Active Traffic Management: Comprehension, Legibility, Distance, and Motorist Behavior in Response to Selected Variable Speed Limit and Lane Control Signing

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FOREWORD

Active traffic management (ATM) incorporates a collection of strategies allowing the dynamic management of recurrent and nonrecurrent congestion based on prevailing traffic conditions. These strategies help to increase peak capacity, smooth traffic flows, and enhance safety on busy major highways.

This final report describes a series of experiments that developed alternative signs focusing on dynamic lane assignment and variable speed limits and used the deployments in Minnesota and Washington as one of the inputs to sign development. Laboratory and field studies determined both the comprehension of the ATM signs as well as their respective legibility distances. Two driving simulator studies helped determine how motorists respond to these signs in a simulated driving environment.

While this document provides useful information on comprehension, preferences, human behavior, and decisionmaking with regard to ATM signing, the *Manual for Uniform Traffic Control Devices* provides the official Federal Highway Administration guidance in this area. The report and its findings and recommendations will be of interest to transportation professionals involved in operations, safety, and human factors, as well as others interested in safe and efficient roadway operations.

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16. Abstract

Active traffic management (ATM) incorporates a collection of strategies allowing the dynamic management of recurrent and nonrecurrent congestion based on prevailing traffic conditions. These strategies help to increase peak capacity, smooth traffic flows, and enhance safety on busy major highways.

This final report describes a series of experiments that developed and tested alternative signs focusing on lane control signs (LCS) and variable speed limit (VSL) signs and used the deployments in Minnesota and Washington as inputs to sign development. Laboratory and field studies determined both the comprehension of the ATM signs as well as their respective legibility distances. Two driving simulator studies helped determine how motorists responded to these signs in a simulated driving environment.

Research results are discussed for the various studies, including legibility distances, driver behavior, speed selection, and visual clutter with respect to the used of the LCS and VSL signs.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

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LIST OF ABBREVIATIONS

ATM	active traffic management
CMS	changeable message sign
MM–ALR	Managed Motorways–All-Lane Running
LCS	lane control sign
VSL	variable speed limit
DCZ	data collection zone
FHWA	Federal Highway Administration
GEE	general estimating equation
HOV	high occupancy vehicle
LED	light-emitting diode
MUTCD	*Manual on Uniform Traffic Control Devices*
RA	road ahead
ROI	region of interest
STD	standard deviation
LCD	liquid crystal display
RGB	red, blue, green

EXECUTIVE SUMMARY

Active traffic management (ATM) incorporates a collection of strategies allowing the dynamic management of recurrent and nonrecurrent congestion based on prevailing traffic conditions. These strategies help to increase peak capacity, smooth traffic flows, and increase safety on busy, major highways. Some popular approaches include variable speed limits (VSLs), lane control signs (LCSs), and hard-shoulder running, which are all controlled by overhead changeable message signs (CMSs).

This report describes four studies (one in a laboratory setting, one in a field setting, and two in a driving simulator) in which two particular ATM approaches were researched: VSLs and LCSs. The field study was conducted at a drag strip in Manassas, VA. All laboratory and simulator studies were conducted at the Federal Highway Administration's (FHWA) Turner-Fairbank Highway Research Center. Across these latter three studies, the following five scenarios were used to investigate participant response under various driving situations. Scenarios were presented on roadways with four lanes in the direction of travel, where lane 1 was the leftmost lane and lane 4 was the rightmost lane.

- Resting condition for the signs (normal operations for all lanes).
- Stalled vehicle closing one lane (lane 3).
- Vehicle crash closing two left lanes (lanes 1 and 2).
- Vehicle crash closing two right lanes (lanes 3 and 4; with exit ramp open).
- Message in the event of slow-moving traffic in all lanes (speed reduction).

The laboratory study examined how well drivers interpreted different VSL and LCS configurations, symbols, and messages as a function of scenarios. In addition, the comprehension of the different alternatives for the signs was tested (e.g., regulatory versus advisory speed limit signs, different signs for merge). Participants also rated their preference for alternative ATM signs. Sign stimuli were created using actual sign specifications and other information provided by the Minnesota and Washington transportation departments and the sign manufacturer for the Washington deployment. Individual sign types included lane open, lane open with caution, lane closed, lane closed ahead, merge, and VSLs.

The results of the laboratory study showed that participants frequently interpreted the ATM signs correctly as the signs were presented in sequence for a given scenario. Participants in the study had no previous experience with these types of signs, suggesting the ATM signs were, for the most part, intuitive. Errors included interpreting advisory VSL signs as regulatory speed limit signs, incorrectly interpreting green overhead guide signs, misinterpreting the lane closed ahead sign with a legend, and confusing the meaning of the lane open with caution options (both static and flashing). Participants were challenged in the scenario in which the two right lanes were closed except for the exit. One participant stated, "How can the lanes be open and closed at the same time?" These results were based on static testing in which participants only needed to pay attention to the signs. There was no driving task or other additional workload present in the test situation.

A subset of the ATM signs used in the laboratory study were selected for further field testing. This test was for a large number of CMS messages in which the ATM signs were a small subset. The principal focus of the field test was to obtain legibility distances for the signs. Data were collected on a closed course while participants drove an instrumented vehicle equipped with a dashboard-mounted eye-tracking system. Audio recordings were made to document participant response and comprehension.

The mean legibility distances for the speed limit signs were close to the maximum legibility distance in this test (1,250 ft (381 m)). The lane closed ahead sign had the lowest mean legibility distance (1,040 ft (317 m)) and the highest standard deviation (STD). The greater legibility distance and STD in responding to this sign was in part a result of the method used to obtain a response. A response did not conclude until the participant completed reading the message. Thus, if a participant struggled in interpreting the true meaning of the sign (i.e., the lane was closing in the near future), then the response duration was longer. In turn, the legibility distance decreased. A factor in the design of signs and the letter height used is the available time to read a sign at highway speeds. The lane closed ahead sign had an average legibility distance of 1,040 ft (317 m) at a speed of 65 mi/h (105 km/h); the reading time was approximately 11 s, which was greater than the design guideline minimum of 8 s. The ATM signs using the new CMS displays with high resolution resulted in legibility distances exceeding design guidelines for non-light-emitting diode (LED) signs (e.g., highway guide signs).

The next study used a driving simulator to examine driver decisionmaking in a dynamic environment. The study employed the same scenarios that were used in the laboratory study (the speed reduction scenario was shown twice) and examined drivers' responses (behavioral and eye-gaze movements) to and compliance with LCS and VSL signs.

Participants generally followed the directions on the ATM signs. In the speed reduction scenario, VSL signs showed lower speed limits every 0.5 mi (0.8 km). Participants decreased their speeds about 328 ft (100 m) after passing the signs. Although drivers slowed down in response to the VSL signs, they were traveling above the speed limit by an average of 10 mi/h (16 km/h). Eye-gaze behavior showed participants looked at the VSL signs about two times during these scenarios. Mean fixation durations ranged from 0.3 to 0.5 s and decreased significantly from the first to the second viewing of the VSL signs.

For the stalled vehicle scenario, participants exited their travel lane upon encountering the stalled car; no participant collided with the vehicle. Most of the participants (about 70 percent) exited their lane well in advance of when they were required to exit the lane. From a safety perspective, this may prove to be an effective behavior. However, early exiting of the lane by a large volume of traffic may not be optimal behavior from a traffic flow perspective. On average, participants slowed to about 5 mi/h (8 km/h) below the speed limit while approaching the stalled vehicle. The mean fixation duration to the LCS for this scenario was about 0.51 s, which was significantly longer compared with the other scenarios. Participants were able to obtain information from the signs without long (greater than 2 s) fixations.

When the two left lanes were closed because of a crash, most of the drivers remained in their lane or moved to the right lane, both of which would be correct responses. Speed behavior was similar to that observed for the stalled vehicle scenario. Average fixation duration to the LCS was about 0.4 s, which was shorter than for the stalled vehicle scenario but similar to the other scenarios. Participants were able to obtain information from the signs without long (greater than 2 s) fixations.

The scenario with the two right lanes closed owing to a crash was a bit challenging. Drivers were instructed at the start of the simulation to exit at Holt Ave (the exit in this scenario). Results showed the majority (74 percent) of the participants successfully exited at Holt Ave according to instructions. Drivers slowed (less than 5 mi/h (8 km/h) until they approached the exit and then significantly decreased their speeds as they neared the exit.

The second simulation study used the same scenarios as the previous laboratory and simulation studies. In addition, two different levels of roadway clutter (low and moderate) were included on the sides of the road. The focus of this study was driver behavior and decisionmaking under different scenarios.

Driver exit-taking behavior at Holt Ave was reviewed to determine whether the amount of visual information on the sides of the road had an effect on participant response. Results showed there was no difference in the exit-taking behavior under low and moderate levels of clutter. Overall, about 63 percent of the participants correctly exited at Holt Ave.

In the speed reduction scenario, the VSL signs displayed reduced speed limits every 0.5 mi (0.8 km). Participants decreased their speeds after they encountered the signs. Behavioral results of this second simulation experiment were similar to the results of the first. Eye-gaze data showed participants looked at the VSL signs an average of six times during these scenarios, and fixation durations averaged about 0.33 s. Compared with the first simulation study, there were more fixations on the VSL signs, but they were of a shorter duration.

For the stalled vehicle scenario, participants exited their travel lane upon encountering the stalled car; no participant collided with the vehicle. The majority of the participants (about 61 percent) exited their lane well in advance of when they were requested to do so. In this experiment, participants were shown VSL signs reducing the speed limit as they approached the stalled vehicle. Drivers responded to the VSL signs but were still traveling about 5 mi/h (8 km/h) above the new posted speed limits. These results were similar to those found in the previous simulation experiment. The mean fixation duration on the LCS for this scenario was about 0.33 s. However, there were multiple fixations on these signs (on average about eight fixations). This was different from the first simulation experiment where there were fewer, but longer, fixations on the LCS. Participants obtained information from the signs without long (greater than 2 s) fixations.

When the two left lanes were closed because of a crash, most of the drivers remained in their lane or moved to the right lane, both of which would be correct responses. Speed behavior was similar to that observed for the stalled vehicle scenario. Participants slowed in response to the speed limit decrease shown on the VSL sign but were traveling about 5 mi/h (8 km/h) above the new posted speed limit. The average fixation duration on the LCS was about 0.33 s, and there was an average of 7.5 fixations on the ATM signs. Fixations were of short duration but frequent, similar to what was observed in the stalled vehicle scenario. Participants obtained information from the signs without long (greater than 2 s) fixations.

The scenario with two right lanes closed due to a crash was a bit challenging. Drivers were instructed at the start of the simulation to exit at Holt Ave. Results showed the majority (63 percent) of the participants successfully exited at Holt Ave according to instructions. In this experiment, VSL signs were used to reduce the speed limit during the scenario. Data suggested participants did respond to the reduced speed limit and drove approximately 10 mi/h (16 km/h) above the new speed limits. The mean fixation duration on the ATM signs in this scenario was 0.33 s. However, the number of fixations on the ATM signs in this scenario was significantly greater (about 10 fixations on average) than for all of the other scenarios. Participants had many fixations on the ATM signs but they were of short duration.

The current report used a range of approaches to test different sign options for ATM. Numerous signs were screened using laboratory methods suitable for estimating sign comprehension and preference. In addition, field testing used an actual CMS for estimation of legibility distance because high resolution and brightness of the CMS could not be modeled with a laboratory liquid crystal display (LCD). Use of a subset of ATM signs in the field allowed accurate estimation of the legibility distance of these signs. A driving simulator was used to evaluate different sign options under various driving conditions, which allowed the evaluation of responses to the signs in a dynamic environment. The combination of approaches used resulted in assessment of the signs' comprehension, legibility distance, and effect on driver decisionmaking.

CHAPTER 1. INTRODUCTION

ATM incorporates a collection of strategies that allows the dynamic management of recurrent and nonrecurrent congestion based on prevailing traffic conditions.[1] These strategies help to increase peak capacity, smooth traffic flows, and increase safety on busy, major highways. Some popular ATM approaches include VSL signs, LCSs (also called dynamic lane markings), and hard-shoulder running, which are all controlled by overhead CMSs.

Although approaches vary, ATM strategies and signing are deployed or in development in the United States, the Netherlands, Germany, United Kingdom, Denmark, Australia, Austria, New Zealand, Israel, Greece, and other parts of the world.[1,2] This report describes research done on two particular types of ATM: VSL signing and LCSs. Previous research on VSL signs showed both safety benefits and efficiency improvements, although the evidence for efficiency improvements was less conclusive than desired.[2] The safety benefits from VSL signs are most often associated with reducing rear-end collisions. This is not surprising because VSL signs are effective at reducing speed variability.[3] In contrast, there have been relatively few studies on the impact of LCSs on driving behavior, safety, and throughput. However, one study involving a dynamic lane merge traffic control system that was deployed in Michigan indicated that this type of system could be helpful in reducing aggressive driving, increasing safety, and reducing delay at work zone lane closures.[4] Other studies compared the use of graphic displays to their equivalent text messages and found that graphic displays could improve drivers' abilities to identify available lanes in a problem area and help comprehension for non-native language drivers.[5]

In the United Kingdom, the Transport Research Laboratory conducted driving simulation studies to support the development of a new approach to the design of managed motorway schemes. The approach is referred to as Managed Motorways-All-Lane Running (MM-ALR).[6] The MM-ALR approach employs gantry-mounted signs for speed and lane control similar to those used in the United States for ATM. The studies focused on examining drivers' understanding of the signs, as well as their driving behavior in a simulator. The studies generally found that drivers understood the signs and executed the appropriate behaviors. The simulations included simulated traffic, which appeared to affect the participant's compliance with the speed limits. Participants tended to exceed the speed limit more than 50 percent of the time under all of the conditions that were evaluated.[7] The authors concluded that in busy traffic conditions, the speed of an individual driver was greatly influenced by the speed of surrounding traffic. Furthermore, some drivers may not have felt the need to maintain awareness of the current speed limit because it would influence their speed choice so little in busy traffic.

Although there is an increasing interest in VSL and LCS deployment in the United States, there are no design standards and a lack of empirical data on driver behavior as a function of sign design. At the time of this study, two LCS and VSL deployments in Washington and Minnesota used different approaches for sign structure and content. The two sites were using different symbols. In Minnesota, the per-lane CMSs were being added to existing sign structures and thus were in proximity to conventional highway signs. In Washington, the per-lane CMSs were installed on dedicated gantries, and additional CMS were used in conjunction with the per-lane signs. Both sites were operating under FHWA approvals to experiment with novel ATM signs (see chapter 1, section 1A.10, *Manual on Uniform Traffic Control Devices* (MUTCD), regarding experimentation).[8]

This report describes four studies (one in a laboratory setting, one in a field setting, and two in a driving simulator) in which two particular ATM approaches were researched: VSLs and LCSs. Chapter 2 describes a laboratory study in which participants viewed a series of lane control scenes from the perspective of a driver. Participants described what they thought the signs were intended to mean and what they would do in response to the signs. Subsequently, participants were asked which sign content alternatives they preferred. Chapter 3 describes a field test in which the legibility distance of a selected subset of sign alternatives was assessed. Chapters 4 and 5 describe experiments conducted in FHWA's Highway Driving Simulator to examine how drivers might behave in response to various scenarios in which LCSs and VSLs were employed. The experiments described in chapters 4 and 5 examined driver lane choice, speed, and eye-glance behavior in a dynamic environment in response to the same signs and scenarios examined in a static environment in chapter 3. Chapter 6 synthesizes the report and summarizes the important contributions made by this ATM study. The studies reported here were intended to contribute to the development of guidelines for consistent and effective ATM signing.

