reported in chapter 5, the finding that faces and travel-time signs attracted similar amounts of attention suggests that the frequently changing faces displays were weak in capturing attention. In the present experiment, a face-recognition test was administered after participants finished the experimental drive. Participants were not informed in advance that they would be tested for recall of the pictures shown on the overhead signs. The purpose of the test was to provide another measure of the degree to which the face stimuli captured attention.

METHOD

The same driving simulator and eye-tracking system were used in this experiment as were used the experiment reported in chapter 5.

The blank, travel-time, and faces signs were used again in this experiment. However, in this experiment, all participants were presented with all three CMS content types. Each of the content types appeared on every third sign. As described in the following subsections, the content of the first sign in this sequence depended on the group to which the participant was assigned.

The Simulation

The simulated freeway was the same as that described previously except that the drive was reduced to 37 mi (59.5 km) and 72 CMSs. There were two between-group conditions: (1) whether the CMS beyond the spilled load of logs displayed the faces, the travel-time, or the blank content and (2) whether the spilled load was before the 4th CMS encountered or before the 72d CMS. An example of the appearance of the spilled load is shown in figure 42.

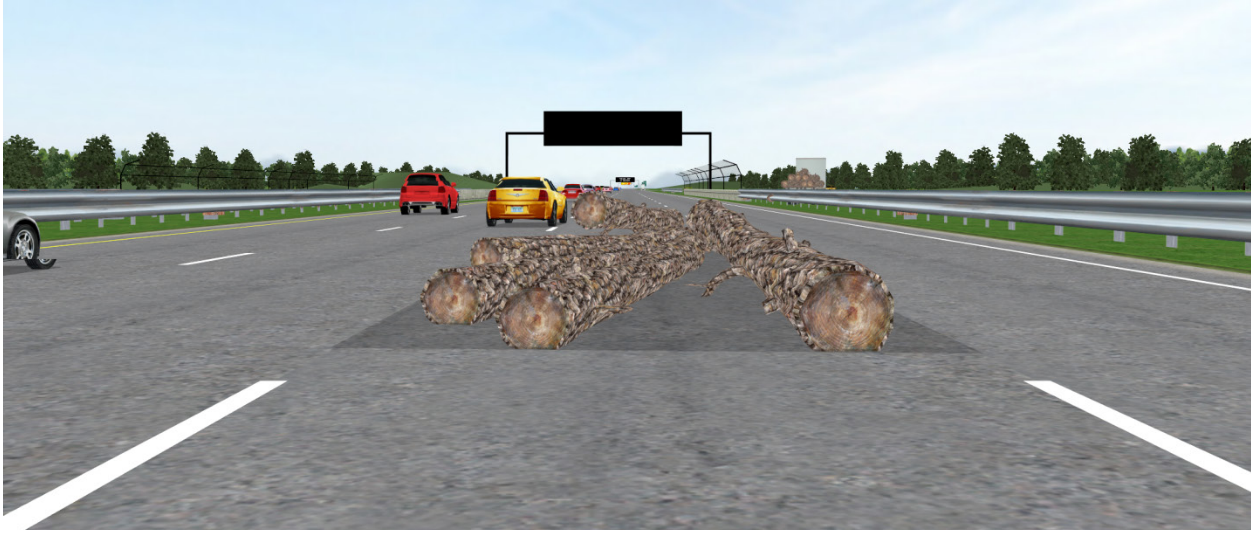


Figure 42. Screen capture. Driver's view of spilled load from 128 ft (39 m).

Traffic was generated at a rate of 5,000 vehicles per hour for the first 6.7 min. Vehicles entered and exited from every other ramp intersection at a rate of 500 vehicles/h. Because the spilled load was in the second lane from the right, participants were instructed prior beginning the test to drive in that lane whenever it was safe to do so and to try to maintain the posted speed of 65 mi/h. Participants were told that they would receive a $10 bonus if they drove in the instructed lane and maintained 65 mi/h whenever possible. To prevent slower vehicles from motivating participants to change lanes, the minimum desired speed of all other vehicles was set to 69 mi/h. Fifty-five percent of simulated other vehicles were programmed to seek to travel 69 to 71.7 mi/h, while the remaining vehicles were programmed to seek speeds between 71.7 mi/h and 80 mi/h. In the left-most lane, all vehicles were set to maintain 80 mi/h.

In the data collection zones where the spilled load was placed, other traffic began clearing the lane containing the logs 1,211 ft (369 m) before the logs. This distance, plus the average time headway of 559 ft (170 m), ensured the participants had adequate sight distance to detect the logs and respond to them by hard braking or changing lanes.

There were zones in which all traffic slowed markedly. These zones were in the same locations relative to the start of the simulation as in the previous experiment. Because the scenario was shorter than in the experiment reported in chapter 5, there were only 5 congestion locations, the first located between the 4th and 5th CMS, and thereafter there was 1 congestion zone for every 15 CMSs (e.g., the next congestion zone was between the 19th and 20th CMS). The purpose of these zones was to keep the participants engaged in the driving task. Gaze behavior was not analyzed in these zones.

Recognition Test

Upon exiting the driving simulator, participants were shown a series of 64 pictures on a laptop computer. Half of the pictures (32) were pictures of faces that had been displayed during the drive. The other half were foils (similar face pictures that had not been shown during the drive). For celebrities and other well-known persons (e.g., Barack Obama, Elizabeth Taylor, and Prince Charles), a different picture of the same individual was included as a foil for the picture in the simulation. For other images, the similarity of the foils was based on salient characteristics of the target pictures (e.g., hair color and style, nationality of dress, and facial expression). Each picture (whether target or foil) was presented individually, and participants were asked to indicate "yes" if they had seen the picture during the drive or "no" if they did not recall the picture from the overhead signs. Participants were instructed to guess when they were not sure.

Participants

Complete data, including interpretable eye tracking, were obtained from 73 participants. A total of 80 participants (51 males and 29 females) completed the drive and provided behavioral performance data. The median age of the participants who completed the test was 33.5 years (range 18 to 73 years). An additional five participants failed to complete the study, two because of simulator sickness symptoms and three because of driving simulator hardware or software failures.

RESULTS

Throughout this report, error bars in charts and graphs represent 95-percent confidence limits around the means.

Response to the Encounter With a Spilled Load

The spilled load presented the participants with a challenging task as evidenced by 26 percent of drivers hitting the logs. However, the message content of the CMS that was visible as the spilled load was approached had no significant effect on whether the logs were avoided. Nor did the location of the logs have a significant effect on the probability of hitting the logs. Table 25 shows the frequency of participants hitting or avoiding the logs as a function of CMS content and location of the spill.

Table 25. Number of participants who hit or avoided spilled load shown as a function of load location and CMS content.

Location in Drive Time	Avoided/Hit	Message Content			
		Blank	**Travel Time**	**Face**	**Total**
Early	Avoided	5	11	8	24
	Hit	7	2	4	13
	Total	**12**	**13**	**12**	**37**
Late	Avoided	12	12	11	35
	Hit	3	3	2	8
	Total	**15**	**15**	**13**	**43**

Gaze Behavior

Gaze behavior was scored for a subset of 27 of the 72 CMSs in the study. Gaze was scored for signs 1–9, 16–18, 32–34, 48–50, and 64–72. The same three measures of gaze behavior were examined: glances, looks, and fixations. All data collection zones began 10 s upstream of the point where the sign passed from view and ended when the sign passed from view. There were nine zones with each type of sign content.

Glance Results

The probability of glancing at each sign was examined as a function of sign content (faces, travel time, or blank) and time headway. Each sign was classified by whether it received a glance (no = 0, yes = 1) and by whether the mean headway in the data collections zone (i.e., 1.5 s or less) or long (i.e., greater than 1.5 s). The data were analyzed using a GEE model that assumed a binomial distribution with a logit link function. Sign content, headway, and their interaction were modeled as predictors of the probability of a glance. Only the effect of sign content was significant, χ^2 (2) = 41.06, $p < 0.001$. As can be seen in figure 43, the probability of a glance at faces and travel-time signs was about the same, and the probability of a glance at blank signs was about half that for the non-blank signs. These findings are quite similar to those for the previous experiment when headways were long.

There were two important differences between this and the experiment reported in chapter 5 that may have resulted in the failure to find a headway effect in this experiment. First, in this experiment, outside the congestion areas, other traffic always traveled at speeds greater than 65 mi/h, whereas 12 percent of traffic traveled at less than 65 mi/h in the previous experiment. Second, the data collection areas in this experiment did not contain, and were not near, congested zones where headways would shrink. As a result, there were few opportunities for short headways in this experiment. Mean headway distance in this experiment was 559 ft (170 m) compared with 326 ft (99 m) in the previous experiment. Because headway had no effect on the glance results, headway was dropped from the subsequent look and fixation analyses.

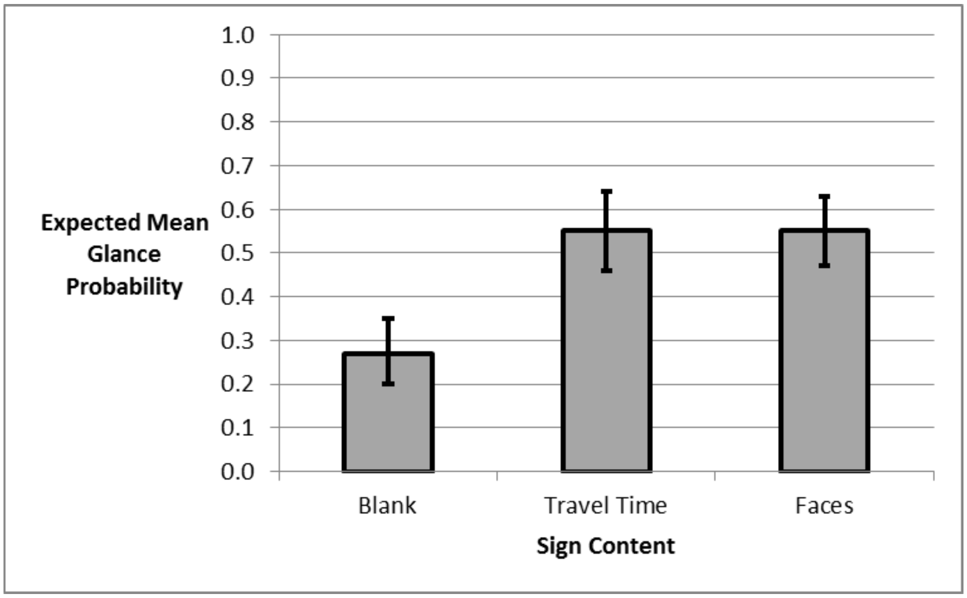


Figure 43. Chart. Predicted probability and confidence limits for a glance at a CMS as a function of sign content.

Glance duration was computed as the sum of all 0.0083-s glance vectors to the sign ROIs. The GEE models with glance duration as the predicted variable and sign content, headway, and the content by headway interaction were tested. These models assumed a gamma distribution with identity link function. Because the gamma distribution does not include zero, two durations were computed for each ROI: (1) the first method included all ROIs regardless of whether they received a glance, and where no glances were recorded, glance duration was assigned a duration of 0.00001 s; and (2) the second measure included only ROIs that received a glance. Both models led to similar conclusions. Only the sign content main effects were significant: (1) with zero durations coded as 0.00001 s, $\chi^2(2) = 41.2$, $p < 0.001$, and (2) with zero durations coded as missing, $\chi^2(2) = 27.96$, $p < 0.001$. Figure 44 shows predicted glance durations and their confidence limits by both methods of computing glance duration. By either method, the durations to faces and travel-time signs were not significantly different from each other, and the durations of glances at blank signs were significantly less than at the non-blank signs.

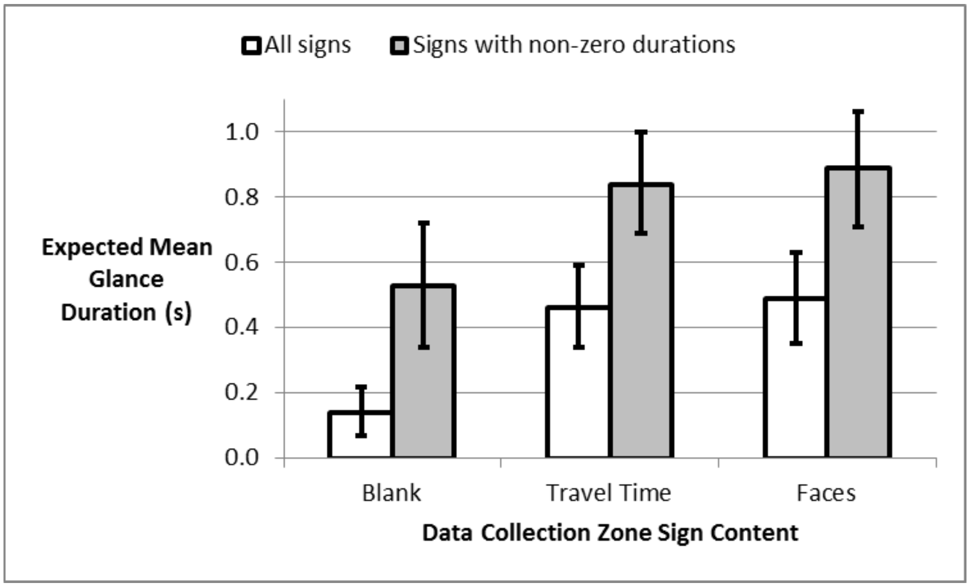
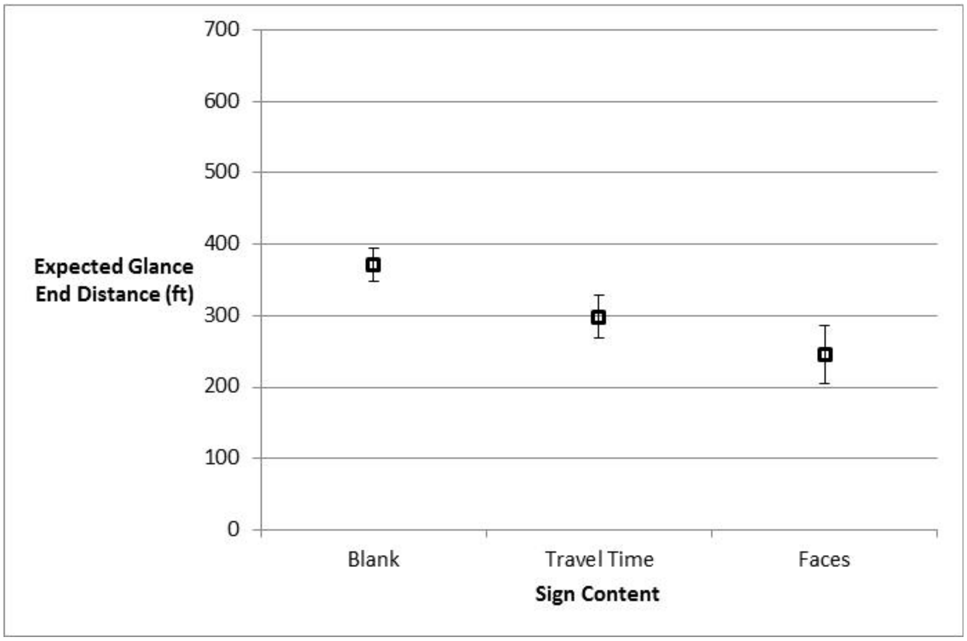


Figure 44. Chart. Expected mean duration of glances at CMSs and confidence limits as a function of sign content.

The expected distance, in feet, for the end of a glance is shown in figure 45. The effect of sign content on end-of-glance distance was significant, $\chi^2(2) = 31.18$, $p < 0.001$. Post hoc tests indicated that glance-end distance to blank signs was significantly greater than glance-end distance to travel-time or faces signs, which were not significantly different from each other.



1 ft = 0.305 m

Figure 45. Chart. Expected glance-end distance as a function of sign content.

Look Results

The probability that a participant would look at a CMS was modeled with sign content as the predictor. A binomial response distribution and logit link function were assumed. The sign content main effect was significant; $\chi^2(2) = 31.83$, $p < 0.001$. Post hoc comparisons indicated that the probability of looking toward a blank sign was significantly less than the probability of looking toward a faces sign, $\chi^2(1) = 27.39$, $p < 0.001$; or travel-time sign, $\chi^2(2) = 30.66$, $p < 0.001$. The difference between the probability of looking at faces signs and at travel-time signs was not significant. The predicted means and respective confidences limits are shown in figure 46.

The number of looks at each CMS was modeled as a function of sign content. The GEE model assumed a Poisson response distribution and log link function. Sign content was significant; $\chi^2(2) = 25.55$, $p < 0.001$. Post hoc comparisons indicated that the number of looks toward a blank sign was significantly less than the number of looks toward a faces sign, $\chi^2(1) = 25.52$, $p < 0.001$, or a travel-time sign, $\chi^2(1) = 21.40$, $p < 0.001$. The difference in the number of looks at faces signs and at travel-time signs was not significant. The predicted means and the confidence limits for those means are shown in figure 47.

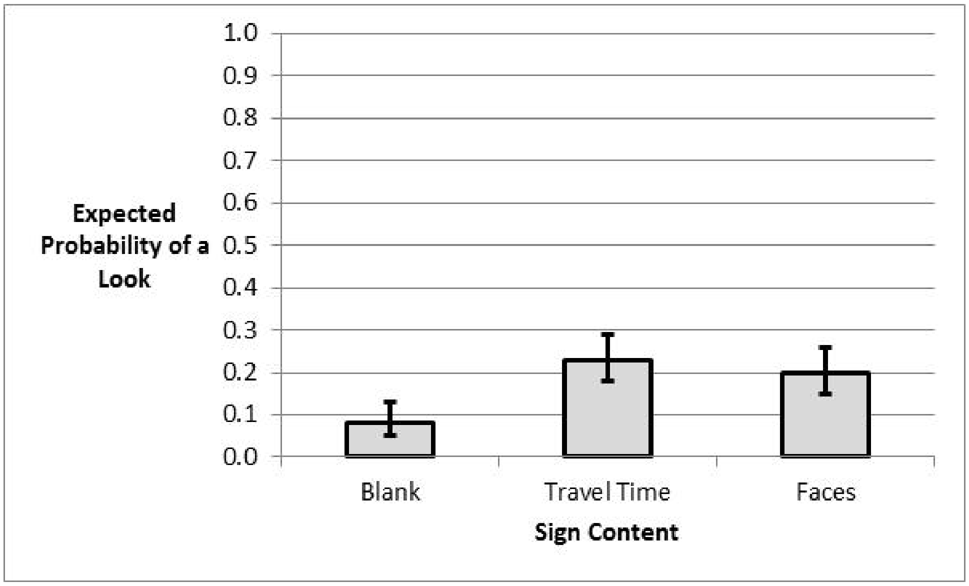


Figure 46. Chart. Probability of at least one look at a CMS as a function of type of sign content.

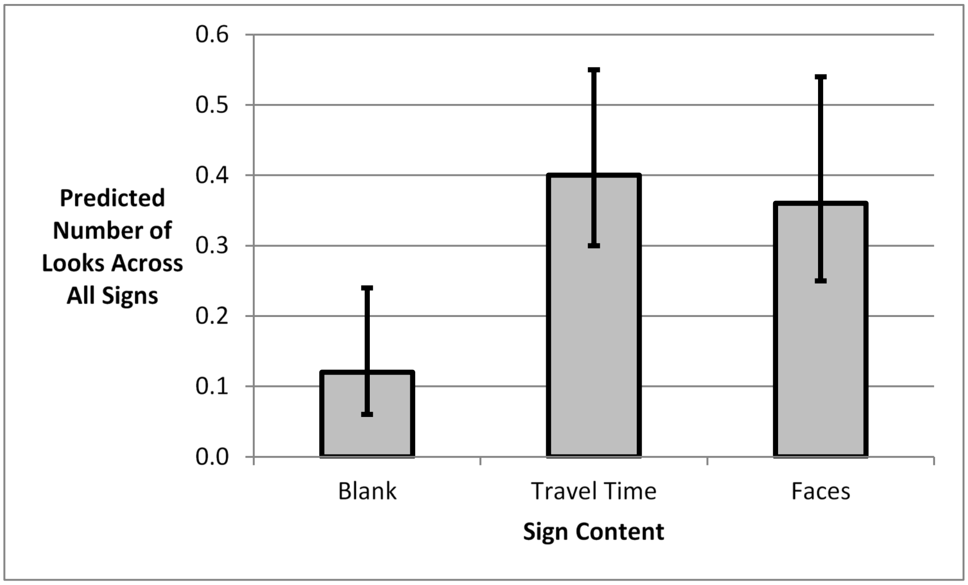


Figure 47. Chart. Predicted number of looks at a CMS as a function of type of sign content.

The number of looks at signs that received at least one look and the average duration of those looks were also modeled. GEE was used to model the number of looks assuming a Poisson response distribution and log link function. Given that there was at least one look at a sign, knowing the content of the sign did not add additional predictive information. The predicted mean number of glances given at least one look is shown in figure 48. The duration of individual looks to the CMSs was modeled to determine whether sign content had a significant effect on look duration. Only signs that the participant looked at (i.e., for which at least one look was recorded) were included in the analysis. A gamma response distribution and identity link function were assumed. The resulting expected mean look durations are shown in figure 49. Sign content was a significant predictor of look duration, χ^2 (2) = 6.58, $p = 0.037$. Post hoc comparisons suggest that the main effect was the results for looks at blank signs, which were significantly shorter than looks at faces signs, $\chi^2 = 6.50$, $p = 0.011$. There was no significant difference between the duration of looks toward faces signs and travel-time signs.

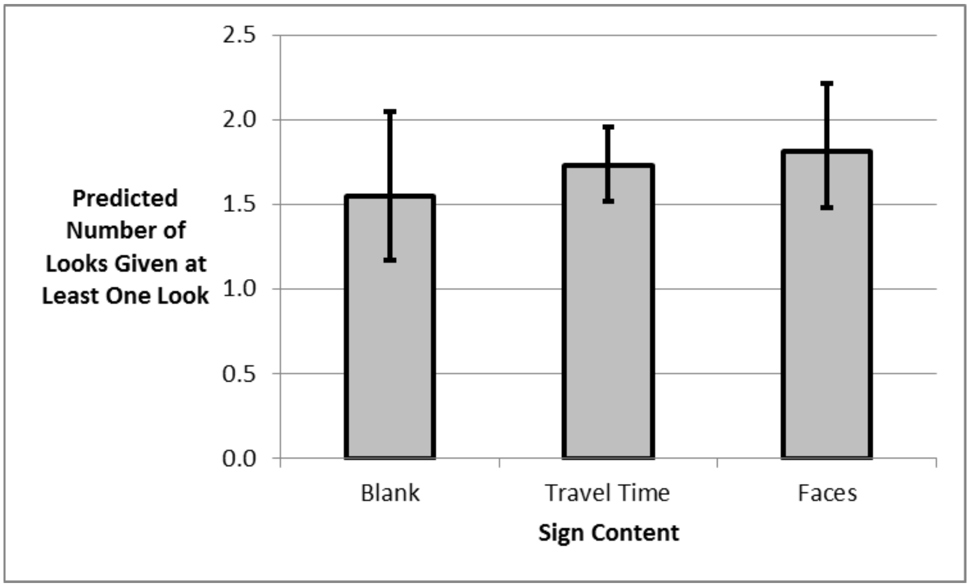


Figure 48. Chart. Number of glances at each CMS that received at least one look.

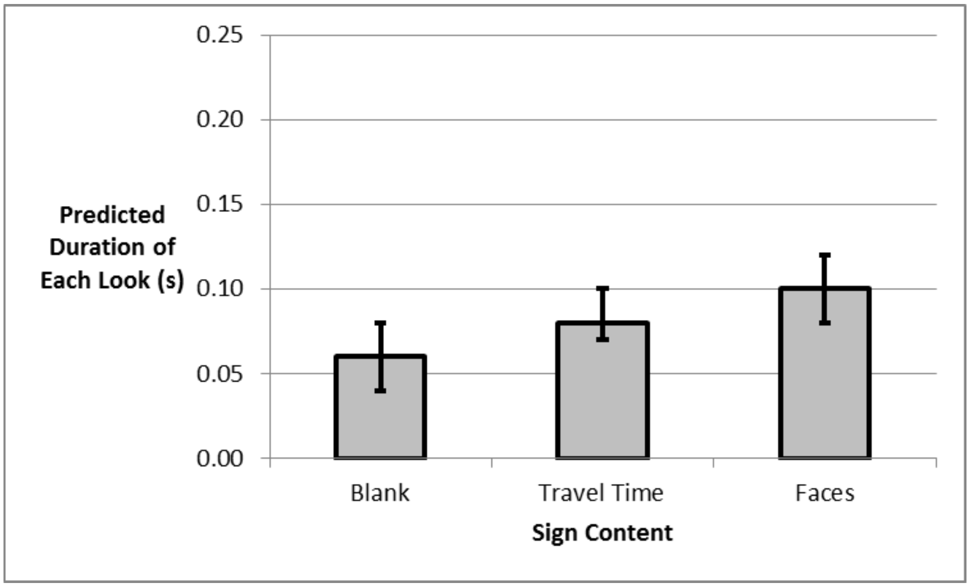


Figure 49. Chart. Predicted mean duration of individual looks as a function of sign content.

Fixation Results

GEE were used to model the probability of a participant fixating on each CMS. A binomial response distribution and logit link function were assumed. The predictor was the sign content. Sign content was a significant predictor of fixation probability, $\chi^2(2) = 84.30$, $p < 0.001$. Post hoc comparisons indicated that the probability of fixating on a blank sign was significantly less than the probability of fixating on faces or travel-time signs and that the difference between the probabilities of fixating on travel-time and faces signs was not significant. Figure 50 shows the probability of fixating on individual CMSs as a function of their content.

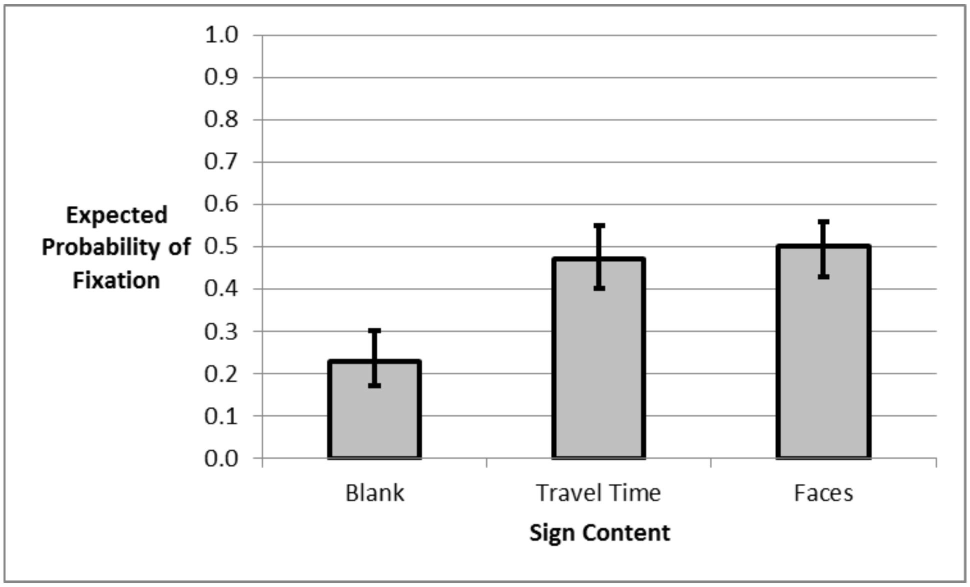


Figure 50. Chart. Expected mean probability of a fixation on a CMS as a function of sign content.