CHAPTER 2. SIGN COMPREHENSION STUDY

This study focused on comprehension of LCS and VSL signing and how drivers interpret different configurations, symbols, and messages as a function of scenario (e.g., one lane closed ahead, congestion ahead). Participants also rated their preference for alternative ATM signs.

METHOD

This study employed the sign-testing laboratory at Turner-Fairbank Highway Research Center. Signs were projected on a 60-inch (1.5-m) diagonal LED/LCD. Media Lab® software presented signs and recorded participant responses.[9]

STIMULI

Sign stimuli were created using sign specifications and other information provided by State transportation department staff and a sign manufacturer. All the LCSs were created using vector-based graphics software. Side-mounted CMSs and larger CMSs similar to those deployed in Washington were created in a CMS sign control and message generation software package.

The LCS was created using a matrix of circles that simulated the size and spacing of illuminated pixels on a real sign. (One pixel represents one group of red, blue, green (RGB) LEDs.) Because there were differences in the characteristics of the signs used in the deployment locations, a different matrix was developed for the two different sets of signs. Table 1 shows the characteristics of the sign stimuli based on the actual dimensions, pixel spacing, and color capabilities of the various sign types for each deployment location.

Table 1. Sign stimuli characteristics.

Deployment Location	Sign Matrix Dimension	Pixel Spacing (Pitch)	Color Capability
Washington—LCS	64 by 64 pixels	22 mm	Full color
Washington—SMS	80 by 80 pixels	22 mm	Full color
Washington—CMS	80 by 235 pixels	22 mm	Amber
Minnesota	64 by 80 pixels	20 mm	Full color

1 mm = 0.039 inches.
SMS = State-mounted dynamic message sign.

The scenarios were developed using information provided by the two State transportation departments that described typical standard operating procedures used in those locations.[10]

SCENARIO TESTING

The participants were presented a series of ATM signs representing a given scenario, with five ATM signs per scenario. The five scenarios were as follows:

1. VSL to manage congestion (recurring type, i.e., commute traffic).
2. Incident—lane closed (left-center with restricted high-occupancy vehicle (HOV) lane on left).

3. Incident—two right lanes closed with exit ramp open.
4. Incident—single center lane closed (right-center).
5. Resting condition (normal operations, free flow, etc.).

Two variations for these scenarios were presented to the participants. One variation was similar to the signs used in the Washington deployment, and the second was similar to the deployment in Minnesota. Figure 1 shows an example of a scene used in the scenario sign comprehension test. For each of the signs, the participants were asked the following questions:

- What do the signs mean to you?
- What action(s) would you engage in based on these signs?

Figure 1. Photo. Example slide from the scenario sign comprehension test (sign based on Washington deployment).

Figure 2 is a composite of five pictures for the VSL scenario (i.e., congestion). In the study, each of the photos was presented individually with the order of presentation proceeding from bottom to top of figure 2.

The first gantry showed the per lane signs in their "resting" condition (i.e., the signs are blank). The CMS on the right side informed the driver that there was a reduced speed zone ahead. The drivers should remain in their lane and drive within the speed limit. The second gantry showed a speed reduction to 45 mi/h (72 km/h) in the three right lanes. The third gantry showed a further reduction in the speed limit to 35 mi/h (56 km/h) in the three right lanes and to 45 mi/h (72 km/h) in the left lane. The drivers should remain in their lane and slow down to the new speed limit. The fourth gantry showed the speed limit had returned to the facility-set speed limit. The drivers could increase their speed to the new limit. The fifth gantry showed the signs in their “resting” condition. Drivers should now comply with the facility speed limit.

Figure 2. Screen capture. VSL scenario that shows the progression of what a driver would see driving down the road, going from bottom to top.

All of the scenarios based on a given State were presented together. The order of presentation of the scenarios was counterbalanced across participants. Half of the participants viewed the Washington-based scenarios first and the Minnesota-based ones second. The other half of the participants viewed the same signs in the reverse order.

INDIVIDUAL SIGN TESTING

Following the scenarios, participants were presented individual ATM signs for additional comprehension assessment. This assessment only included 45 LCSs that were presented in a different random order for each participant. The following sections describe the sign alternatives for the following LCS message categories: lane open, lane open with caution, lane closed, lane closed ahead, merge, and speed limit (regulatory or advisory).

Lane Open

Two different signs were shown. Both signs showed a downward pointing arrow in which one sign was based on the Washington deployment (see figure 3) and the other based on the Minnesota deployment (see figure 4).

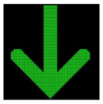


Figure 3. Graphic. Lane open sign adapted from Washington State deployment.

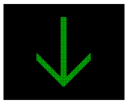


Figure 4. Graphic. Lane open sign adapted from Minnesota deployment.

Lane Open With Caution

Two different signs were shown based on the Minnesota deployment. One was a yellow arrow pointing down that flashes (at 1 Hz), and the second sign was the same yellow arrow in a static state (see figure 5).

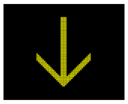


Figure 5. Graphic. Flashing or static lane open with caution sign adapted from Minnesota deployment.

Lane Closed

Three lane closed signs were included: (1) red X as used in Washington (see figure 6), (2) red X with the word "CLOSED" as used in Minnesota (see figure 7), and (3) red X as used in Minnesota without text legend.

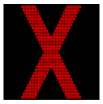


Figure 6. Graphic. Lane closed sign adapted from the Washington State deployment.

Figure 7. Graphic. Lane closed sign adapted from the Minnesota deployment.

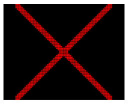


Figure 8. Graphic. Lane closed alternative without text legend.

Lane Closed Ahead

Five lane closed ahead signs were included: (1) yellow X with "1 mile" legend in white text (see figure 9), (2) thick yellow X without a text legend (see figure 10), (3) yellow X with "1 mile" legend as used in Minnesota (see figure 11), (4) yellow X with "1 mile" legend in yellow text (see figure 12), and (5) thin yellow X without a text legend (see figure 13).

Figure 9. Graphic. Lane closing in 1 mi sign adapted from Washington State deployment.

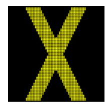


Figure 10. Graphic. Lane closing sign adapted from Washington State deployment.

Figure 11. Graphic. Lane closing in 1 mi sign adapted from Minnesota deployment.

Figure 12. Graphic. Alternative lane closing sign with yellow legend.

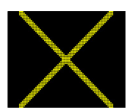


Figure 13. Graphic. Alternative lane closing sign.

Merge

Eighteen different yellow merge signs were shown to the participants. Nine of the signs used chevrons based on the signs in Minnesota: three signs with streaming chevrons for merge right (see figure 14), left (see figure 15), and split (see figure 16), each with the "MERGE" legend; three signs with streaming chevrons for merge left, right, and split without the word "MERGE" (see figure 17); and three signs with static chevrons for merge left, right, and split, with the "MERGE" legend (see figure 14 through figure 16 for a similar image). Nine different merge signs were based on the Washington deployment: three signs had the diagonal yellow arrow for merge left, right, and split; three signs had the diagonal yellow arrow for merge left (see figure 18), right, and split (see figure 19), each with the addition of the word "MERGE" in white text; and three signs had the diagonal yellow arrow for merge left, right, and split with the addition of the word "MERGE" in yellow text. In the Washington ATM deployment, white text was used, and so those signs were replicated here.

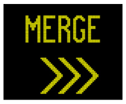


Figure 14. Graphic. Merge right sign adapted from Minnesota deployment.

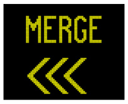


Figure 15. Graphic. Merge left sign adapted from the Minnesota deployment.

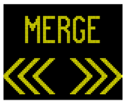


Figure 16. Graphic. Merge split sign adapted from Minnesota deployment.

Figure 17. Graphic. Example of merge sign without the text legend.

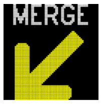


Figure 18. Graphic. Merge left sign adapted from Washington State deployment.

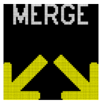


Figure 19. Graphic. Merge split sign adapted from Washington State deployment.

VSL Signs

White (regulatory speed limit) and yellow (advisory speed limit) signs were also presented to participants. For each function type (regulatory or advisory), there were signs using legends with the following combinations: number only (see figure 20); "SPEED LIMIT" preceding a number (see figure 21); and "MPH" following the number (see figure 22). In addition, a version of the Washington speed limit and Minnesota advisory speed limit signs with negative contrast were shown (see figure 23). A total of 15 speed limit signs were presented. Eight of the signs had larger fonts, as used in Washington, and seven had smaller fonts as used in the Minnesota deployment (see figure 24). Each VSL sign was presented once in yellow and black and once in white and black (e.g., figure 25). Although the use of yellow with the "SPEED LIMIT" text legend was inconsistent with the MUTCD, such signs were included to assess whether participants would detect the contradiction between regulatory wording and advisory coloring.[8]

Figure 20. Graphic. Number-only regulatory speed limit sign with large font.

Figure 21. Graphic. VSL adapted from Washington deployment.

Figure 22. Graphic. VSL with "MPH" legend and large font.

Figure 23. Graphic. VSL with negative contrast.

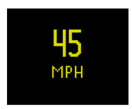


Figure 24. Graphic. VSL with font and color adapted from Minnesota deployment.

Figure 25. Graphic. VSL with yellow (advisory) colors.

SIGN COMPARISON

Following the presentation of the individual signs, the participants were presented the signs in each of the previously defined categories simultaneously on the LED/LCD. The participants' task was to select the sign that they preferred and to indicate why they preferred the selected sign.

Participants

There were 26 participants (14 males and 12 females). Participants ranged in age from 20 to 56 years old, with a mean age of 36 years old.

Scenarios

Participants were tested individually and instructed to assume they were driving alone and in the left-center lane of a multilane freeway (four lanes in each direction). For the Washington-based scenarios, the participants were instructed that the speed limit was 60 mi/h (97 km/h) unless posted otherwise. For the Minnesota-based scenarios, they were instructed that the speed limit was 55 mi/h (89 km/h). This was done to replicate the speed limits used in the Washington and Minnesota ATM deployments.

Scenarios were presented one picture at a time. There were five pictures for all of the scenarios except for the resting condition, which had four pictures. For each picture, participants were instructed to indicate when they were ready to describe what they would do in response to the depicted sign array, at which point the picture was removed from the screen. The accuracy of response was stressed over response time. The researcher recorded participant answers. This procedure was repeated for each picture in each scenario.

A brief break was taken when switching between the two types of scenarios (i.e., Washington or Minnesota deployments).

For convenience, this report describes the scenarios as emulating the Minnesota or Washington approaches. It is important to note that there was no intent to compare or evaluate the approaches taken in those States. Rather the intent was to explore a range of content and contexts. The existing experimental deployments provided sources of content and contexts. Some of the sign content was novel and not used in either deployment. An example of novel content was the use of white legends that implied a regulatory message with yellow symbols that implied advisory messages.

There were five scenarios that were intended to emulate the Minnesota ATM approach by using LCS and VSL content similar to that used in the State and suspending the per-lane CMS below conventional freeway signage.

The first Minnesota scenario contained the following pictures:

1. Four freeway lanes were displayed with an HOV designation for the leftmost lane. The CMS over the HOV lane displayed an HOV diamond symbol with positive contrast. The CMSs over the remaining three lanes were blank. Above the CMS with the diamond symbol was an MUTCD-compliant HOV regulatory sign.[8] A navigation sign spanned the area above the other three CMSs and displayed downward-pointing arrows for I-66 West.

2. The configuration was similar to the first picture, but now a 45 mi/h (72 km/h) speed advisory (see figure 24) was displayed above the three non-HOV lanes. The I-66 navigation sign spanned two center lanes, and a US-50 advance exit sign spanned the area above the rightmost CMS.

3. The configuration was similar to the second picture except for the following changes: the HOV-lane CMS was blank, the other three CMSs displayed a 40 mi/h (64 km/h) (advisory speed, the I-66 West sign was not displayed, and the US-50 advance exit sign spanned the area above the second lane from the right.

4. The configuration was similar to the second picture except that the advisory speed was 35 mi/h (56 km/h), and the CMS above the HOV lane was blank.

5. The configuration was similar to the second picture except that the three rightmost CMSs were blank, and the HOV diamond was displayed on the CMS above the HOV lane.

The second Minnesota scenario contained the following pictures:

1. Four freeway lanes were displayed with an HOV designation for the leftmost lane. The CMS over the HOV lane displayed an HOV diamond symbol with positive contrast. The CMSs over the remaining three lanes displayed advisory speed limits of 40 mi/h (64 km/h) (see figure 24). Above the CMS with the diamond symbol was an MUTCD-compliant HOV regulatory sign.[8] A guide sign spanned the area above the other three CMSs and displayed downward-pointing arrows (see figure 4) for I-66 West.

2. The configuration was similar to that in the first picture except for the following: the advisory speed limit was 35 mi/h (56 km/h), the I-66 West navigation sign spanned only the area above the center two lanes, and a US-50 advance exit sign was above the CMS over the rightmost lane.

3. The configuration was the same as in the second picture except for the following: the CMS above the HOV lane was blank, a yellow X with the legend “1 mile” was displayed over the lane next to the HOV lane, and the two per-lane CMSs on the right were blank.

4. The configuration was similar to that in the third picture except for the following: the CMS that had displayed a yellow X now displayed a scrolling merge right message as shown in figure 14, the US-50 advance exit sign was over the second lane from the right, and there was no I-66 West guide sign.

5. The sign configuration was similar to the second picture except for the following: a red X with the legend “CLOSED” was displayed over the lane next to the HOV lane (see figure 7); a flashing downward-pointing yellow arrow was displayed over the lane to the right of the closed lane (see figure 5), and a static green downward-pointing arrow (see figure 4) was displayed on the CMS over the right lane.

The third Minnesota scenario contained the following pictures:

1. The configuration was the same as the first picture in the second scenario.

2. The configuration was the same as the second picture in the second scenario except for the following: a yellow X with the legend “1 MILE” was displayed over the rightmost lane.

3. The configuration was the same as the third picture in the second scenario except for the following: the CMS over the third lane from the right was blank, the CMS over the second lane from the right displayed a yellow X with a “1 MILE” legend, and a merge left with scrolling chevrons message (see figure 15) was displayed over the rightmost lane.

4. The configuration was the same as the fourth picture in the second scenario except for the following: the CMSs over the two leftmost lanes were blank, the CMS over the second lane from the right displayed the merge left message with scrolling chevrons, and the CMS above the rightmost lane displayed a red X with the “CLOSED” legend.

5. The configuration was the same as the fifth picture in the second scenario except for the following: the two CMSs on the right displayed red Xs with the “CLOSED” legend, and

the CMS over the lane next to the HOV lane displayed a yellow flashing downward-pointing arrow.

The fourth Minnesota scenario contained the following pictures:

1. The configuration was the same as the first picture in the second scenario.

2. The configuration was the same as the second picture in the second scenario.

3. The configuration was the same as the third picture in the second scenario except that the yellow X with the "1 MILE" legend was over the second lane from the right rather than the third lane from the right.

4. The configuration was the same as the fourth picture in the second scenario except for the following: the merge sign was over the second lane from the right instead of the third lane from the right, and the merge chevrons suggested a merge into the lanes to the left or right (see figure 16).

5. The configuration was the same as in the fifth picture in the second scenario except for the following: the flashing yellow downward-pointing arrows were over the first and third lanes, and the red X indication was over the second lane from the right.