GEE models were used to model the number of fixations on the CMSs. A Poisson response distribution and log link function were assumed, and sign content was the predictor. Figure 51 shows the predicted mean number of fixations as a function of sign content. Sign content was a significant predictor, $\chi^2(2) = 35.90$, $p < 0.001$. Post hoc comparisons indicated all three predicted means were significantly different from each other.

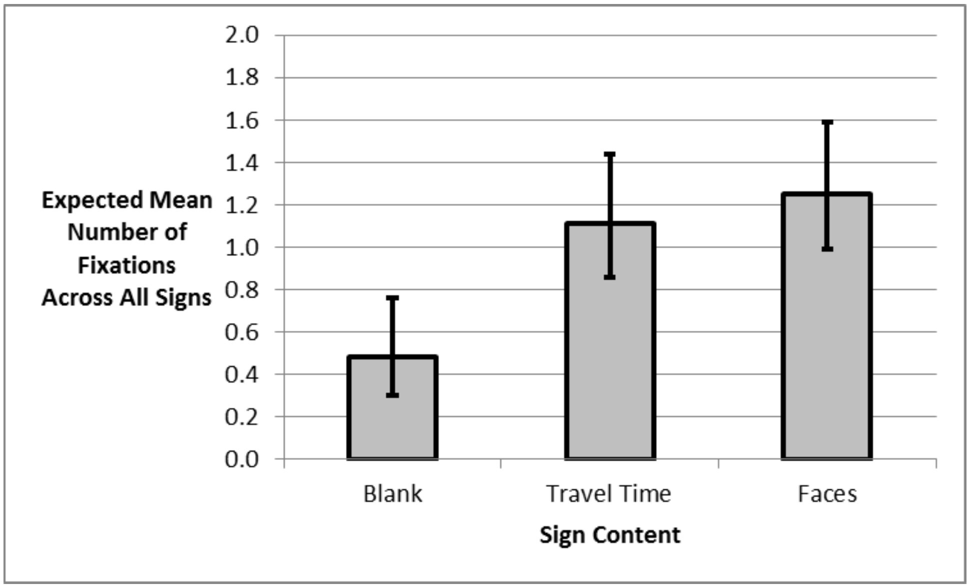


Figure 51. Chart. Predicted mean number of fixations across all signs as a function of sign content.

Mean fixation duration was examined for those signs that received at least one fixation. GEE models were used to evaluate fixation duration. A gamma response distribution and identity link function was assumed. Sign content was the predictor variable. Sign content significantly predicted fixation duration, $\chi^2(2) = 15.10$, $p = 0.001$. Post hoc comparisons indicated mean fixations on travel-time signs were significantly longer than those on blank or faces signs, and the latter two were not significantly different from each other. Figure 52 shows expected mean fixation durations for blank, travel-time, and faces signs along with the 95-percent confidence limits for those means.

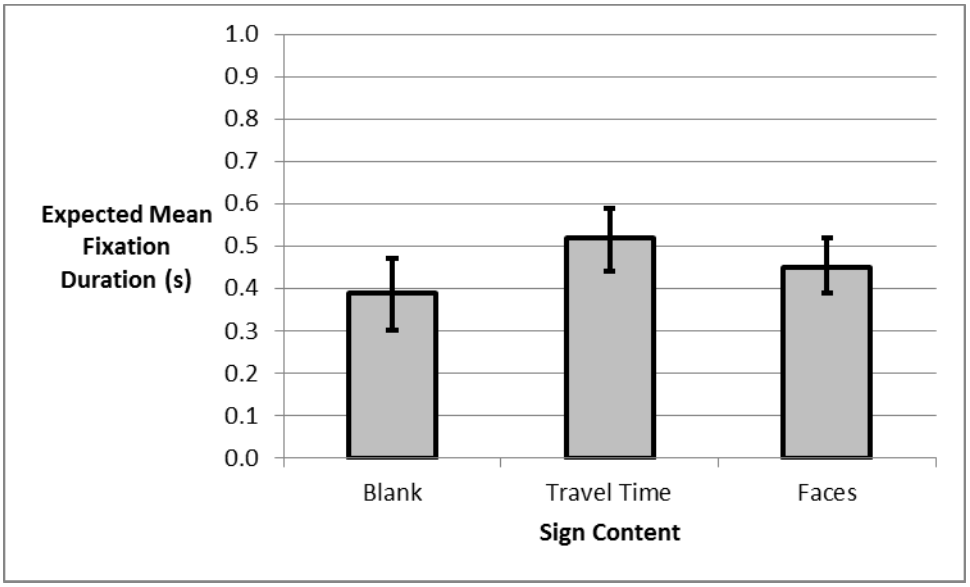


Figure 52. Chart. Expected mean fixation duration as a function of sign content.

The average fixation duration was 0.5 s or less. However, the average duration may not reflect the existence of long fixations on CMSs that might represent an unsafe driver distraction. For in-vehicle device distraction, it is suggested that display devices that capture visual attention for more than 2 s represent a safety risk.(55,56) Although no such guidance is available for display devices located above the roadway, it is doubtful whether displacement of gaze only a few degrees above the forward roadway would be unsafe. However, should generalization of the 2-s capture rule be considered appropriate, then a few unsafe fixations were observed. Table 26 shows that 1.8 percent of fixations on the simulated CMSs in this study were greater than 2 s.

Table 27 shows that more than 50 percent of the durations greater than 2 s were for travel-time messages.

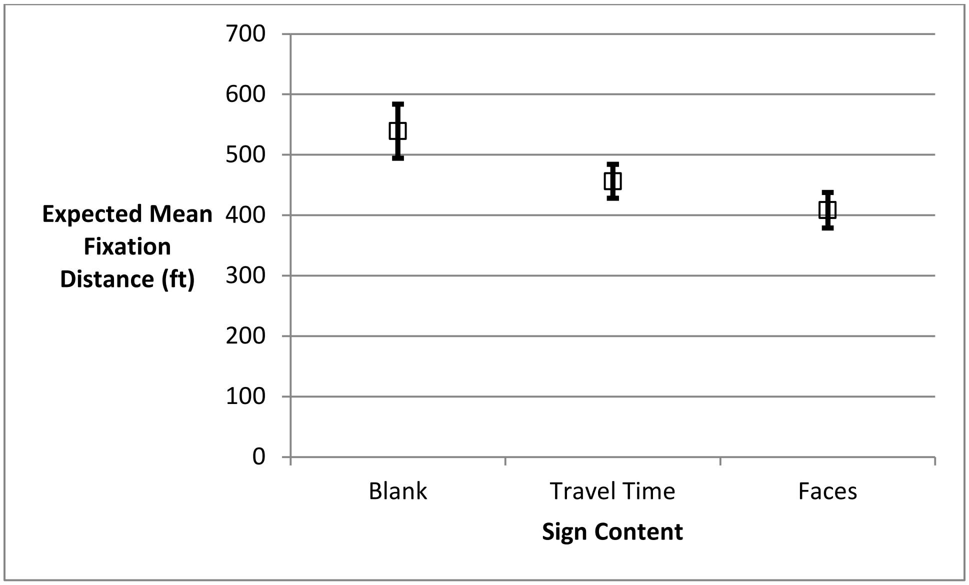
Table 26. Distribution of fixation durations.

Duration	Frequency	Percentage
Less than 1 s	1,629	90.95
Between 1 and 1.5 s	101	5.64
Between 1.5 and 2 s	28	1.56
Greater than 2 s	33	1.84
Total	**1,791**	**100.00**

Table 27. Frequency of fixations greater than 2 s.

Sign Category	Frequency of Fixations > 2 s Duration
Blank	6
Faces	8
Time	19

In chapters 5 and 6, beginning and end of glances were examined. It was found that glances began at about the same distance regardless of sign content and that glances at faces signs ended closer to the sign than did glances at blank or travel time signs. Similarly, mean fixation distance was examined. The overall test and post hoc tests were all GEE models, with sign content as the predictor for mean fixation distance. Mean fixation distance was assumed to be gamma distributed, and an identify link function was used. The main effect of sign content was significant, χ^2 (2) = 23.01, $p < 0.001$. The mean fixation distance results are in line with those for glances: expected mean distance was greatest for blank signs and least for faces signs, with travel-time signs falling between. Post hoc comparisons showed all three expected means, as shown in figure 53 are significantly different from each other.



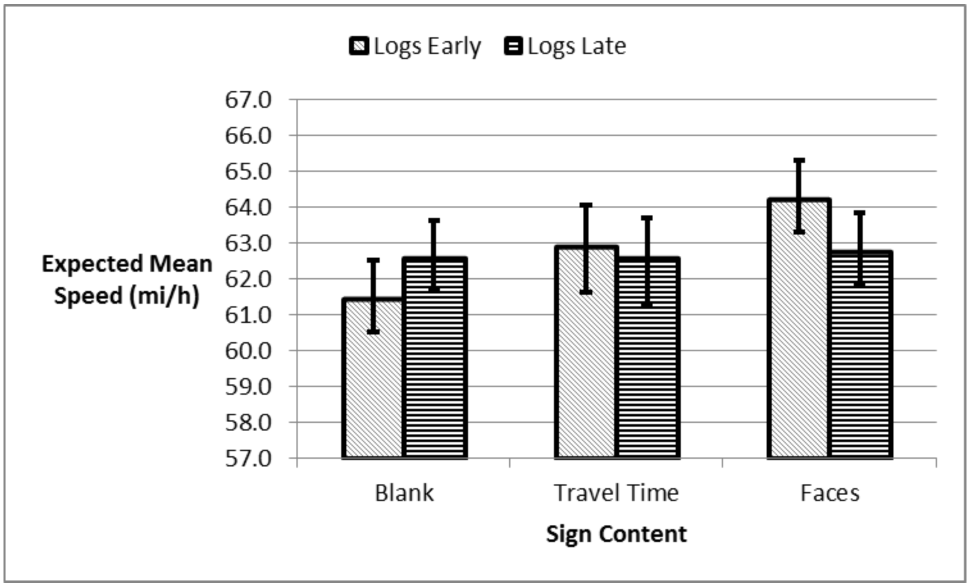
1 ft = 0.305 m

Figure 53. Chart. Expected mean distance of fixations on a CMS as a function of sign content.

Driving Performance Measure

Travel speed was analyzed with a GEE model that assumed a gamma distribution and identity link function. The sign content of the data collection zone and location of the logs served as predictor variables. The travel speed dependent measure was based on mean travel speed for each data collection zone for each participant. Data collection zones 4 and 72 (the zones with logs in the roadway) were excluded from the analysis. Figure 54 shows the resulting expected mean speeds as a function of the content on the CMS and log location. The interaction of log location and sign content was significant, $\chi^2(2) = 8.94$. $p = 0.011$. This unexpected interaction resulted because the group that encountered the logs late in the trip exhibited a nearly constant speed regardless of CMS content, whereas the group the encountered the spilled logs early in the trip drove significantly slower than average when approaching blank signs and significantly faster than average when approaching faces signs. Also striking is that all groups drove below the instructed and posted speed in all three data collection zone types.

No predictor variable (sign content, log location, or data collection zone order) was significantly related to speed variability.



1 mi/h = 1.6 km/h

Figure 54. Chart. Expected mean speed as a function of sign content.

Faces Recognition

The *d′* measure from signal detection theory was used to assess the ability of participants to distinguish between pictures they had been exposed to during the drive and similar pictures not previously displayed.(57,58) The obtained estimate was quiet low, mean *d′* = 0.25, SD (standard deviation) = 0.37. A *d′* of zero would indicate no ability to distinguish between targets and foils. This finding indicates that participants showed very little ability to distinguish the new pictures from the ones displayed during the drive.

DISCUSSION

Distraction From Monitoring the Road Ahead

A total of 59 of 80 drivers were successful in detecting and avoiding the spilled load of logs. The detection task was difficult enough that many of the remaining 21 drivers struck the logs because they were indecisive in reacting, such as deciding to seek a gap in the adjoining lanes and then failing to find that gap in time to avoid the logs. A few drivers showed no indication of detecting the logs. In any case, failure to detect or react successfully to the threat did not appear to vary with the content of the sign that was being approached. The log avoidance measure yielded no evidence that driving-irrelevant stimuli, even stimuli considered highly salient in other contexts, would distract drivers from their primary (driving) task more than would a blank overhead sign.

Eye Gaze Distraction Evidence

The eye gaze data from all three metrics (glance, look, and fixation) converged on the same general conclusion: drivers were about equally likely to shift their visual attention to travel-time messages as they were to colorful, changing, and driving-irrelevant content (e.g., faces), and less likely to shift visual attention to a blank CMS than to a sign with information content.

There were few fixations on the CMSs longer than 2 s, and the majority of these were on travel-time signs. It was thought that faces of celebrities or faces displaying strong emotions might attract attention more than predictably structured text messages. To enhance the saliency of the faces, they changed every 3 s. Nonetheless, the faces did not attract gaze more than travel-time messages.

Recognition of Faces

The finding that pictures not shown before could not be reliably distinguished from pictures that were repeatedly presented on the CMS may suggest that the foils chosen for use in the test were too similar to the targets. However, the findings also suggest that participants did not devote much attention to studying the pictures on the overhead signs (and the gaze data would seem to confirm this). Because the participants were not told that recognition of the face pictures would be tested, there was no motivation for them to study the pictures beyond whatever intrinsic value the pictures might hold. A stronger test of the ability of drivers to avoid distraction from the primary task—driving—might be to offer some incentive to drivers to attend to the CMS messages. The challenge of a study with incentives to attend to the CMSs would be to avoid making the driving task secondary because of unrealistic contingencies.

SUMMARY AND CONCLUSIONS

These findings suggest that messaging on CMSs that is not related to driving would be no more distracting than traffic-related messaging or blank signs. As in the previous experiment, these results apply to a single relatively long trip. Should drivers habituate to frequently occurring CMSs, then any distraction away from detecting road hazards should be less.

The findings indicated that when a message is displayed on a CMS, drivers move their center of gaze to the sign about 50 percent of the time. When the CMS is blank, drivers still have a 25-percent probability of shifting their gaze to it. These gazes are generally short, about 0.5 s. The number of short glances is generally small, with an average of one fixation per sign with content.

The aims of this and the experiment reported in chapter 5 were limited to a strong test of whether travel-irrelevant content on CMSs would distract drivers. The answer is that under the conditions tested, irrelevant messaging, even if designed to be salient in other settings, would not be more distracting than traffic-related messaging, which itself did not appear to stress the visual attention capacity of drivers.

The present tests did not present the CMSs in environments with high amounts of visual clutter, as might be present in an urban environment with tall buildings, billboards, and overpasses, in addition to other critical highway signs. The tests simulated daytime conditions with signs that were not brighter than static signs or the simulated sky. The contrast ratio of white text to the black background, measured in a previous study in the simulator, was 14.6. This ratio is somewhat greater than that recommended by the MUTCD (8 to 12) (see section 2L.04, paragraph 11) but much less than contrast ratio of the CMS reported in chapter 3.(2) Aside from the logs in the road in the experiment reported in this chapter, eye gaze behavior was not assessed in areas with hazardous driving conditions. The participants in these experiments were not young novice drivers. For these and other reasons, it is possible that in some conditions, with some driver populations, some CMS content might be distracting and pose a safety risk. These experiments suggest that it would be challenging to present visual information that would compel drivers to shift their attention from the primary driving task.

CHAPTER 7. THE EFFECT OF FREQUENCY AND SPACING OF GUIDE SIGNS ON DRIVER BEHAVIOR

This study examined the effects of the frequency, spacing, and information content of guide signs on driver performance. Specifically, it looked at the effects of the number and spacing of supplemental guide signs and specific-service logo guide signs.

Highway agencies (e.g., State departments of transportation and toll authorities) are sometimes under pressure to post more supplemental guide signs than is permitted in the MUTCD.(2) For instance, when a college or university is listed on a supplemental sign, other higher education institutions near the same interchange may request similar acknowledgment. The demand for listing on specific-service signs (i.e., signs for gas, food, lodging, camping, attractions, and 24-h pharmacies) may also exceed available sign locations that conform to MUTCD requirements.

Supplemental guide signs provide information regarding destinations accessible from an interchange other than places displayed on the standard interchange signing. Like standard interchange guide signs, supplemental guide signs have white lettering on a green background. The MUTCD limits supplemental guide signs to one per interchange and a supplemental sign may list no more than two destinations.(2) The manual also specifies that there should be at least 800 ft (244 m) between a supplemental sign and other guide signs but cautions that the supplemental sign may overload drivers' ability to process information.

Specific-service guide signs have white lettering on a blue background. The MUTCD recommends that these signs be spaced a minimum of 800 ft (244 m) apart from each other and from other guide signs.(2) The services on a specific-service sign may be represented by either text or a logo, with a maximum of six services per sign. A maximum of four specific-service signs may serve an interchange. The limitation on the number of guide signs, the distance between them, and the amount information on individual signs is intended to avoid overloading drivers' ability to receive information and to make appropriate decisions.(2)

Although it seems reasonable that too much signing could decrease the effectiveness of navigation-related signing, there is little empirical evidence that this is the case, and no empirically based literature is available that would enable quantification of what is too much. NCHRP Report 488: *Additional Investigations on Driver Information Overload* presents a model for quantifying the relative information load of sign arrays along a highway segment but does not provide a method for determining the absolute level at which too much information is present.(20)

NCHRP 488 describes driver information overload and its potential consequences as follows:(20)

> "Driver information overload" is defined as providing a motorist with too much information, through a series of devices or conditions, for a driver to have adequate time to perceive and respond properly. Therefore, the information load on a driver is a property not only of the specific sign he or she is encountering, but also of the roadway context in which the sign occurs, the information context in which the sign occurs, characteristics of the driver, and the particular navigational task. Where drivers are confronted with more information than they can process, they may decelerate severely or drive unduly slowly, make late or erratic

> maneuvers, take an improper route alternative, ignore critical information, fail to monitor other traffic, or have excessive eyes-off-the-road time episodes. These behaviors have obvious safety and operational consequences. (p. 1)

A key point is that the information load from guide signs is not a property of the signs themselves but rather depends on the driver's navigation task and the context in which the sign is encountered. Given that the driver requires navigation information, overload may occur if the driver cannot readily obtain, in the time available, the needed information on a sign or cannot determine that the needed information is not on that sign. The time available depends on the demands of traffic, roadway geometry, and the number of other signs that the driver needs to monitor. Drivers on a familiar route would not need navigation sign information and should not experience information overload attributable to guide signs. As long as other signs near the roadway, such as billboards, do not resemble highway signs, guide sign information overload should not occur.(59) In addition, because guide signs are color coded (i.e., blue background for specific-service signs and green background for other interchange and supplemental guide signs), drivers who need only one type of information (i.e., either services or destination guidance) should not be expected to be overloaded by the presence of both types of signing. Furthermore, legends on specific-service signs (e.g., lodging, gas) are intended to relieve the driver of searching all specific-service signs for a specific type of service. The use of color coding and service legends assumes drivers use this information to reduce the load imposed on them. With respect to specific-service sign legends, this experiment provided a test of that assumption.

Drivers who need navigation information may have insufficient time to acquire the information in the context of too many signs insufficiently spaced if the legibility distance is insufficient, if it is unclear which signs to attend to, or if the roadway and traffic demands are high.

Given the potential consequences of information overload, quantification of what is too much could be useful in guiding and supporting rule-making and guiding agencies that perceive a need to post guidance information that goes beyond current sign frequency and spacing guidelines and regulations.

The origin of the FHWA requirement for an 800-ft (244-m) minimum spacing between freeway guide signs is unclear. The first interstate freeway signing and marking manual, published by American Association of State Highway Officials (now AASHTO) in 1958, includes the provision that "in no case shall guide signs…be spaced closer together than 800 feet."(60) Although the origin of the 800-ft (244-m) minimum is unclear, there is supporting justification for a distance of about that magnitude. One assumption behind the minimum distance between signs is that the most vulnerable (inexperienced and elderly) drivers can process only one sign at a time and the minimum spacing ensures that vulnerable drivers will not be simultaneously confronted with two signs that must be read. Another is that each sign must be available for a minimum amount of time so that the driver can time-share sign reading with other driving demands. Mace, Hostetter, and Seguin conducted a series of laboratory and on-road experiments and concluded that any exposure time of more than 2 s is adequate for processing highway guide signs.(59) Their subjects were not vulnerable road users so a minimum greater than 2 s is probably reasonable. Assuming a travel speed of 65 mi/h (104 km/h), 2 s would represent 190 ft (58 m) of travel distance. With 10-inch- (25-cm-) high letters, the minimum height for the smallest lettering on freeway signs, the legibility distance would be 300 ft (91 m) with an assumed minimum visual acuity of 20/40. Having read a guide sign and determining that a lane change maneuver is required, a maneuvering distance must be accounted for. The 18-inch (46-cm) letter height for critical freeway guide sign information yields a minimum legibility distance of 540 ft (165 m), and a maximum legibility distance of 1,080 ft (376 m). For a driver with 20/20 vision signs would need to be about 1,000 ft (305 m) apart to guarantee two guide signs would not be legible at the same time. Whether the presence of two legible guide signs less than 8.4 s apart (800 ft (244 m) divided by 95 ft/s (29 m/s) confronts drivers with a time-sharing challenge (i.e., information overload) is an empirical question that has not been adequately addressed.

The purpose of this study was to explore the effect of varying numbers of guide signs and their spacing on driver performance. The effects of the following variables were addressed:

- Sign spacing of drivers' performance in obtaining and using guide sign information.
- Number of destinations listed on guide signs on driver performance.
- Sign spacing on driver performance.
- Guide sign frequency on visual scanning of the road ahead.

The study examined driver performance in the case where the driver had information needs that relied on guide and specific-service signs.

METHODS

Participants in this study drove on a simulated freeway with four lanes in their direction of travel. They were instructed to take freeway exits for Holt Avenue, Harvard University, and the Holiday Inn®. This instruction was intended to require participants to monitor all three types of signing: interchange guide signs, supplemental guide signs, and specific service signs. The freeway had 21 entrances and 22 exits that comprised 21 unique freeway segments, where a segment extended from exit gore to exit gore. Participants were not informed of how many exits were signed for the assigned destinations. There was one of each. The number of specific service signs per segment varied between zero and three. The number of specific service signs also varied from zero to three. There were always two advance guide signs per segment, but some exits had two street name destinations per sign while the remainder listed only one street name. The number of street names on the exit for Holt Avenue was a between-group variable with two levels (one or two street names). The number of supplemental guide signs per exit varied between one and three and was a with-group variable. The number of destinations per sign varied from one to two. The number of supplemental guide signs and the number of destinations at the exit for Harvard varied among subjects.

Dependent measures were the probability of taking correct and incorrect exits, the frequency and duration of various eye-glance measures, and speed and lane keeping in the proximity of guide signs.

The Simulator

The experiment was conducted in the FHWA highway driving simulator. In the simulator experiments described earlier in this report, the simulator's out-of-vehicle display consisted of a horizontal projection of a 240-degree field of view onto cylindrical screen. However, at the time of this study, the projectors had exceeded their life expectancy and were no longer capable of achieving the necessary brightness or resolution to support a sign study. Because the projectors could not be replaced within the timeframe of this study, three high-resolution LCD monitors were used to display the forward 104 degrees of the field of view. Figure 55 shows the view of the roadway on the LCD monitors. (The image on the monitors is from a subsequent study.) Two of the original projectors were used to complete the side portions of the 240-degree horizontal display. Each of the LCDs was 30 inches (0.76 m) on the diagonal with a 16:10 aspect ratio. The LCD monitors' resolution was 2,560 horizontal pixels by 1,600 vertical pixels. LCD brightness was approximately 108 fl (370 cd/m^2) with a typical contrast ratio of 1,000:1. The distance of the monitors from the driver's eye point varied with driver height and seat position. The nominal distance of the center monitor was 36 inches (0.9 m). The right and left monitors were 39 and 49 inches (1 and 1.2 m) from the design eye point, respectively. All distance measurements were to the center of the respective displays. Images on each display were scaled to present a 1:1 correspondence with the real-world equivalents of the virtual world. All displays refreshed at 60 Hz. The minimum pixel response time on the LCD was 8 ms.

Figure 55. Photo. View of the three LCD monitors from slightly behind the driver's eye point.

Because the LCDs were relatively close to the driver's eye point, the simulated horizon height was adjusted to account for eye-point height differences of individual participants.

The LCD monitors were mounted in the windshield area of the sedan in the simulator. This placement required removal of the windshield. The simulator's motion base was not enabled in this experiment. The car's instrument panel, steering, brake, and accelerator pedal all functioned in a manner similar to real-world compact cars. Rear view mirrors were simulated using 7.8-inch-wide (20 cm) by 4.8-inch-high (12 cm) color LCD with 800 pixels horizontally and 480 pixels vertically. These displays had a contrast ratio of 400:1. Left and right outside simulated mirrors were mounted over the sedan's original outside mirrors. The center-mounted rear view LCD was placed as near as possible to the location of the vehicle's original mirror.

The simulated vehicle was equipped with a hidden intercom system that enabled communications between the participant and a researcher who ran the experiment from a remote control room. The researcher in the control room could also view the face video from the eye-tracking system and thereby monitor the participant's wellbeing.

The Simulation Scenario

Seven signing conditions were simulated across 21 freeway segments, where each segment had one entrance merge and one exit. Table 28 summarizes the key attributes of each condition. All conditions had three interchange guide signs; a 1-mi (1.6-km) advance sign, a 0.5-mi (0.8-km) advance sign, and a sign at the exit gore. Specific-service signs always preceded the 1-mi (1.6-km) advance guide sign. The distances between each specific-service sign and the third specific-service sign with the 1-mi (1.6-km) advance sign are shown in the column labeled "Distance Between Signs" in table 28. With one exception, the supplemental guide signs were placed between the 1-mi (1.6-km) advance sign and the 0.5-mi (0.8-km) advance sign. In condition 3, one supplemental sign followed the 1-mi (1.6 km) advance sign by 800 ft (244 m), and one supplemental sign followed the 0.5-mi advance sign by 800 ft (244 m). The distances between the 1-mi (1.6 km) advance sign and the other supplemental guide signs is specified in the "Distance Between Signs" column of table 28. The number of destinations applies to both the advance guide signs and the supplemental guide signs. Each destination appeared once across the 21 segments.

Table 28. Summary of the seven signing conditions.

Condition	Advance Guide Signs	Supplemental Guide Signs	Specific-Service Signs	Number of Destinations	Distance Between Signs (ft)
1	3	0	0	1	2,640
2	3	1	1	1	800
3	3	1	1	2	800
4	3	2	1	1	800
5	3	2	2	2	800
6	3	3	3	2	400
7	3	3	3	2	200

1 ft = 0.305 m

The Holt Avenue exit was always on one of the first seven segments, the Harvard University exit was always on one of the second series of seven segments (i.e., 8 through 14), and the Holiday Inn® exit was always on one of the final seven exits. There were seven different orders in which the seven signing conditions were presented, and the seven target exits occurred equally often in each condition. With the exception of 2 participants, who were inadvertently run in the wrong conditions, each of the 49 combinations of targeted exits with order of conditions was presented to 2 participants.