The fifth "resting" Minnesota scenario contained four pictures in which the conventional signage was the same as in the four other Minnesota scenarios. The per-lane CMSs were the same in all four pictures. That is, the diamond symbol was displayed over the HOV lane in each picture, and the CMSs over the other three lanes were blank.

There were five scenarios that were intended to emulate the Washington State ATM approach by using LCS and VSL content similar to that used in the State and suspending the per-lane CMS on gantries dedicated to ATM. In addition to the per-lane CMS, the Washington approach sometimes included a somewhat larger side-mounted CMS that provides additional information regarding the over-lane messaging.

The Washington scenarios also depicted four freeway lanes, with the leftmost lane dedicated to HOV. The first scenario contained the following pictures:

1. An HOV 2 indication was displayed on the CMS over the HOV lane and blank. There were CMSs over the three right lanes. The right side-mounted CMS contained white text on a black background with the text "REDUCED SPEED ZONE AHEAD."

2. A 60-mi/h (97-km/h) limit (see figure 21) was displayed on the CMS over the HOV land and a 45-mi/h (72-km/h) limit over the three right lanes. The right side-mounted CMS contained with text on a black background that read "REDUCED SPEED ZONE."

3. A 45 mi/h (72 km/h) limit was displayed over the HOV lane and 35-mi/h (56-km/h) limits over the three lanes to the right. The side-mounted CMS was the same as the previous picture.

4. CMSs were displayed over each lane with 60-mi/h (97-km/h) limits. The right side-mounted CMS was blank.

5. An HOV 2 indication was displayed on the CMS over the HOV lane, and blank CMSs were over the three right lanes. The side-mounted CMS was blank.

The second Washington scenario contained the following pictures:

1. An HOV 2 indication was displayed on the CMS over the HOV lane. A left side-mounted CMS with the following white text was displayed on a black background: "1 CENTER LANE CLOSED AHEAD." The CMSs over the right three lanes were blank.

2. The same HOV 2 indication was displayed as in the first picture. The same "1 CENTER LANE CLOSED AHEAD" was displayed on left and right side-mounted CMSs. The CMS on the lane to the right of the HOV lane displayed a yellow arrow pointing down to the right at a 45-degree angle with the word "MERGE" in white text above the arrow (similar to figure 18). The CMSs over the rightmost two lanes had downward-pointing green arrows (see figure 3).

3. The configuration was the same as in the second picture except for the following: the CMS to the right of the HOV lane displayed a large red X (see figure 6). There was no side-mounted CMS on the left side of the gantry, and the right side-mounted CMS read "1 CENTER LANE CLOSED."

4. The same HOV 2 indication was displayed as in the third picture. Left and right side-mounted CMSs were blank. There were downward-pointing green arrows over the three right lanes.

5. The configuration was the same as the first picture in this scenario except for the following: left and right side-mounted CMSs were blank, and the CMSs over the rightmost three lanes were blank.

The third Washington scenario contained the following pictures:

1. Left and right side-mounted CMSs were displayed with the message "2 RIGHT LANES CLOSED AHEAD." An HOV 2 indication was displayed on the CMS over the HOV lane. The three remaining per-lane CMSs were blank.

2. An HOV 2 indication was displayed on the CMS over the HOV lane. A downward-pointing green arrow was displayed on the CMS to the right of the HOV lane. The per-lane CMSs over the rightmost two lanes displayed yellow arrows pointing down and to the left at a 45-degree angle with the legend "MERGE" in white characters above the arrows. On the right, a large CMS was mounted at the same level as the per-lane CMSs that contained the two-line message "2 RIGHT LANES EXIT ONLY" in yellow text.

3. A left side-mounted sign read "2 RIGHT LANES CLOSED" in white text. A right side-mounted sign read "2 RIGHT LANES EXIT ONLY." Large red Xs were displayed on the CMSs over the right two lanes. A large downward-pointing green arrow was

displayed over the third lane from the right. An HOV 2 indication was displayed over the HOV lane.

4. Left and right side-mounted signs were blank. Large downward-pointing green arrows were displayed on the CMSs over the right three lanes. An HOV 2 indication was displayed over the HOV lane.

5. Left and right side-mounted CMSs were blank. The CMSs over the rightmost three lanes were blank. An HOV 2 indication was displayed on the CMS over the HOV lane.

The fourth Washington scenario contained the following pictures:

1. A left side-mounted CMS displayed the message “1 CENTER LANE CLOSED AHEAD,” and an HOV 2 indication on the CMS was over the HOV lane. The three remaining per-lane CMSs were blank.

2. Left and right side-mounted CMSs displayed the message “1 CENTER LANE CLOSED AHEAD,” and a HOV 2 indication on the CMS was over the HOV lane. Downward-pointing green arrows were displayed over the first and third lanes from the right. Yellow arrows pointing down and to the left and right were displayed over the second lane from the right. “MERGE” in white lettering appeared above the two yellow arrows pointing downward to the left and right at a 45-degree angle (see figure 19).

3. A right side-mounted CMS displayed “1 CENTER LANE CLOSED,” and an HOV 2 indication was on the CMS over the HOV lane. The yellow arrows in the second picture were replaced by a red X in this picture.

4. Left and right side-mounted CMSs were blank. An HOV 2 indication was on the CMS over the HOV lane. Downward-pointing green arrows were displayed over the three right lanes.

5. Left and right side-mounted CMSs were blank. An HOV 2 indication was on the CMS over the HOV lane. The CMSs over the three right lanes were blank.

The fifth Washington scenario contained the following pictures:

1. A 60-mi/h (97-km/h) speed limit was displayed on the right side-mounted CMS. An HOV 2 indication on the CMS was over the HOV lane. The CMSs over the three right lanes were blank.

2. Left and right side-mounted CMSs were blank. An HOV 2 indication was on the CMS over the HOV lane. The CMSs over the three right lanes were blank.

3. A 60-mi/h (97-km/h) speed limit was displayed on the right side-mounted CMS. An HOV 2 indication was on the CMS over the HOV lane. The CMSs over the three right lanes were blank.

4. Left and right side-mounted CMSs were blank. An HOV 2 indication on the CMS was over the HOV lane. The CMSs over the three right lanes were blank.

Individual Signs

Following the assessment of sign comprehension in scenario contexts, each content display alternative was presented individually. Participants were asked what they thought the sign was intended to mean and how they would respond to it. This task was self-paced, and accuracy was stressed.

Next, for each set of alternative contents intended to have the same meaning (e.g., the speed limit, lane merge, or lane closure), participants were presented with all the alternatives together and asked to select their preferred alternative and to explain reasons for their selection.

RESULTS

Participant responses to each scenario are described in terms of meaning and stated actions. For the preference ratings, Chi squared tests of association or z-tests for two proportions are reported.

Scenario Testing

Washington-Based Signs

Congestion Ahead Scenario:

The participants generally interpreted the signs appropriately and proposed taking appropriate actions. There were very few responses that could be interpreted as incorrect. An example of an inappropriate interpretation by two participants occurred in response to the second picture in the first Washington scenario (see figure 26). Those participants indicated that they would move into the HOV lane and drive 60 mi/h (97 km/h). Because the participants were told that they were to assume that they were driving alone in their vehicle, this was an inappropriate response.

Figure 26. Photo. Second picture in the congestion ahead scenario (Washington-based sign).

For the third picture in the scenario, there was one inappropriate response in which the participant indicated that he/she would drive in the HOV lane. For the rest of the pictures, the participants made responses that were consistent with the signs' intended meaning.

Incident With Center Lane Closed Scenario:

The participants generally interpreted the signs correctly and proposed taking appropriate actions based on the signs. For the first picture in the scenario, 8 of 26 participants indicated that they would change lanes immediately. Figure 27 shows the first picture for this scenario. The intended meaning of this sign was that drivers should prepare to merge because the lane would be closed ahead. The third picture in the series showed a red X over the center lanes, which is intended to indicate that the lane is closed. One of the participants said the red X meant that drivers should prepare to exit.

Figure 27. Photo. First picture in the incident with center lane closed scenario.

Incident With Two Right Lanes Closed Scenario:

The participants had problems interpreting the signs correctly; however, given their assumed travel lane and task (driving in the left-center lane), their proposed actions based on the signs were generally appropriate. More than half of the participants interpreted the first picture to mean the two right lanes were closed ahead. One participant indicated he was confused because he could not understand how the right two lanes could be open and closed at the same time. The side-mounted sign on the first gantry indicated the right two lanes were closed, and the side-mounted sign on the second gantry indicated the two right lanes were for exit only. The participants correctly interpreted the last three signs in the scenario.

Incident With Right-Center Lane Closed Scenario:

Participants generally interpreted the signs correctly and proposed taking appropriate actions based on the signs. However, for the first photo in the scenario, there were seven responses that were incorrect. More specifically, participants indicated they would merge out of the center lane. In the directions for these scenarios, the participants were told to assume that they were driving in the left-center lane (lane 2) and so at this point in the scenario they were not informed which lane was to be closed. In fact, the right-center lane (lane 3) was the one closed in the scenario and so the best strategy for the participants was to stay in their current lane. For the rest of the pictures in the scenario, the participants gave correct interpretations and proposed actions.

Resting Condition Scenario:

The participants generally interpreted the signs correctly and proposed taking appropriate actions based on the signs. A concern sometimes voiced was that blank signs might be interpreted as broken or out of operation. Half of the participants were shown these blank signs (see figure 28) at the beginning of the scenario testing, and the other half were shown these blank signs at the end. There appeared to be no effect of seeing the resting condition photo first or last. Participants made similar interpretations for these signs whether they were shown at the beginning or end of the experiment.

Figure 28. Photo. Picture for the resting condition for Washington-based signs.

Minnesota-Based Signs

Congestion Ahead Scenario:

The participants generally interpreted the ATM signs correctly and proposed taking appropriate actions based on the signs. They also frequently interpreted the advisory VSL signs as regulatory speed limit signs. Errors in interpretation were made regarding the guide signs—some participants interpreted the guide signs to indicate that the right lane was an exit lane.

Incident With Center Lane Closed Scenario:

The participants generally interpreted the ATM signs correctly and proposed taking appropriate actions based on the signs. They also incorrectly interpreted the guide signs, stating that the center lanes were to Front Royal, and the right lane was an exit lane. Participants continued to interpret the advisory VSL signs as regulatory speed limit signs.

Incident With Two Right Lanes Closed Scenario:

The participants had problems interpreting the ATM signs correctly (see figure 29 for a picture from this scenario). However, given their assumed travel lane and task, their proposed actions based on the signs were generally correct. This was a challenging scenario in that participants had been instructed to exit at US-50 where the ATM signs indicated that the two right lanes were closed. Also, the pictures that were modified to create the stimuli presented a large number of ATM sign violators (other vehicles in the closed lanes). The participants continued to misinterpret the guide signs where the right lane was thought to be an exit lane. This error in interpretation was independent from the use of the ATM signs.

Figure 29. Photo. Picture shown for the two right lanes closed scenario for the Minnesota-based signs.

Incident With Right-Center Lane Closed Scenario:

The participants generally interpreted the ATM signs correctly and proposed taking appropriate actions based on the signs. About one-half of the participants thought the flashing yellow arrow meant to proceed with caution in the lane. The other participants interpreted the sign to mean that the lane was open. One participant found the flashing yellow arrow to be confusing. About one-half of the participants interpreted the advisory VSL signs as regulatory speed limit signs. Again, some participants misinterpreted the guide signs where the right lane was thought to be an exit lane. This error was independent from the ATM signs.

Resting Condition Scenario:

The participants generally interpreted the signs correctly and proposed taking appropriate actions based on the signs. As with the Washington-based signs, one-half of the participants were shown this sign at the beginning of test and the other half at the end. There appeared to be no effect of seeing the resting condition sign either first or last. The participants' interpretations of the resting condition signs were the same for the two presentation orders.

Individual Sign Testing

Lane Open (Green Arrow)

The participants correctly interpreted these signs (see options in figure 30) as indicating that the lane was open and that they could continue to stay in their lane (see table 2). This was true for the Minnesota- and Washington-style signs.

Participants preferred the larger green arrow, as used in the Washington deployment ($Z = 3.46$, $p < 0.001$). The participants stated that the bolder and larger green arrow was more legible and easier to interpret from far away, as shown in option A of figure 30.

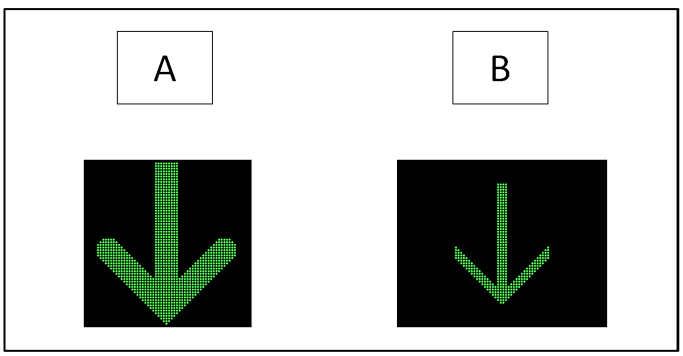


Figure 30. Screen capture. Screen used to rate preference for two lanes open LCS where (A) similar to a symbol used in Washington and (B) similar to a symbol used in Minnesota.

Table 2. Percent correct and percent preference of lane open LCS.

Label for Figure 30	Sign Choice (percent)	
	A	**B**
Lane Open[M]	92	96
Thru Traffic[M]	4	0
Stay In Lane[M]	4	4
Continue/Stay in Lane[A]	100	96
Nothing[A]	0	4
Preference	96	4

[M] Indicates interpretation of meaning.
[A] Indicates intended action.

Lane Open With Caution

The responses to the yellow arrow signs shown in figure 31 are presented in table 3. The sign was supposed to convey that the lane was open, but extra caution was warranted. As can be seen in table 3, only 16 to 19 percent of participants had the desired response of proceeding with caution.

The participants showed no clear preference for either the flashing or non-flashing yellow arrow. The participants who selected the flashing arrow stated that it was more attention getting. On the other hand, the participants who selected the non-flashing arrow sign stated that the flashing arrow was distracting.

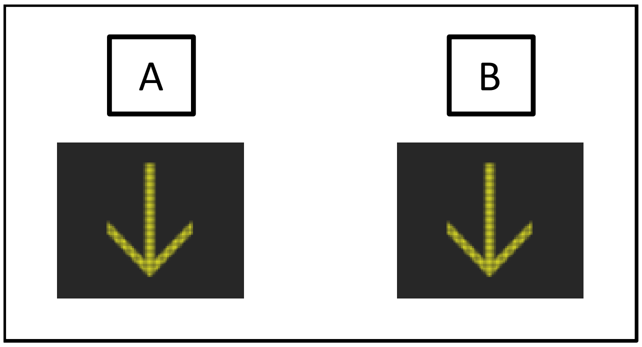


Figure 31. Screen capture. Screen used to rate preference of two lanes open with caution symbols with symbol A (left) static and symbol B (right) similar to A but cycled on and off at 1 Hz.

Table 3. Percent correct and percent preference for yellow lane open with caution arrow.