Guide sign lettering used the FHWA series E (modified) font with nominal 18-inch (46 cm) letter height. To achieve the appropriate legibility distance (800 to 1,000 ft (244 to 305 m) for the signs, all signs were oversized by a factor of 1.5. This resulted in letters subtending a visual angle equivalent to a 27-inch- (68-cm-) high lettering. The street names on the advance guide signs were all interchange street names from I-10 between Los Angeles, CA, and Ontario, CA. The destinations of the supplemental guide signs consisted of colleges, museums, and other destinations with no correspondence to actual geography (e.g., Cal Tech and the University of Virginia appeared on the same supplemental sign).

All specific-service signs displayed six logos. The logos on the specific-service signs, which were also oversized, were business logos used on signs on I-95 in Virginia. More than 30 unique logos were used. The MUTCD specifies that where lodging, food, and gas services are displayed, the signs are sequenced in that order.(2) However, in this experiment when more than one service sign was present, the lodging services sign was always preceded by a food services sign. The reversal in the normal order was intended to make the search task more challenging. It was assumed that most motorists are unaware of the order specified by the MUTCD for service signs. The business logos on the signs varied from exit to exit as did the position of individual logos that appeared on multiple signs. The target logo (i.e., Holiday Inn®) was always in the center of the lower row on the lodging sign. Nominally, condition 1 did not include specific-service or supplemental guide signs. However, as was done for all participants, the research design called for condition 1 participants to take an exit signed for the Holiday Inn® and Harvard University. Therefore, for condition 1 participants, a lodging or supplemental guide sign was added at the intended exits so that all participants in all conditions would correctly take three exits if they made no navigation errors.

To make the driving workload somewhat realistic, a traffic simulation model was used to generate traffic. Although the same traffic was generated for all participants (the traffic model random number seed was constant), the location of individual participants in the traffic stream could and did vary depending on how fast the participant drove and in which lanes he or she traveled. Traffic counters were located between each exit, and the number of vehicles crossing a counter while the participant was between the respective exits was recorded. Table 29 shows the resulting statistics for vehicles per lane per hour during the time a participant was somewhere in the respective zones. Software failures resulted in some data loss as indicated by the Number of Participants column, which shows the number of participants contributing to each zone statistic.

Table 29. Vehicles/lane/h summary statistics for each data collection zone.

Zone	Number of Participants	Mean	Standard Deviation	Minimum	Maximum
1	97	963	222	72	1,213
2	97	985	215	99	1,227
3	96	1,012	201	197	1,223
4	96	1,024	193	111	1,214
5	96	1,050	170	365	1,269
6	96	1,060	170	344	1,289
7	96	1,069	151	364	1,272
8	96	1,077	142	411	1,256
9	96	1,077	138	372	1,357
10	96	1,085	128	423	1,283
11	96	1,091	127	414	1,234
12	96	1,084	132	359	1,311
13	96	1,078	126	382	1,284
14	96	1,073	121	427	1,273
15	96	1,079	131	424	1,411
16	96	1,082	127	400	1,320
17	96	1,070	133	376	1,320
18	96	1,062	131	425	1,301
19	96	1,064	142	368	1,292
20	96	1,049	154	383	1,289
21	50	953	239	423	1,453

The simulated traffic did not enter or exit the freeway at any point. However, the simulated vehicles did change lanes and execute passing maneuvers. Participants who drove faster than 65 mi/h (105 km/h) and attempted to closely follow other vehicles encountered more traffic than participants who maintained 65 mi/h (105 km/h) or less.

Table 30 shows the percent of vehicles in each lane for which each of four desired speeds was specified. The minimum desired speed in the right lane was set at 70 mi/h (113 km/h) so that participants who were instructed to maintain 65 mi/h (105 km/h) would not have an incentive to leave the right lane.

Table 30. Speed parameters (percent vehicles per speed bin per lane) for traffic control by the traffic simulation model.

Lane	Speed (Mi/h)			
	65	70	75	80
Lane 1 (right)	0	50	25	25
Lane 2	10	70	20	0
Lane 3	0	25	71	4
Lane 4 (left)	0	0	95	5

1 mi/h = 1.6 km/h

Eye-Tracking System

The same eye-tracking system was used in this experiment as in the previous simulator experiments in this report. The mean (M) accuracy of left-eye gaze-position across participants was 1.3 degrees (radius) with an SD of 0.65 degrees (95th percentile accuracy M = 2.3, SD = 1.2). The mean accuracy of right-eye gaze-position across participants was 1.6 degrees (radius) with an SD of 0.83 degrees (95th percentile accuracy M = 2.9, SD = 1.9). The eye-tracking data (e.g., gaze direction of each eye, head position, etc.) were merged with data from the simulator (e.g., vehicle speed, lane position, and steering wheel position) and the current forward view of the simulation visual scene (approximately 39 degrees horizontal by 24 degrees vertical). The merge was accomplished using a MAPPS® scene recorder.(61)

To quantify when and for how long participants looked at each guide sign, a researcher used analysis software to indicate an ROI on individual frames of the recorded video image. An example of an analyst's screen with a coded ROI for specific-service signs 400 ft (122 m) apart is shown in figure 56. Also shown is the road ahead ROI. When three specific-service signs were 200 ft (61 m) apart, their ROI overlapped with ROIs for the following advance guide sign and supplemental guide sign. Where ROIs overlapped, a set of priorities determined which ROI was credited to a gaze vector that landed on the overlap. The order of priorities, from highest to lowest, was specific service, supplemental, advance, and road ahead. These priorities had the greatest effect in condition 7, where the signs were 200 ft (61 m) apart. Only conditions 6 and 7 had ROIs that included more than one sign, and only signs that were 200 ft (61 m) or 400 ft (122 m) apart.

Each ROI included the sign and approximately 8 ft (2.4 m) (virtual) to each side of the sign. Each ROI was coded for 10 s on the approach to the sign and terminated when the sign began to pass out of the forward 39-degree field of view (i.e., was more than 19.5 degrees to the right driver's forward view). For ROIs that included more than three signs, the coding began 10 s before reaching the first of the signs and ended when the last sign passed out of the field of view. Figure 57 shows an ROI for a specific-service sign, and figure 58 shows an ROI for an advance guide sign.

Figure 56. Screen capture. Analyst's screen for coding shows ROI for specific-service signs that are 400 ft (122 m) apart.

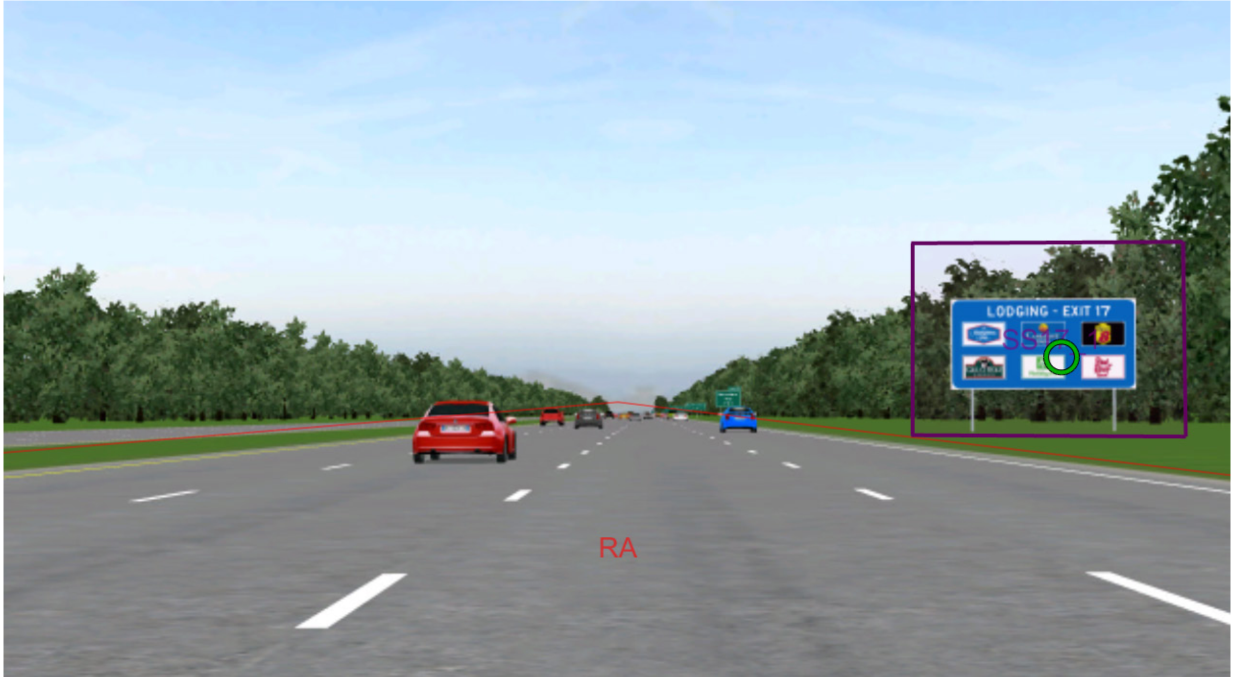


Figure 57. Screen capture. ROI drawn around a specific-service sign.

Figure 58. Screen capture. ROI drawn around an advance guide sign.

Participants

Participants were recruited from a list of volunteers maintained by FHWA's Safety Research and Development Human Factors Team. Of 127 individuals recruited, 113 completed driving the entire scenario. Of the 14 individuals who did not complete the drive, 2 dropped out because of simulator sickness, 2 elderly people had trouble with instructions or controlling the vehicle, 8 persons either could not be calibrated for eye tracking or otherwise did not track well, and with 2 persons, the simulator hardware or software failed.

Of the 113 participants who completed the drive, 98 provided usable eye-tracking data. During recruitment, an attempt was made to balance the sample with respect to age and gender. Because the median age in the participant database was 46 years, the goal was to recruit equal numbers of male and female drivers over 46 and 46 years of age or younger. The mean age of the 98 participants with complete data was 44 years (range 18 to 76 years), with 49 females and 49 males.

Instructions

The instructions to participants were as follows:

> You will be driving on a freeway that has four lanes in the direction you are traveling. There will be other vehicles on the road, although traffic should not be heavy. You should obey the law and drive as you normally would. You can drive in any lane you choose. The posted speed limit is 65 miles per hour. Your task is to watch for three destinations: Holt Ave, Harvard University, and the Holiday Inn. When you see the exit for any of these destinations, take that exit. We will be recording how you drive and where you look. Please drive as you normally

would. If you travel close to 65 MPH and take all the correct exits, you will receive a $10 bonus. Do you have any questions? The trip should take about 45 min.

Remember, you are looking for:

- Holt Ave
- Harvard University
- The Holiday Inn

Participants were also handed a picture of the Holiday Inn® logo so it could be assumed that the target logo was familiar.

Before beginning the test drive, participants completed a practice drive. The practice drive was similar to the test drive except that there was no traffic and there were only three exits. The exits on the practice drive were signed for the Holiday Inn®, Harvard University, and Holt Avenue and were presented in that order. Each of the practice exits had three guide signs, one specific-service sign, and one supplemental guide sign with spacing compliant with the MUTCD guideline.(2)

Participants received $40/h compensation for a typical 1.5 h of participation. In addition, the $10 bonus mentioned in the instructions was paid when appropriate.

RESULTS

Throughout this report, error bars in the charts and graphs represent 95-percent confidence limits around the means.

Exit Taking

Table 31 shows the percent of participant results for the first seven exits, one of which contained advance guide signs with the Holt Avenue destination. Recall that each condition was represented once among the first seven segments. Therefore, for each condition, a correct response is indicated on the positive diagonal (i.e., no/no and yes/yes cells), if guide signs did not include Holt Avenue, then the correct response was not to exit (no/no), and if the guide signs listed Holt Avenue, then the correct response was to exit (yes/yes). If the participant took an exit that did not have Holt Avenue as a destination, then that participant is represented in the upper-right cell for that condition (no/yes), and if the participant failed to take the Holt Avenue exit, then that participant is represented in the lower-left cell for that condition.

Table 31. Percent of participants on segments 1–7 who responded correctly to guide signs (no/no and yes/yes) and false alarms (no/yes) and misses (yes/no) as a function of signing condition.

Condition	Holt Exit Present	Exited? No (percent)	Exited? Yes (percent)
1	No	85.7	0
	Yes	1.0	13.3
2	No	83.7	3.1
	Yes	0	13.3
3	No	85.7	0
	Yes	0	14.3
4	No	84.7	1.0
	Yes	0	14.3
5	No	85.7	0
	Yes	1.0	13.3
6	No	84.7	0
	Yes	0	15.3
7	No	84.7	1.0
	Yes	2.0	12.2

Table 32 shows the analogous results for segments 8–14, where the correct exit had a supplemental guide sign that listed Harvard University as a destination. Table 33 summarizes exit-taking performance for segments 15–21, where the correct exit had a supplemental guide sign with the Holiday Inn® logo.

Table 32. Percent of participants on segments 8–14 who responded correctly to the supplemental guide signs (no/no and yes/yes) and false alarms (no/yes) and misses (yes/no) as a function of signing condition.

Condition	Harvard Exit Present	Exited? No (percent)	Exited? Yes (percent)
1	No	84.7	1.0
	Yes	0	14.3
2	No	86.7	0
	Yes	0	13.3
3	No	85.7	0
	Yes	0	14.3
4	No	84.7	1.0
	Yes	2.0	12.2
5	No	84.7	1.0
	Yes	1.0	13.3
6	No	84.7	0
	Yes	1.0	14.3
7	No	85.7	0
	Yes	3.1	11.2

Table 33. Percent of participants on segments 15–21 who responded correctly to the specific-service signs (no/no and yes/yes) and false alarms (no/yes) and misses (yes/no) as a function of signing condition.