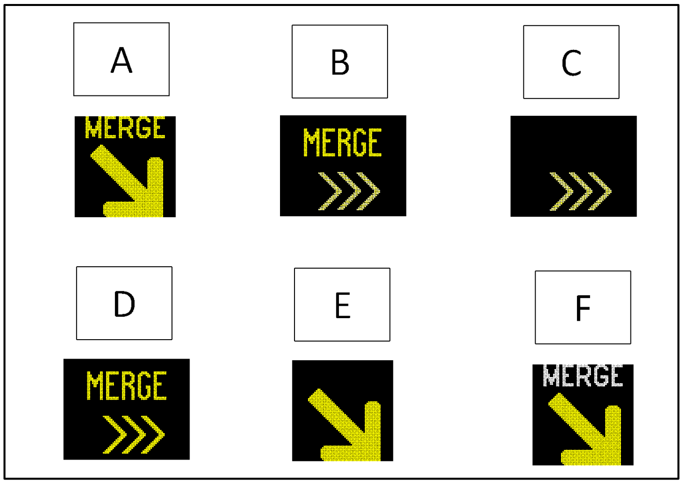
Label for Figure 31	Sign Choice (percent) Static (A)	Sign Choice (percent) Flashing (B)
Lane Open[M]	29	29
Lane Opens With Caution[M]	29	32
Caution/Slow Down[M]	21	29
Lane Closing[M]	0	4
Stay in Lane[M]	21	7
Slow Down[A]	16	23
Merge Out of Lane[A]	9	26
Continue in Lane[A]	56	32
Proceed with Caution[A]	16	19
Maintain Speed[A]	3	0
Preference	62	38

[M] Indicates interpretation of meaning.
[A] Indicates intended action.

Merge

Comprehension and preference findings for the merge right options (see figure 32) are shown in table 4, merge left options (see figure 33) are shown in table 5, and merge left or right options (see figure 34) are shown in table 6. The comprehension findings were similar across merge types. Participants indicated that they were to move out of their lane and merge in the direction indicated by the sign.

In all three merge cases, participants preferred the streaming chevrons merge symbols to the other symbol options: merge right ($\chi^2(5) = 28.92$, $p < 0.001$); merge left ($\chi^2(5) = 29.85$, $p < 0.001$); and merge right or left ($\chi^2(5) = 15.08$, $p < 0.05$).



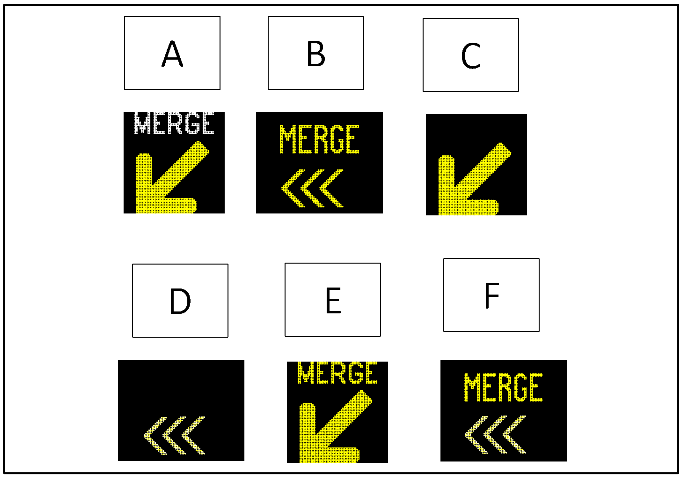
Note: Options B and C were streaming.

Figure 32. Screen capture. Merge right options screened for preference.

Table 4. Percent correct and percent preference for merge right options.

Label for Figure 32	**Sign Choice (percent)**					
	A	**B**	**C**	**D**	**E**	**F**
Merge Right[M]	96	93	96	93	96	93
Lane Going to Right[M]	0	0	4	0	0	0
Caution[M]	0	0	0	0	4	3.5
Lane Closed[M]	4	3.5	0	7	0	3.5
Construction Ahead[M]	0	3.5	0	0	0	0
Merge Right[A]	90	100	100	100	87	90
Caution[A]	3.3	0	0	0	6.5	3.3
Slow Down[A]	3.3	0	0	0	6.5	3.3
Other[A]	3.3	0	0	0	0	3.3
Preference	15	54	0	0	4	12

[M] Indicates interpretation of meaning.
[A] Indicates intended action.



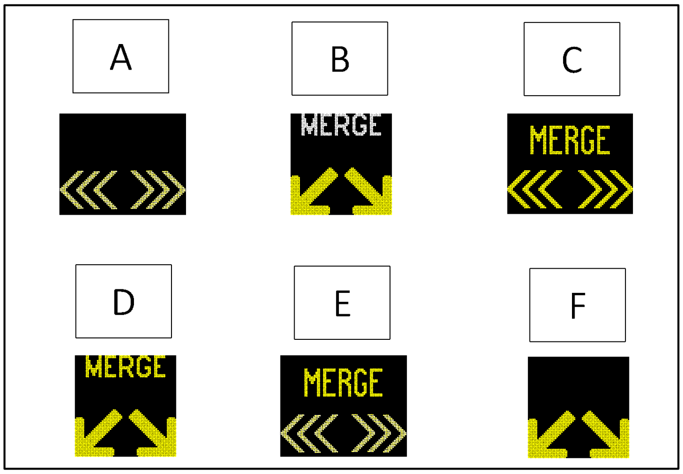
Note: Options B and D were streaming.

Figure 33. Screen capture. Merge left options screened for preference.

Table 5. Percent correct and percent preference for merge left options.

Label for Figure 33	**Sign Choice (percent)**					
	A	**B**	**C**	**D**	**E**	**F**
Merge Left[M]	93	100	96	100	96	100
Lane Going to Left[M]	0	0	4	0	0	0
Caution[M]	3.5	0	0	0	0	0
Lane Closed[M]	3.5	0	0	0	4	0
Merge Left[A]	96	96	93	100	93	100
Caution[A]	4	0	3.5	0	3.5	0
Slow Down[A]	0	4	3.5	0	3.5	0
Preference	8	54	4	0	19	15

[M] Indicates interpretation of meaning.
[A] Indicates intended action.



Note: Options A and C were streaming.

Figure 34. Screen capture. Merge left or right options screened for preference ratings.

Table 6. Percent correct and percent preference for merge left or right options.

Label for Figure 34	Sign Choice (percent)					
	A	B	C	D	E	F
Merge Left or Right[M]	93	80	84	89	84	79
Stay Out of Lane[M]	0	3.5	0	0	0	3.5
Lane Closed[M]	7	13	16	7	13	14
Road Splits[M]	0	3.5	0	0	0	3.5
Left and Right Lanes Open[M]	0	0	0	4	0	0
Caution[M]	0	0	0	0	3	0
Merge Left/Right[A]	100	93	87	96	93	93
Caution/Slow Down[A]	0	7	13	4	7	7
Preference	0	15	38	19	23	4

[M] Indicates interpretation of meaning.
[A] Indicates intended action.

Lane Closed Ahead

Comprehension and preference findings for the lane closed ahead options without a legend (see figure 35) and with a legend (see figure 36) are shown in table 7 and table 8, respectively. When the legend was not present, participants frequently interpreted the sign as meaning the lane was currently closed. With the inclusion of the legend, participants made the correct interpretation that the lane was closing in the near future. Regardless of the inclusion of the legend, however, participants did indicate that they were to move out of their lane.

When the legend was not present, participants preferred the larger and bolder version, as deployed in Washington, because it was easier to read ($\chi^2(1) = 7.54$, $p < 0.01$). Participants had no preference when the legend was included.

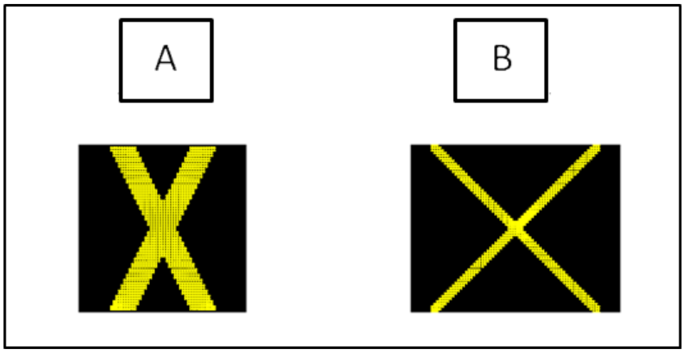


Figure 35. Screen capture. Lane closed ahead options without legend screened for preference ratings.

Table 7. Percent correct and percent preference for lane closed ahead options without legend.

Labels for Figure 35	Sign Choice (percent)	
	A	B
Caution[M]	0	8
Lane Closed[M]	65	73
Lane Closing Ahead[M]	14	12
Slow Down/Caution Ahead[M]	14	0
Delay Ahead[M]	7	0
Reduced Speed[M]	0	3.5
Merge[M]	0	3.5
Change Lanes[A]	93	82
Slow/Caution/Be Aware[A]	7	7
Avoid Lane[A]	0	11
Preference	77	23

[M] Indicates interpretation of meaning.
[A] Indicates intended action.

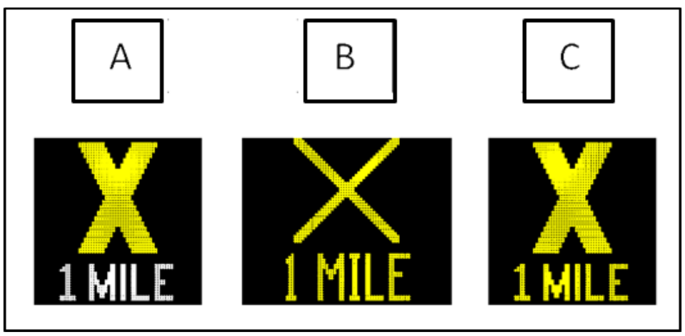


Figure 36. Screen capture. Lane closed ahead options with legend screened for preference ratings.

Table 8. Percent correct and percent preference for lane closed ahead options with legend.

Labels for Figure 36	Sign Choice (percent)		
	A	B	C
Lane Closed in 1 Mi[M]	92	93	86
Caution in 1 Mi[M]	8	0	0
Caution[M]	0	3.5	7
Delay in 1 Mi[M]	0	0	3.5
Next Mi Lane Closed[M]	0	0	3.5
Avoid Lane for 1 Mi[M]	0	3.5	0
Change Lanes[A]	86	93	86
Slow/Caution[A]	10	7	10
Avoid Lane for 1 Mi[A]	4	0	4
Preference	31	27	42

[M] Indicates interpretation of meaning.
[A] Indicates intended action.

Lane Closed

Comprehension and preference findings for the lane closed options (see figure 37) are shown in table 9. For all options, participants correctly indicated that the lane was closed and that they should vacate their lane.

Participants preferred the lane closed option with the legend, similar to the Minnesota deployment, claiming the legend provided useful information ($Z = 2.13$, $p < 0.05$).

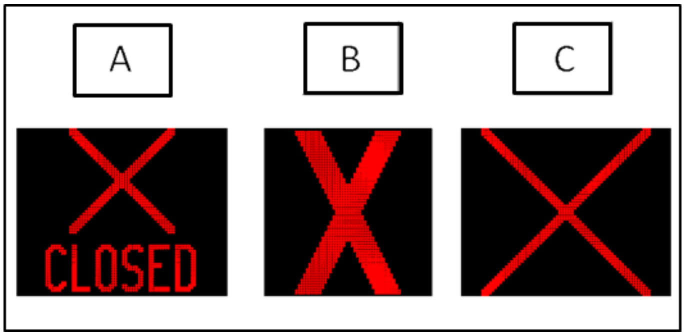


Figure 37. Screen capture. Lane closed options screened for preference ratings.

Table 9. Percent correct and percent preference for lane closed options.

Labels for Figure 37	**Sign Choice (percent)**		
	A	**B**	**C**
Lane Closed[M]	92	92	92
Lane Closed Ahead[M]	8	8	8
Exit Lane/Merge Out[A]	77	81	100
Not Use Lane[A]	23	19	0
Preference	73	27	0

[M] Indicates interpretation of meaning.
[A] Indicates intended action.

Variable Speed Signs

Seven white (regulatory) speed limit signs were presented. For all of the options, the majority of participants correctly interpreted the signs as a speed limit. However, one participant did interpret the option with the number 45 and no legend to mean Route 45.

Two regulatory speed limit signs (see figure 38) were evaluated with respect to preference. Comprehension and preference results for these two options are shown in table 10. The difference in comprehension percent between the positive and negative contrast signs was not statistically significant ($p = 0.298$). Participants preferred the positive contrast version where they stated that it was easier to read compared with the negative contrast sign ($Z = 3.05$, $p < 0.01$).

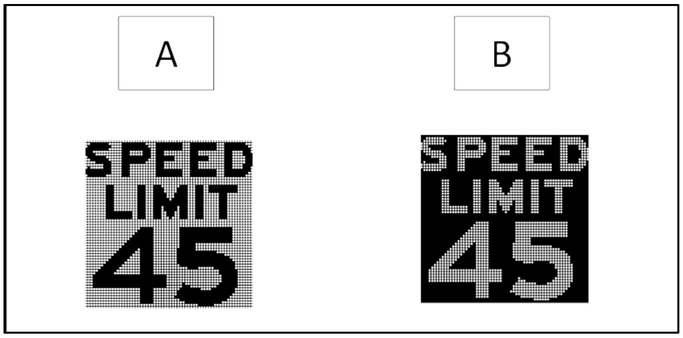


Figure 38. Screen capture. Regulatory speed limit options screened for preference ratings.

Table 10. Percent correct and percent preference for regulatory speed limit options.

	Sign Choice (percent)	
Labels for Figure 38	**A**	**B**
Speed Limit 45[M]	96	88
45 mi/h[M]	4	12
Drive 45 mi/h[A]	92	92
Continue[A]	4	4
Other[A]	4	4
Preference	12	88

1 mi/h = 1.6 km/h.
[M] Indicates interpretation of meaning.
[A] Indicates intended action.

Eight yellow (advisory) speed limit signs were presented. For all of the options, the majority of participants also interpreted the signs as a regulatory speed limit. For the 45-mi/h (72-km/h) sign in negative contrast, one participant indicated that this was an advisory sign.

Four advisory speed limit signs (see figure 39) were evaluated with respect to preference. Comprehension and preference results for these four options are shown in table 11. The differences in comprehension percent across the four conditions are not statistically significant. The positive contrast sign currently in the MUTCD was preferred where the participants indicated that it was easier to read ($\chi^2(3) = 49.69$, $p < 0.001$).

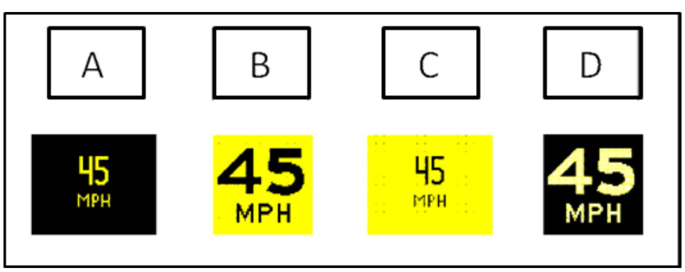


Figure 39. Screen capture. Advisory speed limit options screened for preference ratings.

Table 11. Percent correct and percent preference for advisory speed limit options.

Labels for Figure 39	Sign Choice (percent) A	B	C	D
Speed Limit 45[M]	58	46	70	54
45 mi/h[M]	35	43	22	39
Advisory Speed[M]	0	4	4	0
Caution[M]	3.5	7	4	3.5
Construction[M]	0	0	0	3.5
Other[M]	3.5	0	0	0
Drive 45 mi/h[A]	92	88	92	88
Continue[A]	4	4	4	4
Caution/Slow Down[A]	4	8	0	4
Other [A]	0	0	4	0
Preference	8	8	0	84

1 mi/h = 1.6 km/h.
[M] Indicates interpretation of meaning.
[A] Indicates intended action.

DISCUSSION

The scenario testing portion of this study used the signs as deployed in Washington and Minnesota. In general, the results showed that the participants correctly interpreted the ATM signs as they were presented in a sequence for a given scenario. The participants in this study had no previous experience with these types of signs, suggesting that the ATM signs were, for the most part, intuitive. Errors included interpreting advisory VSL signs as regulatory speed limit signs, incorrectly interpreting the guide signs (not ATM signs), misinterpreting the yellow X sign without a text legend, and confusing the meaning of the yellow arrow (either flashing or static). Participants were challenged in the scenario in which the two right lanes were closed except for the exit. One participant stated, "How can the lanes be open and closed at the same time?" An EXIT ONLY sign over the affected lanes might have aided the participants in selecting the appropriate response in this scenario.

The individual sign testing also resulted in high levels of comprehension. The problematic signs included the following:

- **Lane Open With Caution (yellow arrow)**: This sign resulted in various interpretations, and only 16 to 19 percent of participants provided the exact message that the sign is intended to convey. Two alternatives of this sign were tested: (1) the yellow flashing arrow, as deployed in Minnesota, and (2) an alternative non-flashing yellow arrow. The participants showed no clear preference for either version of the sign.

- **Lane Closed Ahead (without text)**: The yellow X was intended to convey the information that the signal would change to a red X in that lane (location). The yellow X without text was interpreted incorrectly to mean that the lane was closed (at the current location) by 73 percent of the participants. The yellow X with the text legend was interpreted correctly by all participants. The yellow X without text might work well in a situation in which a side-mounted CMS provided additional information, as was done in the Washington deployment. The scenario testing part of the study provided additional evidence that this sign might be misinterpreted—the yellow X might be incorrectly interpreted when it is used as an advance message.

- **VSL Signs:** In general, the participants interpreted all of these signs as regulatory speed limit signs. During preference testing, the participants preferred the positive contrast regulatory speed limit sign (as used in Washington) compared with an alternative speed limit sign with negative contrast. When shown advisory speed limit signs, the participants preferred a positive contrast advisory speed sign.

The other tested signs showed high levels of comprehension, but differences in preference.

- **Lane Open:** The participants preferred the sign as used in the Washington deployment, stating that the bolder and larger green arrow was more legible and easier to interpret from far away.

- **Merge:** The participants showed a preference for the streaming chevrons as deployed in Minnesota.

- **Lane Closed:** There was preference for the red X with the word "CLOSED" as deployed in Minnesota.

These results are based on static testing in which participants needed only to pay attention to the signs. There was no driving task or other workload present in the test situation. The ATM signs were displayed in a highway environment where there was traffic and drivers may need to make route choices (e.g., take an exit). Additional testing was conducted in the Highway Driving Simulator to evaluate comprehension, as well as the actions that drivers took in response to the signs under a variety of scenarios (see chapters 4 and 5).

CHAPTER 3. SIGN FIELD TESTING

A subset of the ATM signs used in the laboratory study were selected for further field testing. This test was for a large number of CMS type signs of which the ATM signs were a small subset. The principal focus of the field test was to obtain legibility distances for the signs. The data were collected on a closed course while participants drove an instrumented vehicle that was equipped with a dashboard-mounted eye-tracking system.

METHODS

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 40. The purpose of the curved path was to require participants to attend to lane keeping in addition to messages displayed on the sign.

Figure 40. Photo. Layout of course on drag strip.

Changeable Message Sign

The CMS was a Daktronics® VF-2320 full color (RGB) matrix display with a 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. Figure 41 shows the sign as deployed for testing on the drag strip.

Figure 41. 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 National Electrical Manufacturers Association standards for LED color displays intended for highway applications.

Five of the signs evaluated in the laboratory test as described in chapter 2 were selected for testing in the field. Table 12 presents a list of the signs that were tested.

Table 12. List of ATM signs used in the field test.

Sign	Source
40 MPH	WSDOT/Regulatory
45 MPH	MNDOT/Advisory
40 MPH	MUTCD/Advisory
Red X Lane Closed	MUTCD[8]
Yellow X Lane Closing 1 mi	MUTCD[8]

MPH = Miles per hour.
WSDOT = Washington State Department of Transportation.
MNDOT = Minnesota Department of Transportation.

Research Vehicle

Participants drove a 2007 Jeep® Grand Cherokee that was equipped with a dashboard-mounted three-camera eye-tracking system. The system sampled eye vectors and head position at 60 Hz. Three scene cameras mounted on the roof of the Jeep®, 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 device, and accelerometer data were recorded and synchronized.[11]

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.

Procedure

Participants were instructed to begin each trial at the approach to the left start line. There they waited for an experimenter in the back seat 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 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.

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

PARTICIPANTS

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

RESULTS

Table 13 presents mean legibility distances for the five ATM signs. The mean legibility distances for the speed limit signs were close to the maximum legibility distance in this test (1,250 ft (381 m)). The yellow X had the lowest mean legibility distance and the highest STD. The greater legibility distance and STD in responding to this sign were in part due to the method used to obtain a response. As previously discussed, a response did not conclude until the participant completed reading the message. Thus, if a participant struggled in interpreting the true meaning of the yellow X sign (i.e., he or she would continue to drive closer to the sign location), then the response duration would be longer. In turn, the legibility distance would decrease.

Table 13. Legibility distance measures for selected ATM signs.

Sign	Mean (ft)	STD (ft)	Minimum (ft)	Maximum (ft)
Regulatory SPEED_WSDOT	1,220.67	16.40	1,213.33	1,250.00
Advisory SPEED_MNDOT	1,225.56	18.93	1,176.67	1,250.00
Advisory SPEED_MUTCD	1,243.89	14.97	1,213.33	1,250.00
Yellow X MUTCD	1,040.48	305.10	480.00	1,250.00
Red X MUTCD	1,187.14	103.09	956.67	1,250.00

1 ft = 0.305 m.

DISCUSSION

Highway guide signs use a letter height of 16 inches (40.64 cm). This letter height is based on a legibility distance of 30 ft/inch (9.14 m/2.54 cm) of letter height. This is a conservative guideline to accommodate a driver with 20/40 vision. A factor in the design of signs and the letter height used is the available time to read a sign at highway speeds. The yellow X had an average legibility distance of 1,040 ft (316.99 m). At a speed of 65 mi/h (105 km/h), the reading time is approximately 11 s, which is greater than the design guideline minimum of 8 s. The ATM signs using the new CMS displays with high resolution result in legibility distances that exceed design guidelines for non-LED signs (e.g., highway guide signs).

CHAPTER 4. DRIVER DECISIONMAKING

This study used a driving simulator to examine driver decisionmaking in a dynamic environment. The study employed the same scenarios that were used in the laboratory study (see chapter 2). The focus of this study was to examine drivers' responses (behavioral and eye-gaze movements) and compliance with LCSs and VSL signs. This experiment used roadway structures similar to those in the Washington deployment. Specific signs were selected based on the laboratory and field test results (see chapter 3) and included signs with designs similar to those in both the Washington and Minnesota deployments.

METHODS

The Simulator

The simulator's screen consists 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 (2.9 m) from the screen. The stimuli were projected onto the screen by five Barco projectors with resolution of 2,048 horizontal by 1,536 vertical pixels. Participants sat in a late model compact sedan as shown in figure 42. 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 42. Photo. The FHWA Highway Driving Simulator.

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 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.

ATM Signs

Figure 43 through figure 49 depict the ATM signs used in this experiment. In addition, the leftmost CMS occasionally displayed HOV2 restriction information. These signs represent a selection of signs that were being used in ATM test deployments in Washington and Minnesota at the time of this study. Selection of these signs was based on the results of sign comprehension and preference testing done in a laboratory setting (see chapter 2).

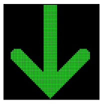


Figure 43. Graphic. Lane open (fully operational) option used in first simulator study.

Figure 44. Graphic. Lane closed option used in first simulator study.

Figure 45. Graphic. Lane closed ahead with legend option used in first simulator study.

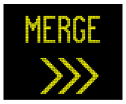


Figure 46. Graphic. Merge right with legend option used in first simulator study with streaming chevrons).

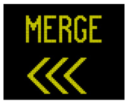


Figure 47. Graphic. Merge left with legend option used in first simulator study with chevrons streaming.

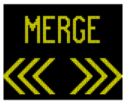


Figure 48. Graphic. Merge left or right with legend option used in first simulator study with chevrons streaming.

Figure 49. Graphic. VSL sign used in first simulator study.

Because the Washington roadway structure design was used, side-mounted CMSs were present. The following messages were displayed on the side-mounted CMSs, depending on which scenario the participant was currently experiencing: (1) STALLED VEHICLE AHEAD, (2) CENTER LANE CLOSED, (3) ACCIDENT AHEAD MERGE RIGHT, (5) RIGHT LANES CLOSED, (6) RIGHT LANES EXIT ONLY, (7) REDUCE SPEED ZONE AHEAD, (8) REDUCE SPEED ZONE, and (9) END REDUCE SPEED ZONE.

Simulation Scenarios

The participants drove on a simulated eight-lane highway (four lanes in each direction of travel) approximately 23 mi (37.0 km) in length. A 1-mi (1.61-km) section of freeway without overhead signs preceded the first overhead ATM sign. The ATM signs (gantries) were spaced every 0.5 mi (0.8 km) along the roadway. 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 twice the size of their real-world equivalent. Figure 50 shows an example of an ATM sign at the start of an area requiring a slowdown in speed.

Figure 50. Screen capture. ATM sign warning of a reduced speed zone ahead.

Each drive was composed of the following scenarios:

1. Resting condition for the signs (normal operations for all lanes).
2. Stalled vehicle closing 1 lane (right-center lane—lane 3).

3. Vehicle crash closing two left lanes (lanes 1 and 2).
4. Vehicle crash closing two right lanes (lanes 3 and 4 with exit ramp open).
5. Message in the event of slow-moving traffic in all lanes (speed reduction).

A resting condition for the signs was used between the other scenarios in the study. Figure 51 shows the ATM sign configuration for the resting condition. Three signs at 0.5-mi (0.8-km) intervals were used for the resting condition. Figure 52 through figure 55 show the configurations of the ATM signs for the other scenarios in the study. With the exception of the resting condition, all of the other scenarios included six ATM signs spaced 0.5 mi (0.8 km) apart.

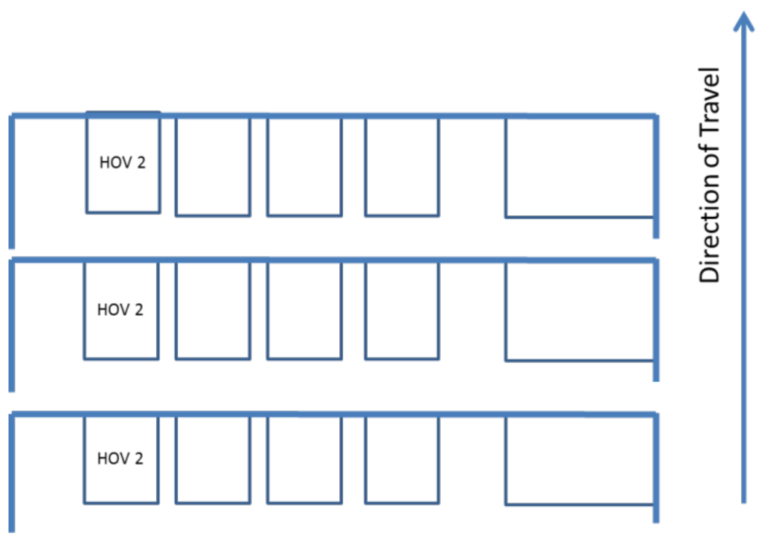


Figure 51. Illustration. Design of scenario 1—resting condition for ATM signs (normal operations for all lanes).

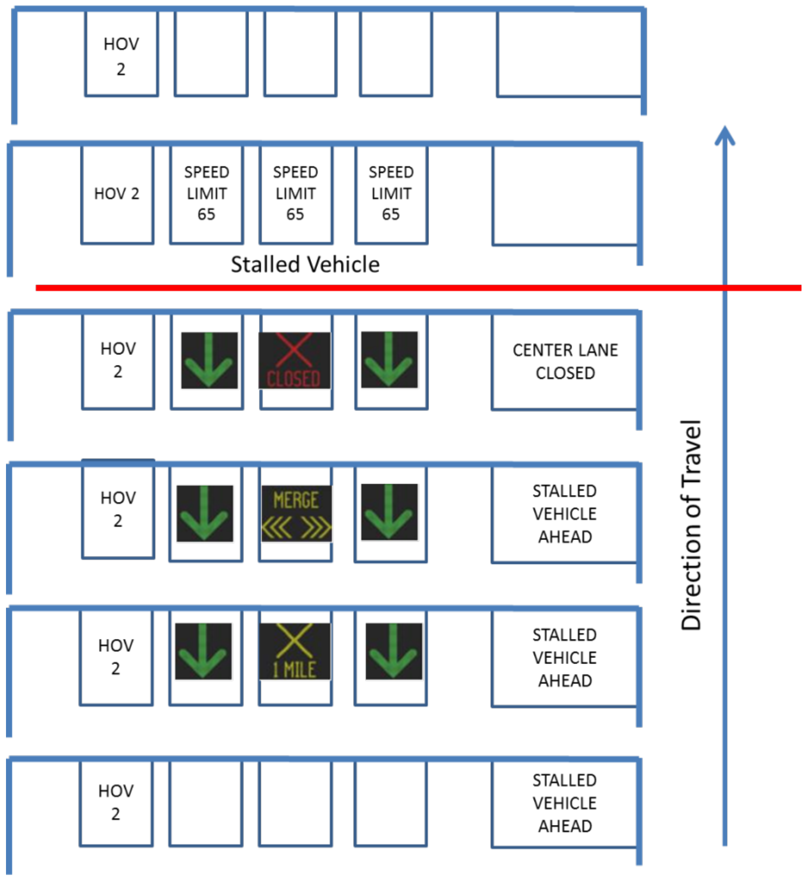


Figure 52. Illustration. Design of scenario 2—stalled vehicle design closing 1 lane (right-center lane—lane 3).

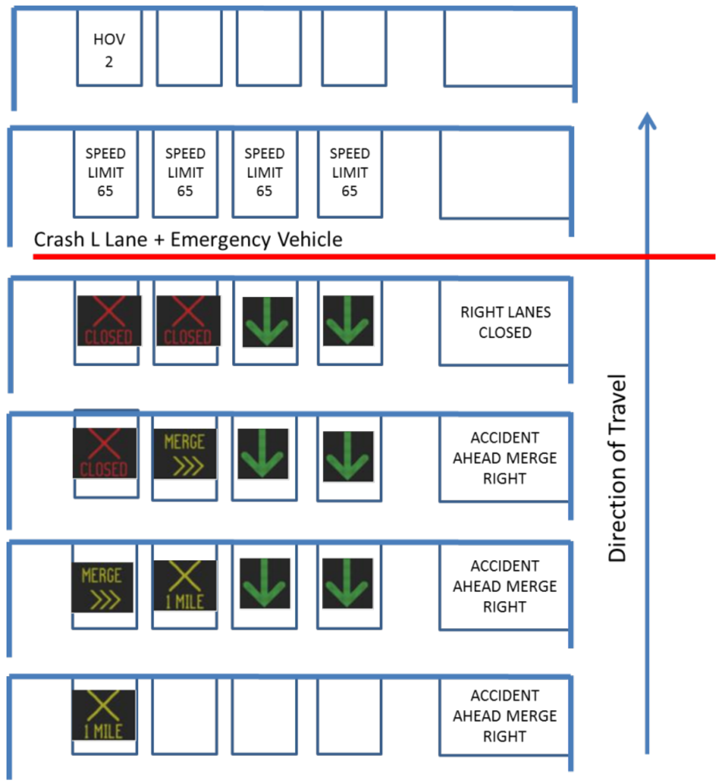


Figure 53. Illustration. Design of scenario 3—vehicle crash scenario design closing two left lanes (lanes 1 and 2).