Condition	Holiday Inn® Exit Present	Exited? No (percent)	Exited? Yes (percent)
1	No	85.7	0
	Yes	1.0	13.3
2	No	86.7	0
	Yes	0	13.3
3	No	85.7	0
	Yes	1.0	13.3
4	No	84.7	1.0
	Yes	1.0	13.3
5	No	85.7	0
	Yes	0	14.3
6	No	84.7	0
	Yes	0	14.3
7	No	85.7	0
	Yes	1.0	13.3

There were very few exit-taking errors, and the errors that were observed did not appear to be associated with a type of sign (i.e., street name, supplemental destination, and specific service) or with any of the variables associated with the seven signing conditions (i.e., sign spacing, number of signs, or number of destinations on the signs). It is important to remember that the participants were not informed which exits might have which target destination and therefore were expected to search for all 3 targets at all 21 exits. The distinction between the three sets of seven exits is made so that if there were a difference in the detection rate of a particular type of target, that could be seen. Also it is evident that the target detection rate was stable across the 21 exits.

The research design was not factorial with respect to the number of signs, the number of destinations on a sign, or the distance between signs. Therefore, pairwise comparisons were used to test for significant differences with respect to individual factors and interactions between factors. For instance, to test whether the distance between signs affected correct exit taking, McNemar's Test was performed on the data in table 34. The No/No cell is empty because no participant made an exit error in both condition 6 (400 ft (122 m) between signs) and condition 7 (200 ft (61 m) between signs). One participant (1.02 percent) made no errors in condition 7 and at least one error in condition 6. Six participants made at least one error in condition 7 but none in condition 6. Ninety-one participants made no errors in either condition 6 or 7. Although there were more errors with 200-ft (61-m) sign separation than with 400-ft (122-m) separation, this difference is small and not statistically significant at the 0.05 level.

Table 34. Percent of participants who responded in either conditions 6 or 7 or both 6 and 7.

	Condition 7	
Condition 6	**No**	**Yes**
No	0	1.02
Yes	6.12	92.86

In all cases, McNemar's Test assuming a binomial distribution was used.(62) No significant differences in correct exit-taking behavior were observed as a function any of the three factors or their interactions.

Gaze Behavior

Only glance and fixation measures were used in the analysis of gaze behavior in this study. Looks were not addressed for two reasons: (1) in the previous experiment, the look measure led to conclusions similar to those for the glance and fixation measures, and (2) where gaze vectors fell near the border between ROIs, it was difficult to determine where one look ended and another began because the vector may frequently shift back and forth across the border between ROIs.

Glance Results

As in the previous simulator experiments, a *glance* was defined as any accumulation of 12 (12 × 0.008 s = 100 ms) or more hits on an ROI, where a hit is a single 120-Hz center of gaze vector estimate that falls on the sign's ROI.

Table 35 shows the probability of a glance to sign ROIs. Where there was more than one ROI for a sign type (e.g., first and second advance guide signs and the (third) exit guide sign), the probabilities for each ROI are shown. Cells are marked "N/A" if there was no second or third ROI. In conditions 5 and 6, there were three specific-service signs and three supplemental guide signs, but only one ROI that cover all three signs of the respective types. The probability of glancing at all unique signs was high and never less than 0.86. The probability of glancing at redundant second and third guide signs tended to be lower than for other signs but was never less than 0.74.

Table 35. Probability of glance at signs as a function of condition and sign type.

Condition	Sign Type	Probability of Glance by Order of Appearance		
		First	Second	Third
1	Guide	0.88	0.87	0.76
	Supplemental guide	0.93	N/A	N/A
	Specific service	0.86	N/A	N/A
2	Guide	0.89	0.89	0.74
	Supplemental guide	0.89	N/A	N/A
	Specific service	0.97	N/A	N/A
3	Guide	0.93	0.92	0.85
	Supplemental guide	0.94	N/A	N/A
	Specific service	0.98	N/A	N/A
4	Guide	0.88	0.83	0.75
	Supplemental guide	0.86	0.85	N/A
	Specific service	0.96	N/A	N/A
5	Guide	0.91	0.86	0.86
	Supplemental guide	0.94	0.96	N/A
	Specific service	0.94	0.96	N/A
6	Guide	0.95	0.92	0.80
	Supplemental guide[1]	0.99	N/A	N/A
	Specific service[1]	1.00	N/A	N/A
7	Guide	0.92	0.90	0.85
	Supplemental Guide[1]	0.99	N/A	N/A
	Specific Service[1]	0.99	N/A	N/A

N/A= Not applicable. No second or third ROI.

[1] One ROI included three consecutive signs.

Although the two advance guide signs and the guide sign at the exit contained redundant information, drivers tended to glance at each sign regardless of glances at the previous sign. Table 36 shows the conditional probability of glances at a second advance guide sign given that the first sign received a glance and the probability of a glance at an exit guide sign given a glance at the preceding (0.5 mi (0.8 km) advance guide sign.

Table 36. Probability of glancing at a subsequent guide sign given a glance at the preceding advance guide sign.

Condition	Probability (Glance to Second Given Glance to First)	Probability (Glance to Third Given Glance to Second)
1	0.91	0.82
2	0.92	0.79
3	0.95	0.87
4	0.89	0.81
5	0.9	0.92
6	0.92	0.83
7	0.91	0.9

The mean duration of glances to sign ROIs was calculated two ways. First, the average duration of glances was computed for all ROI instances where zero duration (actually 0.00001 s) was recorded when drivers did not glance at an ROI. This method provided an estimate of the total attention a sign might attract and is shown in table 37. Cells in table 37 marked "N/A" represent locations where signs did not exist. Second, the average durations of glances at an ROI was computed only for actual glances (i.e., mean duration of a glance given a glance took place). These means are shown in table 38. Recall that glance durations are the sum of all 0.0083-s hits of a gaze vector on an ROI and may include multiple fixations interspersed with glances elsewhere. Specific service-sign ROIs captured considerably longer glances, more than 3 s in all conditions except for the gas sign in condition 5, which still had an average glance duration of more than 2 s. In condition 6, three specific-service signs, 400 ft (122 m) apart, were included in one ROI; that ROI had a mean glance duration of 7.4 s. Assuming a speed of 95 ft/s (20 m/s), the ROI was present for 18 s. Thus for that 18 s, the sign captured visual attention 41 percent of the time, on average. The supplemental guide signs in condition 6 also received a high proportion of visual attention, about 34 percent of the 18 s exposure to that ROI. The specific-service and supplemental guide signs in condition 7 were 200 ft (61 m) apart, which resulted in an approximate exposure duration of 14 s rather than the 18 s in condition 6. For the 14 s that glances at the specific-service sign ROI could be recorded, the signs captured visual attention 42 percent of the time on average.

Table 37. Mean glance duration in seconds where 0 s was used for no glance.

Condition	Sign Type	Mean Glance Duration (s) by Order of Appearance		
		First	Second	Third
1	Guide	1.04	0.90	0.53
	Supplemental guide	1.77	N/A	N/A
	Specific service	3.11	N/A	N/A
2	Guide	0.96	0.94	0.56
	Supplemental guide	1.00	N/A	N/A
	Specific service	3.39	N/A	N/A
3	Guide	1.39	1.28	0.84
	Supplemental guide	1.63	N/A	N/A
	Specific service	3.26	N/A	N/A
4	Guide	0.92	0.85	0.58
	Supplemental guide	0.95	1.04	N/A
	Specific service	3.39	N/A	N/A
5	Guide	1.28	1.25	0.79
	Supplemental guide	1.63	1.96	N/A
	Specific service	2.16	3.18	N/A
6	Guide	1.11	1.35	0.83
	Supplemental guide	6.07	N/A	N/A
	Specific service	7.43	N/A	N/A
7	Guide	0.69	1.49	0.81
	Supplemental guide	4.47	N/A	N/A
	Specific service	5.88	N/A	N/A

N/A = Not applicable. No sign existed.

Table 38 provides mean glance durations without averaging in zero durations. As would be expected, these means were slightly longer than those shown in table 37. However, the patterns remained the same. Specific-service signs garnered glances more than twice as long as those directed at guide signs, and guide sign glance durations were brief. Where there were two destinations on advance and supplemental guide signs (conditions 3 and 5), glance durations were not substantially greater than when there was only one destination (conditions 1, 2, and 4).

Table 38. Mean glance duration in seconds for sign ROIs given a glance occurred.

Condition	Sign Type	Mean Glance Duration (s) by Order of Appearance		
		First	Second	Third
1	Guide	1.18	1.04	0.70
	Supplemental guide	1.91	N/A	N/A
	Specific service	3.63	N/A	N/A
2	Guide	1.08	1.06	0.75
	Supplemental guide	1.12	N/A	N/A
	Specific service	3.51	N/A	N/A
3	Guide	1.50	1.39	1.00
	Supplemental guide	1.74	N/A	N/A
	Specific service	3.34	N/A	N/A
4	Guide	1.05	1.02	0.78
	Supplemental guide	1.10	1.22	N/A
	Specific service	3.53	N/A	N/A
5	Guide	1.41	1.45	0.92
	Supplemental guide	1.74	2.05	N/A
	Specific service	2.30	3.33	N/A
6	Guide	1.17	1.46	1.04
	Supplemental guide	6.15	N/A	N/A
	Specific service	7.46	N/A	N/A
7	Guide	0.76	1.65	0.95
	Supplemental guide	4.50	N/A	N/A
	Specific service	5.96	N/A	N/A

N/A = Not applicable. No sign of this type was presented.

To further explore glance behavior, each 0.0083-s gaze vector was assigned to one of three object categories: signs, road ahead, and other. The other category included all gaze vectors with the forward 39- by 24-degree scene that were not on a sign or road ahead ROI. Such hits could be toward other driving-related information (e.g., traffic) or non-driving-related information (e.g., billboards). Hits on any guide sign, supplemental guide sign, or specific-service sign were included in the sign category.

The proportion of gaze to the three gaze categories was analyzed twice. The first analysis included the entire distance between the on-ramp merge area and exit gore. The second analysis focused on the area around the first advance guide sign so that any effect that resulted from increasing the number of signs and decreasing the space between signs would be maximized. Specifically, this second analysis spanned an area that began at the end of the entrance merge area and ended with last glance at a sign ROI before reaching the second advance guide sign.

The proportions of gaze were analyzed using a GEE model that assumed a gamma response distribution and identify link function. The response variable was proportion of time. Predictors in the model included object category (sign, road ahead, or other), signing condition, and the object-condition interaction. Significance was evaluated with Wald χ^2 statistics. Because the research design was not factorial, conditions were analyzed in pairwise fashion. The number of pairwise comparisons was large, which could increase the probability of type 1 errors (i.e., finding a significant effect due to chance variation in means that are not different in the population). To protect against this increase in type 1 errors due to alpha inflation, a *p* criterion of 0.002 was used rather than the traditional 0.05.

Condition 1 Versus 2—Effect of Addition of Specific-Service and Supplemental Guide Signs:

Condition 1 had no supplemental guide signs or specific-service signs except 2 participants for whom 2 out of 21 exits were designated with one of these signs. Condition 2 had one lodging sign and one supplemental guide sign, and the guide signs listed just one destination. Therefore, condition 1 represent a test of the effect of adding a specific-service and supplemental guide sign.

Category ($\chi^2(2) = 201.00$, $p < 0.001$), condition ($\chi^2(1) = 96.17$, $p < 0.001$), and the interaction ($\chi^2(2) = 105.38$, $p < 0.001$) were statistically significant. Because the interaction was significant, main effects are not discussed. Table 39 displays summary statistics for the comparison of conditions 1 and 2 where the response variable covered the entire data collection zone.

Table 39. Comparison of the GEE estimates proportion of gaze time between conditions 1 and 2 for the entire data collection zone.

	Condition 1			Condition 2		
Category	**Lower Confidence Limit**	**Mean**	**Upper Confidence Limit**	**Lower Confidence Limit**	**Mean**	**Upper Confidence Limit**
Other	0.45	0.48	0.52	0.44	0.47	0.50
Road ahead	0.45	0.49	0.52	0.41	0.44	0.48
Signs	0.03	0.03	0.04	0.08	0.09	0.10

As can be seen in table 40, the proportion of time to other was relatively constant, whereas there was a tradeoff between the proportion of time to road ahead and signs: proportion of time to road ahead decreased from condition 1 to 2, and the proportion of time to signs increased.

As with the full data collection zone analysis, when only the area around the first advance sign is considered, category ($\chi^2(2) = 150.80$, $p < 0.001$), condition ($\chi^2(1) = 82.06$, $p < 0.001$), and the second-order interaction ($\chi^2(2) = 129.10$, $p < 0.001$) were significant. In this second analysis, the same tradeoff between road ahead and signs is evident, but more pronounced.

Table 40. Comparison of the GEE estimates of the proportion of gaze between conditions 1 and 2 for the area around the first advance guide sign.

	Condition 1			Condition 2		
Category	Lower Confidence Limit	Mean	Upper Confidence Limit	Lower Confidence Limit	Mean	Upper Confidence Limit
Other	0.45	0.49	0.53	0.45	0.47	0.50
Road ahead	0.43	0.46	0.50	0.33	0.36	0.40
Signs	0.04	0.05	0.06	0.15	0.17	0.18

Condition 2 Versus 3—Effect of Adding a Second Destination to Guide Signs:

Conditions 2 and 3 had the same number of signs, but the guide and supplemental guide signs in condition 3 listed two destinations. As can be seen in table 41 and table 42, the effect of adding destinations to the guide signs was to decrease the proportion of gaze time to the road ahead and perhaps to other. The interaction between category and condition was significant for both the entire data collection zone, $\chi^2(2) = 51.54$, $p < 0.001$, and the portion of the data collection zone around the first guide sign, $\chi^2(2) = 34.74$, $p < 0.001$.

Table 41. Comparison of the GEE estimates proportion of gaze between conditions 2 and 3 for the entire data collection zone.

	Condition 2			Condition 3		
Category	Lower Confidence Limit	Mean	Upper Confidence Limit	Lower Confidence Limit	Mean	Upper Confidence Limit
Other	0.44	0.47	0.50	0.44	0.47	0.50
Road ahead	0.41	0.44	0.48	0.40	0.43	0.46
Signs	0.08	0.09	0.10	0.10	0.11	0.12

Table 42. Comparison of the GEE estimates of the proportion of gaze between conditions 2 and 3 for the area around the first advance guide sign.

	Condition 2			Condition 3		
Category	Lower Confidence Limit	Mean	Upper Confidence Limit	Lower Confidence Limit	Mean	Upper Confidence Limit
Other	0.45	0.47	0.50	0.43	0.46	0.49
Road ahead	0.33	0.36	0.40	0.32	0.35	0.39
Signs	0.15	0.17	0.18	0.17	0.19	0.21

Condition 2 Versus 4—Effect of Adding a Second Supplemental Guide Sign:

The difference between conditions 2 and 4 was that condition 2 had only one supplemental guide sign, whereas condition 4 had two supplemental guide signs. All signs were 800 ft (244 m) apart with both supplemental guide signs coming after the first advance guide sign.

As can be seen in table 43, there was a slight increase in the proportion of gaze time at the signs and a slight decrease in the proportion of time at the road ahead when there were two supplemental guide signs rather than one. This resulted in a significant interaction of ROI category and condition, $\chi^2(2) = 17.33, p < 0.001$. When only the partial data collection zone was considered, the interaction effect was not statistically significant.

Table 43. Comparison of GEE estimates of the proportion of gaze between conditions 2 and 4 for the entire data collection zone.

	Condition 2			Condition 4		
Category	Lower Confidence Limit	Mean	Upper Confidence Limit	Lower Confidence Limit	Mean	Upper Confidence Limit
Other	0.44	0.47	0.50	0.45	0.48	0.51
Road ahead	0.41	0.44	0.48	0.39	0.42	0.46
Signs	0.08	0.09	0.10	0.09	0.10	0.11

Condition 3 Versus 5—Addition of a Second Specific-Service Sign and a Second Supplemental Guide Sign:

Conditions 3 and 5 both had two destinations listed on the guide signs. The difference between conditions 3 and 5 was that condition 3 had one specific-service sign and one supplemental guide sign, whereas condition 5 had two signs of each of those types. The second supplemental guide sign came 800 ft (244 m) after the second advance guide sign.

As can be seen in table 44, there was a tradeoff between the proportion of gaze time at the road and at signs. With the increase in the number of specific-service and supplemental guide signs, the signs captured more visual attention at the expense, primarily, of gaze at the road ahead. The interaction between condition and category was significant, $\chi^2(2) = 151.85, p < 0.001$.

Table 44. Comparison of GEE estimates of the proportion of gaze between conditions 3 and 5 for the entire data collection zone.

	Condition 3			Condition 5		
Category	Lower Confidence Limit	Mean	Upper Confidence Limit	Lower Confidence Limit	Mean	Upper Confidence Limit
Other	0.44	0.47	0.50	0.43	0.46	0.49
Road ahead	0.40	0.43	0.46	0.36	0.39	0.42
Signs	0.10	0.11	0.12	0.14	0.15	0.17

The partial data collection zone did not include the second supplemental guide sign. Thus, the partial data collection zone comparison was actually a test of the effect of adding a second specific-service sign.

As can be seen in table 45, signs captured about 6-percent more of the proportion of gaze when there were two specific-service signs rather than one. This increase in the proportion of gaze at the signs came at the expense of both the other and road ahead categories. The interaction between category and condition was statistically significant, $\chi^2(2) = 117.79$, $p < 0.001$.

Table 45. Comparison of GEE estimates of the proportion of gaze between conditions 3 and 5 for the partial data collection zone.

Category	Condition 3 Lower Confidence Limit	Condition 3 Mean	Condition 3 Upper Confidence Limit	Condition 5 Lower Confidence Limit	Condition 5 Mean	Condition 5 Upper Confidence Limit
Other	0.43	0.46	0.49	0.40	0.43	0.46
Road ahead	0.32	0.35	0.39	0.29	0.32	0.35
Signs	0.17	0.19	0.21	0.23	0.25	0.28

Condition 5 Versus 6—Effect of Adding a Third Specific Service and Supplemental Guide Signs and Reducing Distance Between These Signs to 400 ft (122 m):

Because the data collection zones were all the same length, adding a third specific-service sign and a third supplemental guide sign required reducing the distance between signs. In condition 4, the signs were all 800 ft (244 m) apart and thus were compliant with the MUTCD sign spacing requirement.(2) In condition 5, all signs prior to the second advance service sign were 400 ft (244 m) apart. Two destinations were listed on all guide signs in both conditions. The third specific-service sign was a gas sign that followed the lodging sign.

As can be seen in table 46, increasing the number of signs and decreasing the distance between signs increased the proportion of gaze at the signs at the expense of both the road ahead and other. The interaction between category and condition was statistically significant, $\chi^2(2) = 133.73$, $p < 0.001$. All of the differences between conditions 5 and 6 were in the partial data collection zone around the first advance guide sign. As can be seen in table 47, the proportion of gaze at the signs in this area increased by about 14 percent at the expense of both the road ahead (5 percent) and other (10 percent). The category by condition interaction was statistically significant, $\chi^2(2) = 280.81$, $p < 0.001$.

Table 46. Comparison of GEE estimates of the proportion of gaze between conditions 5 and 6 for the entire data collection zone.

Category	Condition 5 Lower Confidence Limit	Condition 5 Mean	Condition 5 Upper Confidence Limit	Condition 6 Lower Confidence Limit	Condition 6 Mean	Condition 6 Upper Confidence Limit
Other	0.43	0.46	0.49	0.39	0.41	0.44
Road ahead	0.36	0.39	0.42	0.35	0.38	0.41
Signs	0.14	0.15	0.17	0.20	0.21	0.23

Table 47. Comparison of the GEE estimates of the proportion of gaze between conditions 5 and 6 for the partial data collection zone.

Category	Condition 5 Lower Confidence Limit	Condition 5 Mean	Condition 5 Upper Confidence Limit	Condition 6 Lower Confidence Limit	Condition 6 Mean	Condition 6 Upper Confidence Limit
Other	0.40	0.43	0.46	0.31	0.33	0.36
Road ahead	0.29	0.32	0.35	0.25	0.27	0.31
Signs	0.23	0.25	0.28	0.37	0.39	0.42

Condition 6 Versus 7—Effect of Reducing Distance Between Signs from 400 ft (122 m) to 200 ft (61 m):

Conditions 6 and 7 were the same except for the distance between signs. In condition 7, the signs were 200 ft (61 m) apart. Because the differences between conditions were in the partial data collection zone, only the partial data collection zone results are presented. As can be seen in table 48, decreasing the distance between signs decreased the proportion of gaze at the signs. This effect may be because the data collection zone was only 600 ft (183 m) shorter in condition 7 than in condition 5, but the area containing the signs was 1,200 ft (366 m) smaller in condition 7. Thus, in condition 7, the proportion of time the signs were legible was reduced compared with condition 6. The reduction in the proportion of gaze time at the signs from condition 6 to 7 was statistically significant as indicated by the significant interaction between category and condition, $\chi^2(2) = 44.28, p < 0.001$.

Table 48. Comparison of GEE estimates of the proportion of gaze between conditions 6 and 7 for the partial data collection zone.

Category	Condition 6 Lower Confidence Limit	Condition 6 Mean	Condition 6 Upper Confidence Limit	Condition 7 Lower Confidence Limit	Condition 7 Mean	Condition 7 Upper Confidence Limit
Other	0.31	0.33	0.36	0.33	0.35	0.38
Road ahead	0.25	0.27	0.31	0.27	0.30	0.33
Signs	0.37	0.39	0.42	0.33	0.35	0.37

Summary of Paired Gaze Comparisons:

As signs were added and the space between signs was reduced, the proportion of time attending to the road ahead, as defined by the road ahead ROI, went down, and the proportion of gaze to signs increased. Table 49 shows how the proportion of time that the gaze vector fell on signs as a function of condition. Consistent with the duration of gaze data in table 38, the biggest increases in gaze at signs came when specific-service logo signs were added: from none to one (conditions 1 to 2), from one to two (condition 2 to 5), and from two to three (conditions 5 to 6).

Table 49. Summary of findings for proportion of gaze to signs.

Condition	Condition Description	Estimated Mean Proportion of Time to Signs
1	No specific-service or supplemental signs	0.03
2	One specific-service and supplemental sign	0.09
3	Add second destination to signs	0.11
4	Add second supplemental sign (one destination per sign)	0.10
5	Two specific-service and supplemental signs (two destinations)	0.15
6	Three specific-service and supplemental signs (400 ft (122 m) separation)	0.39
7	Three specific-service and supplemental signs (200 ft (61 m) separation)	0.35

Fixation Results

As in the previous simulator experiments, a *fixation* was defined as seven consecutive gaze positions (60 ms) within a fixation radius of 4 percent of the vertical image height (i.e., 29 pixels on a 720-pixel image) and centered on the first of the seven gaze positions that designated the start of a fixation. The fixation continued until there were six consecutive hits (50 ms) outside the fixation radius. For a simulated object 500 ft (152 m) ahead, the fixation radius subtended a visual angle of about 2 degrees. A fixation on an ROI was recorded if the center of the fixation was on the ROI.

The mean probability of at least one fixation falling on a sign ROI is shown in table 50. The probability of fixating on any particular guide sign (advance or exit) was somewhat lower than for specific-service and supplemental signs, perhaps because participants realized the guide sign information was redundant across the three signs and fixations on any one or two of the guide signs could be sloughed off without loss of information.

Table 50. Probability of fixating on each ROI category as a function of condition.

Condition	Sign Type	Probability of Fixation by Order of Appearance		
		First	Second	Third
1	Guide	0.77	0.77	0.61
	Supplemental guide	0.86	N/A	N/A
	Specific service	0.86	N/A	N/A
2	Guide	0.78	0.75	0.61
	Supplemental guide	0.78	N/A	N/A
	Specific service	0.93	N/A	N/A
3	Guide	0.84	0.82	0.72
	Supplemental guide	0.86	N/A	N/A
	Specific service	0.93	N/A	N/A
4	Guide	0.75	0.71	0.66
	Supplemental guide	0.74	0.74	N/A
	Specific service	0.94	N/A	N/A
5	Guide	0.80	0.79	0.71
	Supplemental guide	0.87	0.91	N/A
	Specific service	0.86	0.93	N/A
6	Guide	0.86	0.83	0.68
	Supplemental guide[1]	0.97	N/A	N/A
	Specific service[1]	0.98	N/A	N/A
7	Guide	0.77	0.85	0.74
	Supplemental guide[1]	0.98	N/A	N/A
	Specific service[1]	0.97	N/A	N/A

N/A = Not applicable. No second or third ROI.

[1] One ROI covered three signs from category.

The mean number of fixations as a function of condition and ROI category is shown in table 51. Note that the number of fixations on single lodging service signs is roughly twice that for supplemental guide signs, and food and gas signs received only slightly fewer fixations than the lodging signs. Table 52 shows the mean duration of each fixation on an ROI. For the specific-service signs in condition 6, the product of the average number of fixations multiplied by the average duration of fixations yields a total duration of fixation on that ROI of 7.68 s. With two specific-service signs in condition 4, the sum of the average fixation duration times their respective mean frequencies was 5.81 s. For a single specific-service sign in condition 2, the total fixation duration was 3.65 s. Although participants only needed to search the lodging sign, it is evident that food and gas signs added to their search time.

Table 51. Mean number of fixations as a function of condition and ROI category.

Condition	Sign Type	Mean Probability of Fixation by Order of Appearance		
		First	**Second**	**Third**
1	Guide	2.84	2.36	1.59
	Supplemental guide	4.21	N/A	N/A
	Specific service	7.79	N/A	N/A
2	Guide	2.52	2.53	1.54
	Supplemental guide	2.64	N/A	N/A
	Specific service	8.12	N/A	N/A
3	Guide	3.44	3.15	2.13
	Supplemental guide	4.19	N/A	N/A
	Specific service	8.06	N/A	N/A
4	Guide	2.36	2.28	1.63
	Supplemental guide	2.41	2.68	N/A
	Specific service	8.19	N/A	N/A
5	Guide	3.21	3.16	2.01
	Supplemental guide	4.13	4.93	N/A
	Specific service	5.51	8.00	N/A
6	Guide	3.09	2.27	2.06
	Supplemental guide	15.41	N/A	N/A
	Specific service	18.72	N/A	N/A
7	Guide	2.08	3.57	2.13
	Supplemental guide	12.61	N/A	N/A
	Specific service	15.44	N/A	N/A

NA = Not applicable. No second or third ROI.

Table 52. Mean fixation duration on ROIs given at least one fixation.

Condition	Sign Type	Mean Fixation Duration (s) by Order of Appearance		
		First	Second	Third
1	Guide	0.42	0.40	0.38
	Supplemental Guide	0.46	N/A	N/A
	Specific Service	0.40	N/A	N/A
2	Guide	0.42	0.41	0.38
	Supplemental Guide	0.41	N/A	N/A
	Specific Service	0.45	N/A	N/A
3	Guide	0.46	0.42	0.41
	Supplemental Guide	0.40	N/A	N/A
	Specific Service	0.45	N/A	N/A
4	Guide	0.45	0.38	0.41
	Supplemental Guide	0.42	0.42	N/A
	Specific Service	0.47	N/A	N/A
5	Guide	0.46	0.46	0.42
	Supplemental Guide	0.45	0.43	N/A
	Specific Service	0.43	0.43	N/A
6	Guide	0.42	0.46	0.47
	Supplemental Guide	0.41	N/A	N/A
	Specific Service	0.41	N/A	N/A
7	Guide	0.35	0.45	0.43
	Supplemental Guide	0.34	N/A	N/A
	Specific Service	0.39	N/A	N/A

N/A = Not applicable. No second or third ROI.

The proportion of fixations on the three categories of ROI, sign, road ahead, and other were analyzed in the same manner as the gaze vector hits on ROIs. As before, a GEE model was used that assumed a gamma distribution and identify link function. Significance was evaluated with a 0.002 alpha criterion.