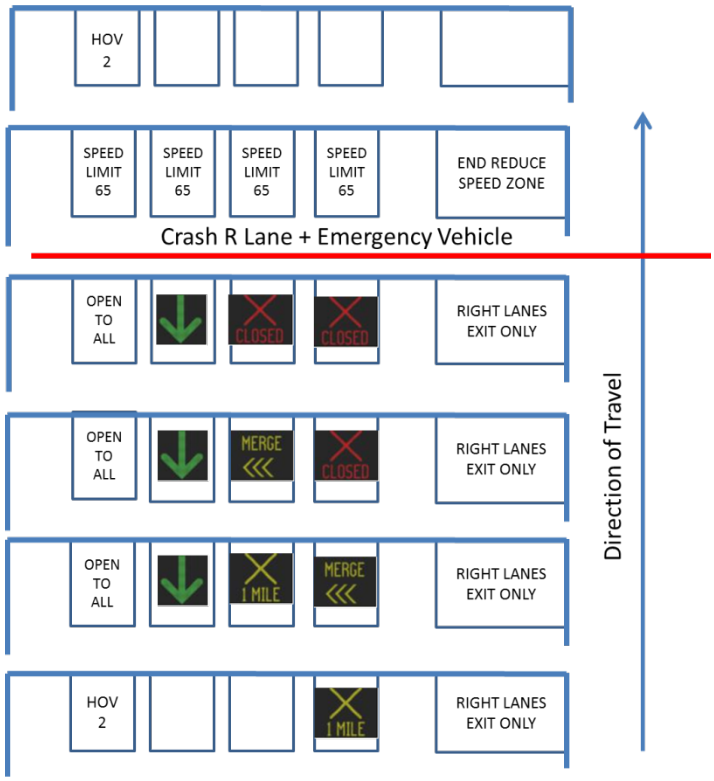


Figure 54. Illustration. Design of scenario 4—Vehicle crash scenario design closing two right lanes (lanes 3 and 4 with exit ramp open).

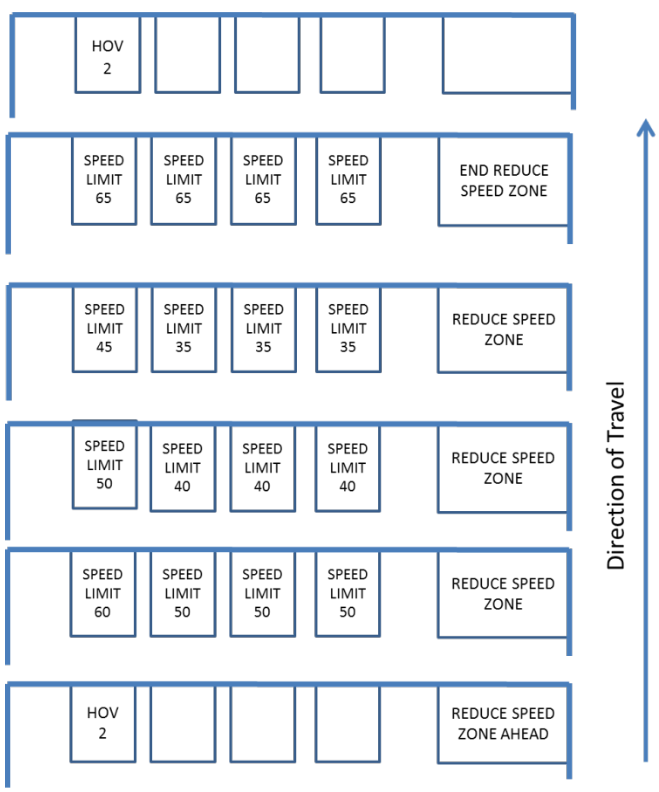


Figure 55. Illustration. Design of scenario 5—slow-moving traffic in all lanes.

The scenarios illustrated in figure 51 through figure 55 were combined to generate a simulated drive (see table 14 for an example). For the experiment, four orders were created from the scenarios using partial counterbalancing. Participants were instructed to exit at Holt Ave, which was always located at the end of the drive during the two right lanes closed scenario. Also, the reduced speed scenario was presented twice during each of the drives. Table 15 presents the four orders of the scenarios used in the experiment. There were eight participants for each of the four driving orders.

Table 14. Sample ordering of scenarios to create a simulated drive.

Length of Scenario (mi)	Scenario Number	Description
1.0	—	Start (no signs for first mile)
1.5	1	Resting condition
3.0	5	Reduce speed
1.5	1	Resting condition
3.0	2	Stalled vehicle
1.5	1	Resting condition
3.0	3	Two left lanes closed
1.5	1	Resting condition
3.0	5	Reduce speed
1.5	1	Resting condition
2.0	4	Two right lanes closed

1 mi = 1.61 km.
— Indicates not applicable.

Table 15. Four orders of scenarios within simulated drives.

Order 1	Order 2	Order 3	Order 4
1 mi start	1 mi start	1 mi start	1 mi start
1	1	1	1
5	3	2	5
1	1	1	1
2	5	3	5
1	1	1	1
3	5	5	2
1	1	1	1
5	2	5	3
1	1	1	1
4	4	4	4

1 mi = 1.61 km.

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.[12] Because the random number seed for the traffic model was always the same, all participants were immersed in the same traffic stream. However, because the participants controlled their own speed, acceleration, and lane choice, they could experience different traffic conditions in their immediate surroundings.

At the beginning of test sessions, 5,000 veh/h (1,250 veh/h per lane) were generated for 6.7 min. Participants were instructed to begin driving 2.5 min into this period of traffic generation. Approximately every 3 mi (4.8 km), 500 veh/h would exit the freeway at off ramps, and 500 veh/h would merge into the traffic stream from on ramps. There were off and on ramps every 1.5 mi (2.4 km), although the traffic model populated only half of these ramps with traffic.

Participants were instructed to maintain 65 mi/h (105 km/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.

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 showed that some participants thought they were supposed to stay on the freeway, regardless of ATM sign warnings or guide signs. Therefore, the training session was modified to ensure that participants knew it was expected they should follow instructions on the ATM signs. The modified training included a side-mounted CMS that instructed participants to take the next exit.

Eye-Tracking System

The simulator was equipped with a Smart Eye® four-camera dashboard-mounted eye-tracking system that sampled at 120 Hz.[13] 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 windscreen. Gaze direction accuracy varied by participant. The mean accuracy of gaze position across participants was 1.36 degrees (radius) with a 0.54-degree STD. The eye-tracking data (i.e., gaze direction of each eye, head position, etc.) were merged with data from the simulator (e.g., vehicle speed, lane position, steering wheel position) and the current forward view of the simulation visual scene (approximately 60 degrees horizontal by 40 degrees vertical). The merge was accomplished using a MAPPS™ scene recorder.[14]

To quantify when and for how long participants looked at each ATM sign, a researcher used analysis software to indicate a region of interest (ROI) on individual frames of the recorded video image. An example of an ROI is shown in figure 56 (the halo around the signs). ROIs were created between the point a sign began to pass out of the driver's view and 10 s upstream of that point. Two ROIs were created for the ATM signs: (1) ATM_LEFT, which encompassed the four per-lane CMSs; and (2) ATM_RIGHT, which encompassed the side-mounted CMS. An ROI for the road ahead (RA) was also created. The ROIs for this study are shown in figure 56.

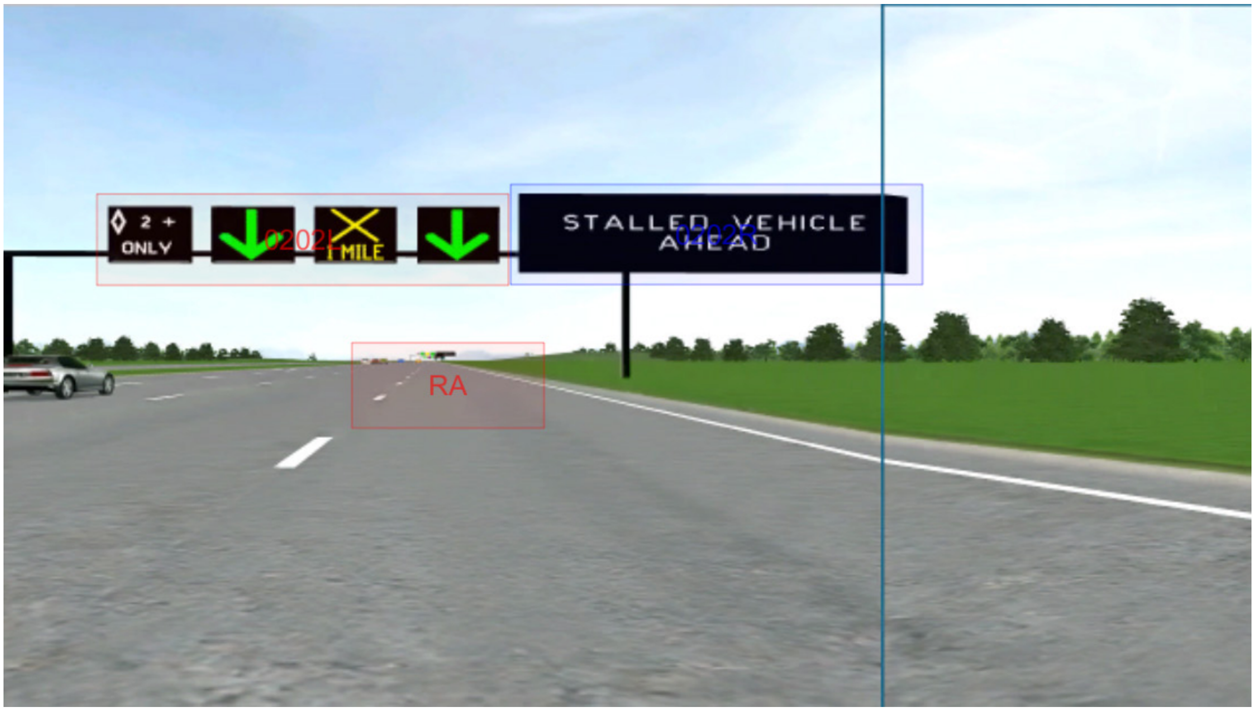


Figure 56. Screen capture. ROIs indicated on the ATM signs.

PARTICIPANTS

Thirty-one participants (15 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 old (range 21 to 72 years old). Of these 31 participants, 27 provided interpretable eye-tracking data. Useable behavioral data were obtained from four participants for whom eye-tracking was unsuccessful. The mean age of the 27 participants (13 males and 14 females) with good eye-tracking data was 45 years old (range 21 to 72 years old). Only one participant reported a mild simulator sickness symptom (headache), and no participant dropped out as a result of simulator sickness.

RESULTS

In all the figures pesented in this section (figure 83 through figure 86), error bars indicate 95-percent confidence limits. Also, for ease of understanding, the scenarios were coded in the figures as follows (there are two codes for scenario 5 (speed reduction) because participants viewed this scenario twice):

1. **REST**: Resting condition for the signs (normal operations for all lanes).
2. **SVRCX**: Stalled vehicle closing 1 lane (right-center lane—lane 3).
3. **2LFTX**: Vehicle crash closing two left lanes (lanes 1 and 2).

4. **2RTXE**: Vehicle crash closing two right lanes (lanes 3 and 4 with exit ramp open).
5. **SLOW1/SLOW2**: Message in the event of slow-moving traffic in all lanes (reduced speed).

The last scenario for all participants included the Holt Ave exit. The participants were informed at the start of the drive to exit the freeway when they came to the Holt Ave exit. After the data collection runs began, researchers noticed that there were only two guide signs for the Holt Ave exit (one advanced guide sign 1 mi (1.61 km) before the exit—HOLT3—and one guide sign at the exit—HOLT1) and a second advanced guide sign 0.5 mi (0.8 km) before the exit (HOLT2) had not been included. After seven participants had completed the experiment, the second advanced guide sign (at 0.5 mi (0.8 km)) was added to the scenario. The first set of analyses compared the exiting behavior of the participants that did not have the 0.5 mi (0.8 km) exit sign with those that did. This analysis was of an exploratory nature given the small sample size for the participants without the 0.5 mi (0.8 km) sign.

Inclusion of Half-Mile Advance Guide Sign

Exit-Taking Behavior

This analysis compared the exit-taking behavior of those participants who were presented with the second advanced guide sign to those participants who were not. First, all participants who completed the study ($N = 31$) were included in the final dataset. Seven participants were not presented with the second advanced guide sign and 24 were. Table 16 shows the relationship (row percentages) between inclusion of the second advanced guide sign and exit-taking behavior. Chi-squared test results indicated that there was no significant association between the presence of the second advanced guide sign and exit-taking behavior.

Table 16. Distribution (row percentages) of inclusion of the second advanced guide sign by exit-taking behavior for all subjects ($N = 31$).

Inclusion of Second Holt Ave Sign	Exit-Taking Behavior (percent)	
	Did Not Take Exit	Took Exit
No	43	57
Yes	21	79

Next, only those participants who had reasonable eye-tracking data ($N = 27$) were included in the final dataset. There were 5 participants who were not presented with the second advanced guide sign and 22 that did. As shown in table 17, the results were similar as in the first analysis. Again, Chi-squared test results indicated that there was no significant association between the presence of the second sign and exit-taking behavior.

Table 17. Distribution (row percentages) of inclusion of the second exit sequence sign by exit-taking behavior for only subjects with reasonable eye-tracking data ($N = 27$).

Inclusion of the Second Holt Ave Sign	Exit-Taking Behavior (percent)	
	Did Not Take Exit	Took Exit
No	20	80
Yes	18	82

Eye-Tracking Behavior

A glance toward an ROI was defined as when a participant registered 12 or more hits (where a hit was defined as one 120-Hz gaze point on an ROI) toward the ROI during a data collection zone (DCZ). For this analysis, each of the three exit signs (HOLT3, HOLT2, and HOLT1) was considered individually. In other words, drivers who were presented with the second advanced guide sign (HOLT2) could have a maximum of three glances during the last scenario, where participants were tasked to exit at Holt Ave (two right lanes blocked); those drivers who were not presented with the second sign could have a maximum of two glances. By this design, if participants dedicated the same amount of attention to each of the signs in the exit sequence, then those drivers who were presented with the second sign (HOLT2) should exhibit a higher probability of glancing than those drivers who were not. Results from a repeated measures logistic regression supported this claim—there was a statistically significant difference in the probability of glancing between the two groups ($\chi^2\ (2) = 4.80$, $p < 0.05$). Figure 57 shows the predicted mean probability of glancing toward an exit sign by driver group.