Condition 1 Versus 2—The Effect of Adding One Specific-Service and One Supplemental Guide Sign:

As can be seen in table 53, adding two signs—a lodging sign and a supplemental guide sign—more than doubled the number of fixations on signs and reduced fixations on the road ahead. This interaction effect was statistically significant, $\chi^2(2) = 89.63$, $p < 0.001$. When looking only at the partial data collection zone, the results were similar, with a higher proportion of fixations on the signs compared with the road ahead, and the interaction effect was again significant.

Table 53. Estimated mean proportion of fixations on signs, road ahead, and other as a function of signing condition over the entire data collection zone.

	Condition 1			Condition 2		
Category	Lower Confidence Limit	Mean	Upper Confidence Limit	Lower Confidence Limit	Mean	Upper Confidence Limit
Other	0.28	0.32	0.37	0.28	0.31	0.35
Road ahead	0.60	0.64	0.68	0.54	0.58	0.62
Signs	0.05	0.05	0.06	0.10	0.11	0.13

Condition 2 Versus 3—The Effect of Adding a Second Destination:

As can be seen in table 54, which shows the proportion of fixations over the entire data collection zone, the addition of a second destination on the guide signs added about 3 percent to the proportion of fixations on signs and reduced the proportion of road ahead fixations by a similar amount. This resulted in a significant category by condition interaction, $\chi^2(2) = 35.95$, $p < 0.001$.

Table 54. Estimated mean proportion of fixations on ROI categories as a function of signing conditions 2 and 3 over the entire data collection zone.

	Condition 2			Condition 3		
Category	Lower Confidence Limit	Mean	Upper Confidence Limit	Lower Confidence Limit	Mean	Upper Confidence Limit
Other	0.28	0.31	0.35	0.28	0.31	0.35
Road ahead	0.54	0.58	0.62	0.52	0.56	0.60
Signs	0.10	0.11	0.13	0.13	0.14	0.15

Condition 2 Versus 4—The Effect of Adding a Second Supplemental Guide Sign:

As can be seen in table 55, which shows the proportion of fixations over the entire data collection zone, the addition of a second supplemental guide sign added about 2 percent to the proportion of fixations on the signs at the expense of fixations on the road ahead and other. This resulted in a significant category by condition interaction, $\chi^2(2) = 19.30$, $p < 0.001$.

Table 55. Estimated mean proportion of fixations on ROI categories as a function of signing conditions 2 and 4.

	Condition 2			Condition 4		
Category	Lower Confidence Limit	Mean	Upper Confidence Limit	Lower Confidence Limit	Mean	Upper Confidence Limit
Other	0.28	0.31	0.35	0.29	0.32	0.36
Road ahead	0.54	0.58	0.62	0.52	0.56	0.60
Signs	0.10	0.11	0.13	0.12	0.13	0.14

Condition 3 Versus 5—The Effect of Adding a Second Specific-Service and Second Supplemental Guide Sign:

As can be seen in table 56, which shows the proportion of fixations over the entire data collection zone, the addition of a second specific-service sign and a second supplemental guide sign added about 6 percent to the proportion of fixations on the signs at the expense of fixations on the road ahead. This resulted in a significant category by condition interaction, $\chi^2(2) = 168.56, p < 0.001$.

Table 56. Estimated mean proportion of fixations on ROI categories as a function of signing conditions 3 and 5.

	Condition 3			Condition 5		
Category	Lower Confidence Limit	Mean	Upper Confidence Limit	Lower Confidence Limit	Mean	Upper Confidence Limit
Other	0.28	0.31	0.35	0.27	0.31	0.35
Road ahead	0.52	0.56	0.60	0.47	0.50	0.55
Signs	0.13	0.14	0.15	0.18	0.20	0.22

Condition 5 Versus 6—The Effect of Adding a Third Specific-Service Sign and a Third Supplemental Guide Sign and Reducing Distance Between Signs to 400 ft (122 m):

As can be seen in table 57, which shows the proportion of fixations over the entire data collection zone, the addition of a third specific-service sign and a third supplemental guide sign added about 7-percent more fixations to the signs at the expense of fixations on other and the road ahead. This resulted in a significant category by condition interaction, $\chi^2(2) = 173.95$, $p < 0.001$.

Table 57. Estimated mean proportion of fixations on ROI categories as a function of signing conditions 5 and 6.

	Condition 5			Condition 6		
Category	Lower Confidence Limit	Mean	Upper Confidence Limit	Lower Confidence Limit	Mean	Upper Confidence Limit
Other	0.27	0.31	0.35	0.23	0.25	0.29
Road ahead	0.47	0.50	0.55	0.45	0.49	0.53
Signs	0.18	0.20	0.22	0.25	0.27	0.29

Condition 6 Versus 7: The Effect of Reducing the Distance Between Signs From 400 ft (122 m) to 200 ft (61 m):

As can be seen in table 58, which shows the proportion of fixations over the entire data collection zone, the reduction in the distance between signs resulted in a 4-percent decrease in the proportion of fixations on signs to the benefit of the road ahead and other. This resulted in a significant category by condition interaction, $\chi^2(2) = 101.26, p < 0.001$.

Table 58. Estimated mean proportion of fixations to the ROI categories as a function of signing conditions 6 and 7.

Category	Condition 6			Condition 7		
	Lower Confidence Limit	Mean	Upper Confidence Limit	Lower Confidence Limit	Mean	Upper Confidence Limit
Other	0.23	0.25	0.29	0.24	0.27	0.31
Road ahead	0.45	0.49	0.53	0.47	0.51	0.55
Signs	0.25	0.27	0.29	0.21	0.23	0.24

Although the trends and statistically significant effects were the same for the proportion of fixations in the full data collection zone and the partial data collection zone, the magnitude of the reduction in fixations on the road ahead is more striking when only the area around the first advance guide sign is considered. In the partial data collection zone for condition 6 (see table 59), which included more than 3,300 ft (396 m) of travel distance, the road ahead captured only 34 percent of fixations compared with the signs, which captured, on average, almost half the fixations.

Table 59. Partial data collection zone estimates of the mean proportion of fixations on ROI categories as a function of signing conditions 6 and 7.

Category	Condition 6			Condition 7		
	Lower Confidence Limit	Mean	Upper Confidence Limit	Lower Confidence Limit	Mean	Upper Confidence Limit
Other	0.16	0.18	0.20	0.18	0.20	0.23
Road ahead	0.30	0.34	0.38	0.32	0.35	0.40
Signs	0.45	0.47	0.51	0.41	0.43	0.46

Driving Performance Measures

Measures of the steering wheel position were not available for this study because of data collection problems related to a change in the driving simulator hardware.

Vehicle speed was analyzed for the partial data collection zones. It was hypothesized that if the signs caused information overload, drivers might slow to give themselves more time to search for the assigned destinations. On average, participants drove at the instructed speed of 65 mi/h (105 km/h). GEE models were used to test for difference in speed as a function of condition. A Gaussian response distribution with identity link function was assumed. Using an alpha level of 0.05, which does not adjust for experiment-wise error rate, there were two significant reductions in speed that were consistent with the hypothesis that information demand caused a speed reduction. The planned comparisons that were examined are shown in table 60. Estimated mean speed in condition 6 was significantly slower than estimated mean speed in condition 5, $\chi^2(1) = 5.36$, $p = 0.021$, and estimated mean speed in condition 2 was significantly faster than estimated mean speed in condition 7, $\chi^2(1) = 4.89$, $p = 0.027$.

Table 60. Planned between-condition vehicle speed comparisons.

Conditions Compared		Speed Reduction Significant?
1—No specific-service or supplemental guide signs.	2—One specific-service and one supplemental guide sign.	ns
2—One specific-service and one supplemental guide sign.	3—One specific-service and one supplemental guide sign. Two destinations per guide sign.	ns
2—One specific-service and one supplemental guide sign.	4—One specific-service and two supplemental guide signs.	ns
3—One specific-service and one supplemental guide sign. Two destinations per guide sign.	5—Two specific-service and two supplemental guide signs. Two destinations per guide sign.	ns
5—Two-specific service and two supplemental guide signs. Two destinations per guide sign.	6—Three specific-service and three supplemental guide signs. Two destinations per guide sign.	$p = 0.021$
6—Three specific-service and three supplemental guide signs. Two destinations per guide sign. Distance between signs: 400 ft (122 m).	7—Three specific-service and three supplemental guide signs. Two destinations per guide sign. Distance between signs: 200 ft (61 m).	ns
2—One specific-service and one supplemental guide sign.	7—Three specific-service and three supplemental guide signs. Two destinations per guide sign. Distance between signs: 400 ft (61 m).	$p = 0.027$

ns = Not significant.

Table 61 shows the estimated mean speed in the partial data collection zones as a function of signing condition. Although statistically significant differences were identified, all differences were less than 1 mi/h (1.61 km/h).

Table 61. Vehicle estimated mean speed (in mi/h) in the partial data collection zones as a function of signing condition.

Condition	Mean (mi/h)	95-Percent Confidence Limits (mi/h)
1	65.40	65.00–65.80
2	65.28	64.92–65.65
3	65.31	64.88–65.74
4	65.46	65.05–65.86
5	65.32	64.90–65.73
6	65.07	64.64–65.49
7	64.96	64.52–65.40

1 mi/h = 1.61 km/h

DISCUSSION

Participants in this experiment were given a task that is probably rare in the real world—to watch for a guide sign destination, a supplementary guide sign destination, or a hotel on a specific-service sign. Both the eye-tracking data and the exit-taking behavior suggest that the participants took the task seriously. The mean speed data suggest, however, that while monitoring the signs for the assigned destination, the participants continued to monitor the driving task sufficient to maintain the instructed speed.

The eye-tracking results appear to support the current MUTCD standards and guidance on the frequency and spacing of guide signs.(2) All additional signing resulted in increased eyes-off-road time. In particular, specific-service signs appear to be problematic. All specific-service signs had six logos. On average, participants fixated on a lone lodging sign for 3.65 s, with an average of about eight fixations that averaged 0.4 s each. Each additional logo sign added about 2 s of total fixation time, even though the additional signs were not lodging signs and did not require a search beyond noting the panel legend. When the fixation data were scored, it appeared that most participants searched all the specific-service signs for the Holiday Inn® logo. This suggests that the sign legends (i.e., food, lodging, and gas) had a minimal effect on search strategy.

The difficulty participants had in searching the logo signs may also be related to the distinguishability of the logos. Recent research that addressed the question of the maximum number of logos on a single specific-service sign used a reaction time paradigm to determine the amount of time it takes to detect a desired business logo on signs with four, six, or nine logos.(63) Participants' only task was to watch a video monitor and strike a key labeled "yes" if a particular logo was on the sign or a key labeled "no" if it was not. From the time the sign appeared until the participants pressed one of keys was the dependent measure. Mean reaction times for participants less than 50 years of age were 1.3 s, 1.6 s, and 2.2 s for four-, six-, and nine-panel signs, respectively. Based on the generally cited criterion that glances away from the road of more than 2 s are unsafe, the investigators recommend that nine-panel logo signs not be approved.(64,20) Two key assumptions underlie this recommendation. One is that looking at logo signs constitutes a glance away from the roadway. For most of the 10-s approach to the logo signs for which fixation data were collected in the present study, the signs were within 10 degrees of the participants' forward field of view. In naturalistic driving studies, these would not be considered glances away from the forward roadway, because in naturalistic driving studies, which to date have not used eye tracking technology, gaze direction measurement is accurate to a radius of 20 degrees.(65) By this criterion, 3.65 s might not be an unsafe amount of time to gaze at a roadside sign. Furthermore, although total fixation and gaze times at the specific-service signs were long, individual glances away from the roadway were general short—less than 0.5 s.

The other key assumption of the laboratory reaction time study was that the reaction time for deciding whether a particular logo is on a sign is an indicator of the amount of time a driver on the roadway would search for a logo on a sign. This assumption may be true in a relative sense, (i.e., longer laboratory reaction times indicate longer on-road search time). The present results suggest that the laboratory reaction time findings are not indicative of the absolute search time in a driving context. Search times on the six-panel signs in this study were more than twice the decision reaction times in the laboratory.

Whether search times of 3.7 s (one six-panel sign), 5.8 s (two six-panel signs) or 7.7 s (three six-panel signs) represent a distraction is not clear, although the search times should raise concerns, particularly when they represent close to half of the fixation time over more than 0.5 mi (0.8 km) of travel distance. A simulator study that presents various roadway hazards while participants search for specified logos might clarify this issue.

It is possible that with more distinctive logos, search times could be reduced. The target logo in the present study was light green on a white background. There were several logos, although none were lodging logos, with similar white backgrounds and low-contrast green images. However, many businesses have logos with low contrast and fine details that are not easily identified. Some national chains have logos that may be quickly identified at distances of 1,000 ft (305 m), but these are not the norm. In that sense, the present search task was a representative one. The MUTCD does not control the design of business logos, only the maximum size of logo panels on specific-service signs.(2)

Total fixation durations (number of fixations multiplied by mean fixation duration) for supplemental guide signs were less than 2 s when there was one supplemental sign containing either one or two destinations. With two supplemental guide signs with a single destination on each, the sum of fixation times was about 0.5 s longer than for two destinations on one sign. This suggests that combining two destinations on one sign, the recommended practice in MUTCD, is a better choice than using two signs for those destinations.(2) When there were two or more supplemental guide signs with two destinations on each, total mean fixation time ranged between about 4 and 6.3 s.

SUMMARY AND CONCLUSIONS

The MUTCD standards for supplemental guide signs are strongly supported by this research.

The findings with respect to specific-service signs are more problematic. The results certainly support not exceeding the current standard of no more than six logos per sign and no more than four signs with minimum separations of 800 ft (244 m). Methods for increasing the conspicuity of specific-service sign legends should be explored so that drivers do not unnecessarily search signs that list services that they are not seeking.

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