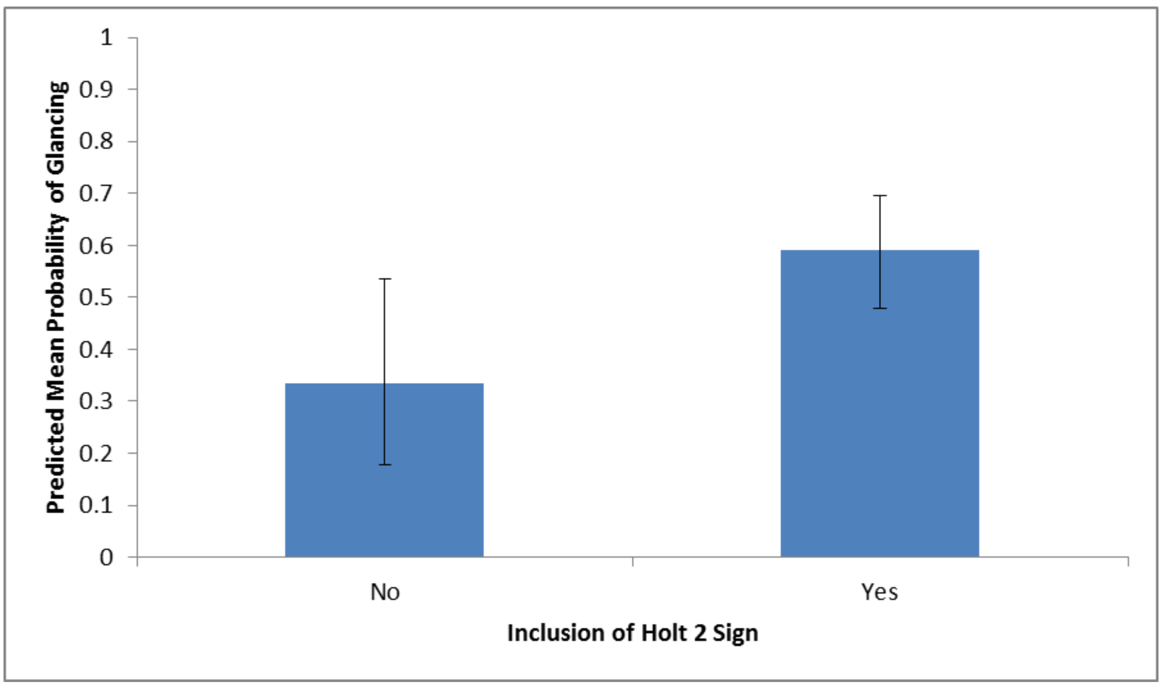


Figure 57. Graph. Predicted mean probability of glancing at an exit sign by inclusion of HOLT2 sign.

Lane Choice Behavior

By Researcher Observation

During data collection, researchers observed a participant's lane position following each gantry in the scenario. In scenario 1 (resting condition), four observations were recorded, one for each gantry. This scenario was presented to each participant at the beginning of the drive and then in between each of the other scenarios. Table 18 shows the distribution (row percentages) of lane choice across participants for each recorded observation. Chi-squared test results indicated that there was no significant association between the observation in the scenario and lane choice.

Overall, participants tended to stay in lane 3 (the right-center lane) as initially instructed by the researcher.

Table 18. Distribution (row percentages) of lane choice by observation for scenario 1(resting condition).

Observation	Lane Choice (percent) Lane 1	Lane 2	Lane 3	Lane 4
Gantry 1	—	2	96	2
Gantry 2	—	1	96	3
Gantry 3	—	1	96	3
Gantry 4	—	—	96	4

— Indicates 0 percent.

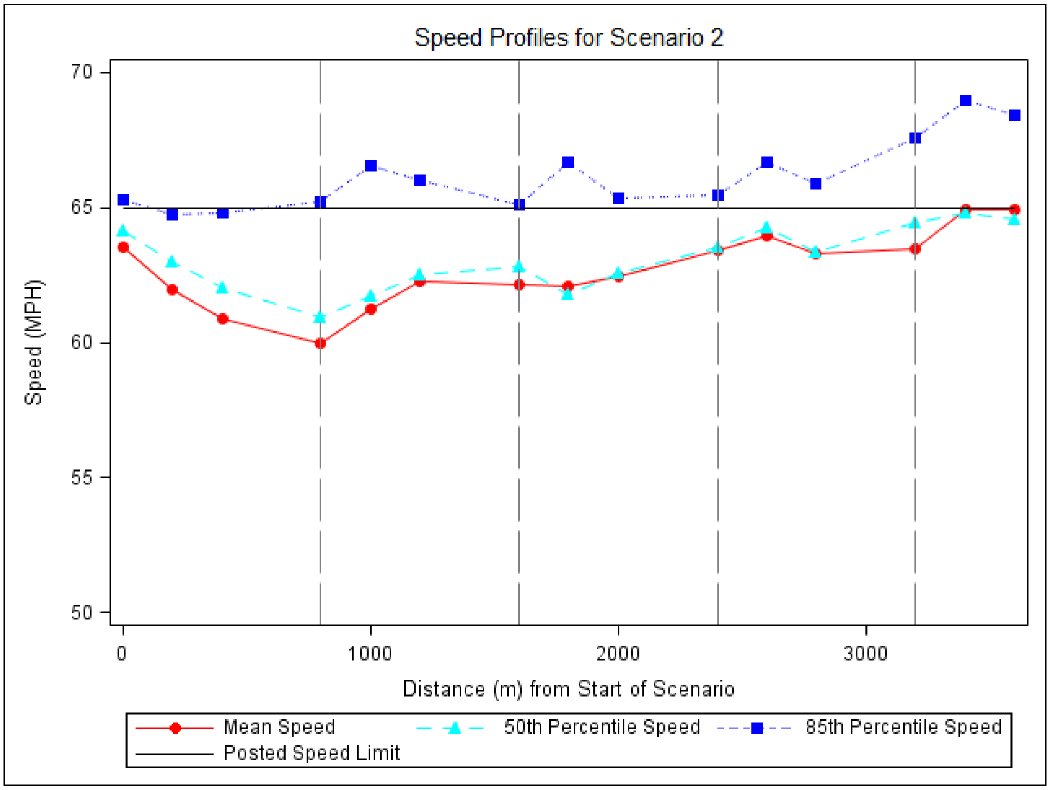
In scenario 2 (stalled vehicle ahead), six observations were recorded, one for each of the five gantries and one for the stalled vehicle between the fourth and fifth gantries. Table 19 shows the distribution (row percentages) of lane choice for each recorded observation. Chi-squared test results indicated that there was a significant association between the observation in the scenario and lane choice (χ^2 (10) = 108.33, $p < 0.001$). The data indicate that participants exited lane 3 in accordance with the instructions on the ATM signs; however, most of the participants exited lane 3 before being shown the sign indicating they should merge out of the lane. After the stalled vehicle was passed, participants reentered lane 3. No participant crashed with the stalled vehicle in lane 3.

Table 19. Distribution (row percentages) of lane choice by observation for scenario 2 (stalled vehicle ahead).

Observation	Lane Choice (percent) Lane 1	Lane 2	Lane 3	Lane 4
Gantry 1	—	—	100	
Gantry 2	—	40	30	30
Gantry 3	—	56	4	40
Gantry 4	—	52	4	44
Vehicle	—	52	7	41
Gantry 5	—	4	85	11

— Indicates 0 percent.

Figure 58 shows the speed profile for this scenario. The participants slowed down about 5 mi/h (8 km/h) on average when encountering the CMS indicating a stalled vehicle ahead. On average, the participants did not deviate much from the posted speed limit, although they did make the necessary lane changes.



1 mi/h = 1.61 km/h.
1 ft = 0.305 m.

Figure 58. Graph. Speed profile for scenario 2 (stalled vehicle ahead).

In scenario 3 (two left lanes closed owing to a crash), six observations were recorded, one for each of the five gantries and one for the crash between the fourth and fifth gantries. Table 20 shows the distribution (row percentages) of lane choice for each recorded observation. Chi-squared test results indicated there was no significant association between the observation in the scenario and lane choice. Compared with scenario 1, there was a shift of traffic into lane 4. The speed profile for this scenario (not pictured) was similar to that observed in scenario 2 (see figure 58).

Table 20. Distribution (row percentages) of lane choice by observation for scenario 3 (two left lanes closed).

	Lane Choice (percent)			
Observation	**Lane 1**	**Lane 2**	**Lane 3**	**Lane 4**
Gantry 1	—	—	89	11
Gantry 2	—	—	74	26
Gantry 3	—	—	85	15
Gantry 4	—	—	85	15
Crash	—	—	82	18
Gantry 5	—	—	85	15

— Indicates 0 percent.

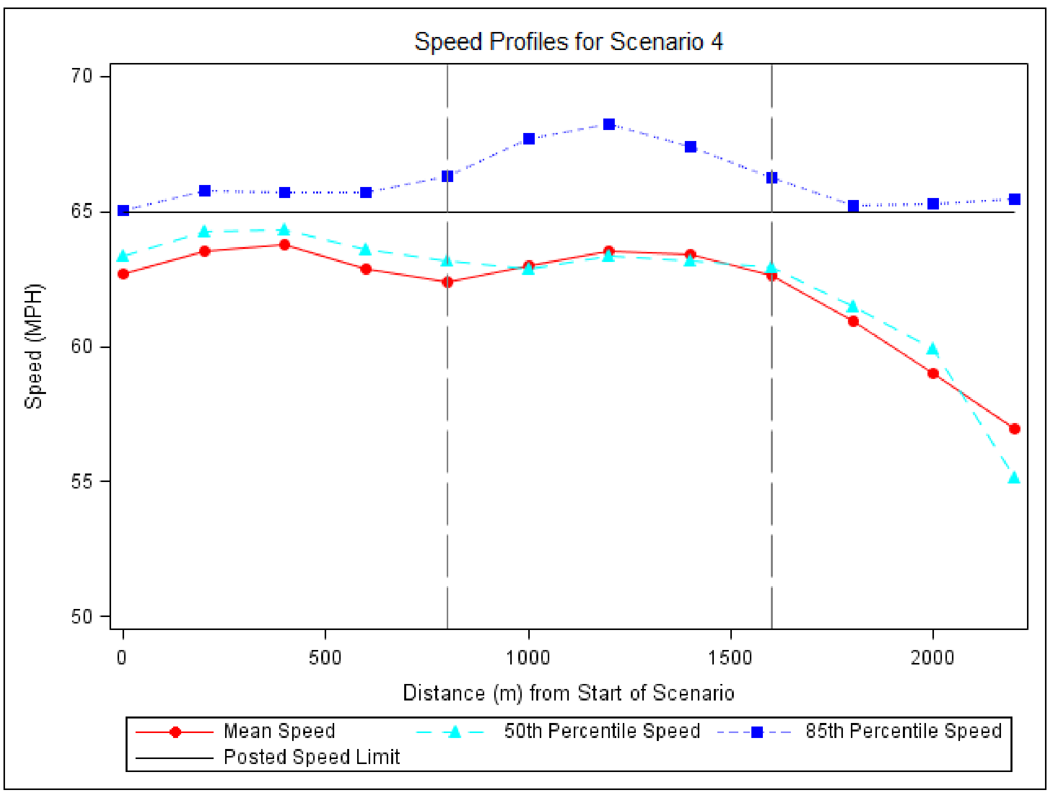
In scenario 4 (two rights lanes closed owing to a crash), three observations were recorded, one for each of the three gantries. Table 21 shows the distribution (row percentages) of lane choice for each recorded observation. Chi-squared test results indicated that there was a significant association between the observation in the scenario and lane choice (χ^2 (4) = 40.20, $p < 0.001$). This was a challenging scenario in which the two right lanes were closed, but the rightmost lane (lane 4) was still open for exiting. However, the majority (74 percent) of the participants successfully exited at Holt Ave in accordance with instructions.

Table 21. Distribution (row percentages) of lane choice by observation for scenario 4 (two right lanes closed).

	Lane Choice (percent)			
Observation	**Lane 1**	**Lane 2**	**Lane 3**	**Lane 4**
Gantry 1	—	4	96	—
Gantry 2	—	48	41	11
Gantry 3	—	52	15	33

— Indicates 0 percent.

Figure 59 shows the speed profile for this scenario. On average, the participants slowed a few miles per hour (less than 5 mi/h (8 km/h)) until they approached the exit and then significantly decreased their speeds (more than 10 mi/h (16 km/h)) when they began to exit.



1 mi/h = 1.61 km/h.
1 ft = 0.305 m.

Figure 59. Graph. Speed profile for scenario 4 (two right lanes closed).

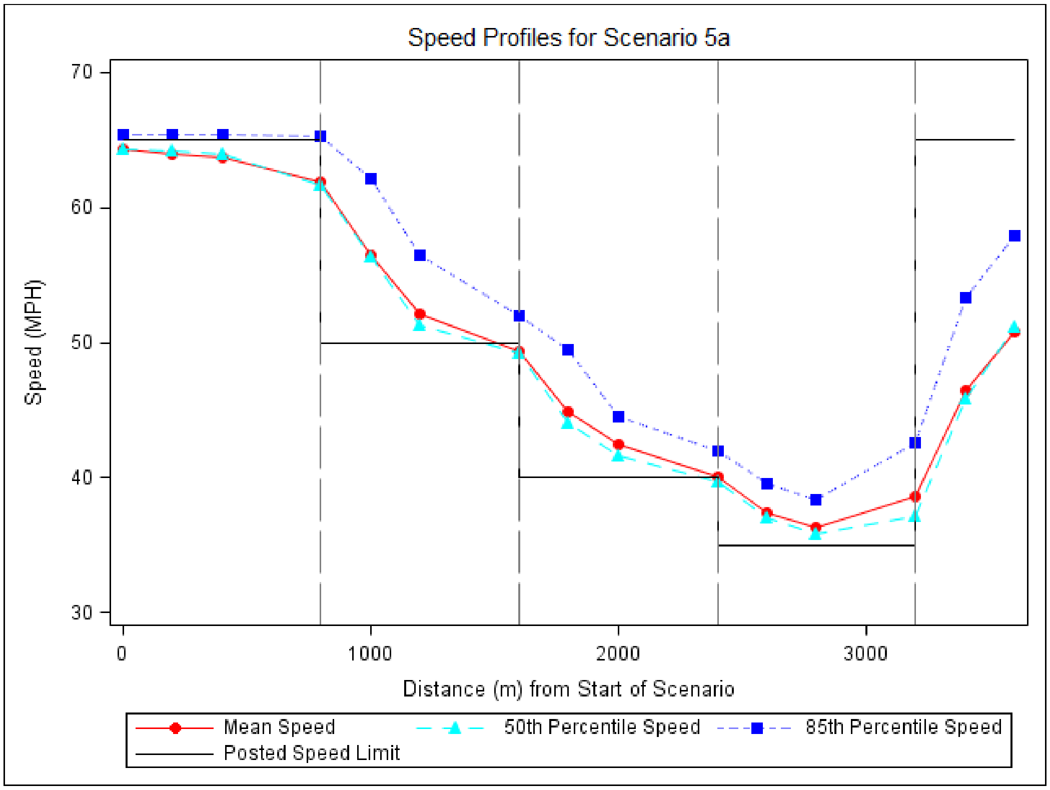
In scenario 5 (speed reduction), five observations were recorded, one for each of the five gantries. This scenario was presented to each participant two times (scenarios 5a and 5b). Table 22 below shows the distribution (row percentages) of lane choice for each recorded observation. Both presentations (scenarios 5a and 5b) resulted in the same distribution; thus, only one table is included. Chi-squared test results indicated there was no significant association between the observation in the scenario and lane choice.

Table 22. Distribution (row percentages) of lane choice by observation for each presentation of scenario 5.

	Lane Choice (percent)			
Observation	**Lane 1**	**Lane 2**	**Lane 3**	**Lane 4**
Gantry 1	—	—	96	4
Gantry 2	—	—	96	4
Gantry 3	—	—	96	4
Gantry 4	—	—	96	4
Gantry 5	—	—	96	4

— Indicates 0 percent.

Figure 60 presents the speed profile for the first presentation of scenario 5 (speed reduction). In this scenario, the participants were informed on the side-mounted CMS that there was slow traffic ahead. The VSL signs showed lower speed limits every 0.5 mile (0.8 km). On average, the participants followed the VSL signs.



1 mi/h = 1.61 km/h.
1 ft = 0.305 m.

Figure 60. Graph. Speed profile for scenario 5a (first speed reduction).

Lane Choice Compliance

Only data from scenario 2 (stalled vehicle ahead) and scenario 3 (two left lanes closed owing to crash) were reviewed to determine lane choice compliance. DCZs started approximately 1,000 ft (304.8 m) prior to the gantry and ended 880 ft (268.2 m) after the gantry. Given that gantries were placed 0.5 mi (0.8 km) apart, the ending location of the DCZ was one-third of the distance to the subsequent gantry. Lane position for the last frame of each DCZ was kept for the final dataset. Table 23 and table 24 show the distribution (row percentages) of lane choice by DCZ for scenario 2 and scenario 3, respectively. Data for scenario 2 suggest that participants exited lane 3 in accordance with the instructions on the ATM signs. Once the stalled vehicle was encountered, participants reentered lane 3. During scenario 3, participants tended to stay out of the blocked lanes (lanes1 and 2).

Table 23. Distribution (row percentages) of lane choice by DCZ for scenario 2 (stalled vehicle ahead).

DCZ	Lane Choice (percent)			
	Lane 1	Lane 2	Lane 3	Lane 4
1	—	—	100	—
2	—	30	44	26
3	—	55	4	41
4	—	56	—	44
5	—	7	89	4

— Indicates 0 percent.

Table 24. Distribution (row percentages) of lane choice by DCZ for scenario 3 (two left lanes closed).

DCZ	Lane Choice (percent)			
	Lane 1	Lane 2	Lane 3	Lane 4
1	—	—	78	22
2	—	—	78	22
3	—	—	85	15
4	—	—	81	19
5	—	4	81	15

— Indicates 0 percent.

Speed Behavior

In the following sections, only the two occurrences of scenario 5 (speed reduction scenario; scenarios 5a and 5b) were reviewed because this was the only scenario that directed participants to vary their speed. DCZs started approximately 1,000 ft (304.8 m) prior to the gantry and ended 880 ft (268.2 m) after the gantry. Given that gantries were placed 0.5 mi (0.8 km) apart, the ending location of the DCZ was one-third of the distance to the subsequent gantry.

Speed Compliance

Data were reviewed to determine whether a participant was compliant at least once during a DCZ. If a participant became compliant multiple times during a DCZ, then only the last point of compliance was kept for analysis. Chi-squared tests were performed to determine whether compliance varied among the five DCZs encountered during scenario 5. When considering only scenario 5a, results indicated there was a significant difference between the five DCZs (χ^2 (4) = 20.70, $p < 0.001$). The greatest deviation from the expected frequency occurred during the fifth DCZ in which no participants were compliant with the posted speed limit of 65 mi/h (105 km/h). Table 25 shows the distribution of speed compliance for each DCZ.

Table 25. Distribution (row percentages) of speed compliance by DCZ for the scenario 5a (first speed reduction).

DCZ	Speed Reduction Compliance (percent) Compliant	Speed Reduction Compliance (percent) Not Compliant
1	19	81
2	48	52
3	33	67
4	44	56
5	—	100

— Indicates 0 percent.

Similarly, when considering only scenario 5b, results indicated there was a significant difference in speed compliance among the five DCZs (χ^2 (4) = 22.87, $p < 0.001$). Once again, the greatest deviation from the expected frequency occurred during the fifth DCZ; only one participant was compliant with the posted speed limit of 65 mi/h (105 km/h). Table 26 shows the distribution of speed compliance for each DCZ.

Table 26. Distribution (row percentages) of speed compliance by DCZ for scenario 5b (second speed reduction).

DCZ	Speed Reduction Compliance (percent) Compliant	Speed Reduction Compliance (percent) Not Compliant
1	26	74
2	44	56
3	56	44
4	56	44
5	4	96

— Indicates 0 percent.

Distance of Speed Compliance

Data were reviewed to determine whether a participant was compliant at least once during a DCZ. If a participant was compliant more than once during a DCZ, then only the last point was kept for analysis. The distance (in meters) from the gantry at which the participant became compliant was calculated. Positive values indicated that the participant became compliant before the gantry, and negative values indicated that compliance occurred after the gantry. Only one DCZ (the first DCZ for scenario 5b) resulted in a positive average distance for the location of compliance. Table 27 and table 28 show the summary statistics of location of speed compliance for scenario 5a and scenario 5b, respectively.

Table 27. Summary statistics for the location of speed compliance relative to the gantry by DCZ for scenario 5a (first speed reduction).

DCZ	*N*	Mean (m)	STD (m)	Minimum (m)	Maximum (m)
1	5	-24.37	169.66	-209.85	202.67
2	13	-119.91	100.42	-248.22	60.13
3	9	-64.88	153.31	-260.96	197.18
4	12	-107.73	87.67	-250.05	19.42
5	0	—	—	—	—

3.28 ft = 1 m.
— Indicates non-calculable values.

Table 28. Summary statistics for the location of speed compliance relative to the gantry by DCZ for scenario 5b (second speed reduction).

DCZ	*N*	Mean (m)	STD (m)	Minimum (m)	Maximum (m)
1	7	30.32	150.28	-254.95	208.31
2	12	-117.15	71.25	-210.26	20.37
3	15	-138.34	136.04	-248.84	254.09
4	15	-127.91	88.09	-257.82	63.50
5	1	-192.66	—	-192.66	-192.66

3.28 ft = 1 m.
— Indicates non-calculable values.

Glance Behavior

A glance toward an ROI was defined as when a participant registered 12 or more hits toward the ROI during a DCZ. If a glance occurred, then the number of hits was multiplied by 120 (the advertised sampling rate of the eye-tracking system) to calculate the duration.

Glance Probability

Repeated measures logistic regression was used to determine whether there was a difference in the probability of a glance across the different scenarios. Recall that scenario 5 (speed reduction) was viewed twice by each participant (scenario 5a and scenario 5b, respectively). However, data from each viewing was kept separate and analyzed as two independent scenarios.

When considering only the overhead ATM signs (ATM_LEFT), results indicated there was a statistically significant difference in the probability of a glance between the different scenarios (χ^2 (4) = 30.44, $p < 0.001$). As is shown in figure 61, scenario 5a (first speed reduction) yielded the largest probability of a glance, and scenario 4 (two right lanes blocked, take exit) yielded the smallest probability.

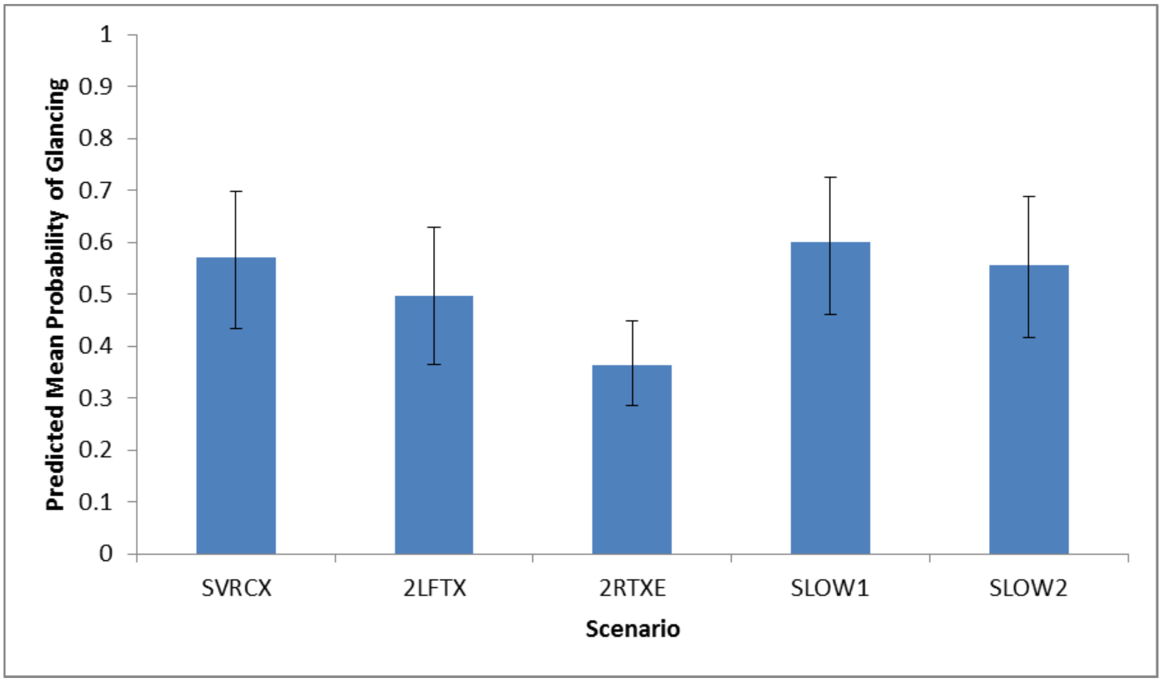


Figure 61. Graph. Predicted mean probability of glancing at ATM_LEFT by scenario.

When considering only the larger side-mounted CMS (ATM_RIGHT), results indicated there was a statistically significant difference in the probability of a glance between the different scenarios (χ^2 (4) = 26.14, $p < 0.001$). As is shown in figure 62, scenario 5a (first speed reduction) yielded the largest probability of a glance, and scenario 4 (two right lanes blocked, take exit) yielded the smallest probability.

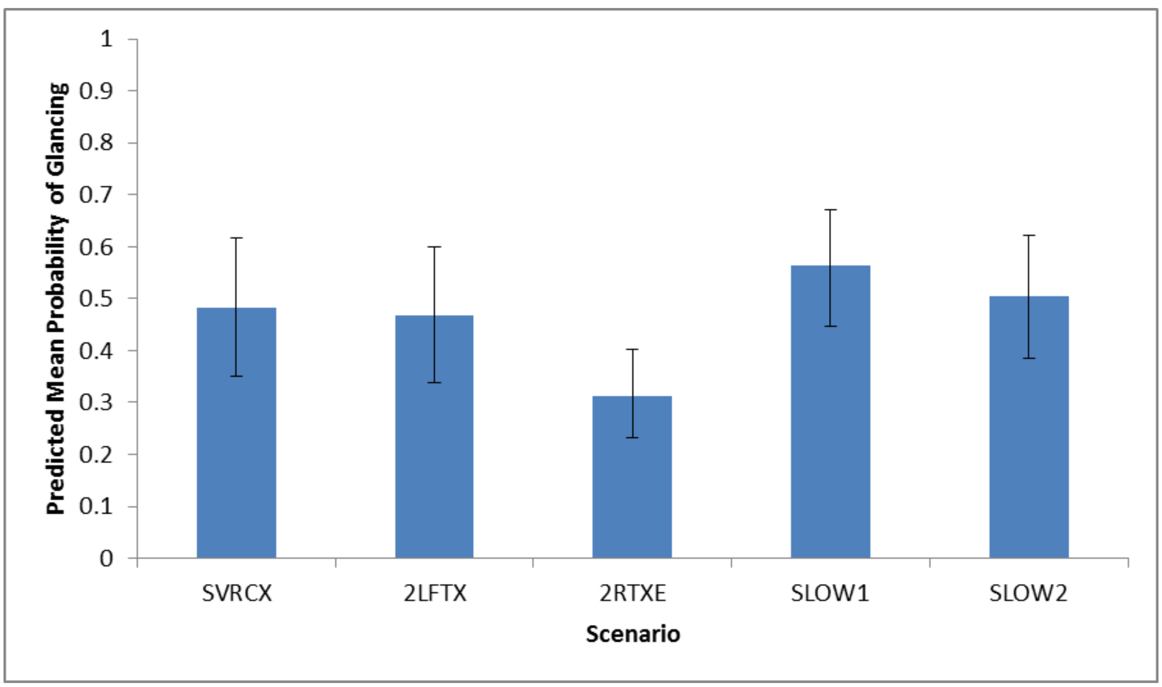


Figure 62. Graph. Predicted mean probability of glancing at ATM_RIGHT by scenario.

Glance Duration

General estimating equations (GEEs) with a Gamma response distribution and identity link function were used to analyze the duration of a glance, given that a glance had occurred. In other words, no durations of 0 s were included in the analysis.

When considering only glances to ATM_LEFT, results indicated that there was a statistically significant difference in the duration of a glance between the scenarios (χ^2 (4) = 13.34, p = 0.010). As is shown in figure 63, scenario 4 (two right lanes blocked, take exit) yielded the longest glance duration, and scenario 3 (two left lanes closed) yielded the shortest.

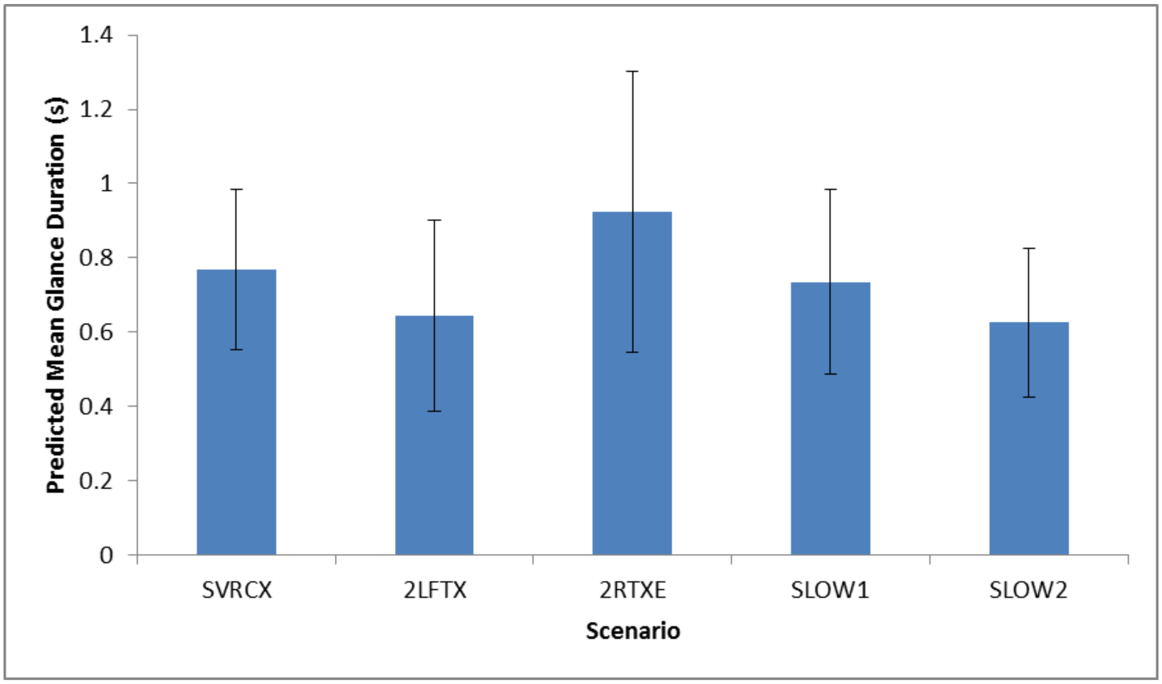


Figure 63. Graph. Predicted mean glance duration at ATM_LEFT by scenario.

When considering only glances to ATM_RIGHT, results indicated that there was no statistically significant difference in the duration of a glance between the scenarios. Overall, the mean glance duration was about 0.59 s. Figure 64 below shows the predicted mean glance duration by scenario.

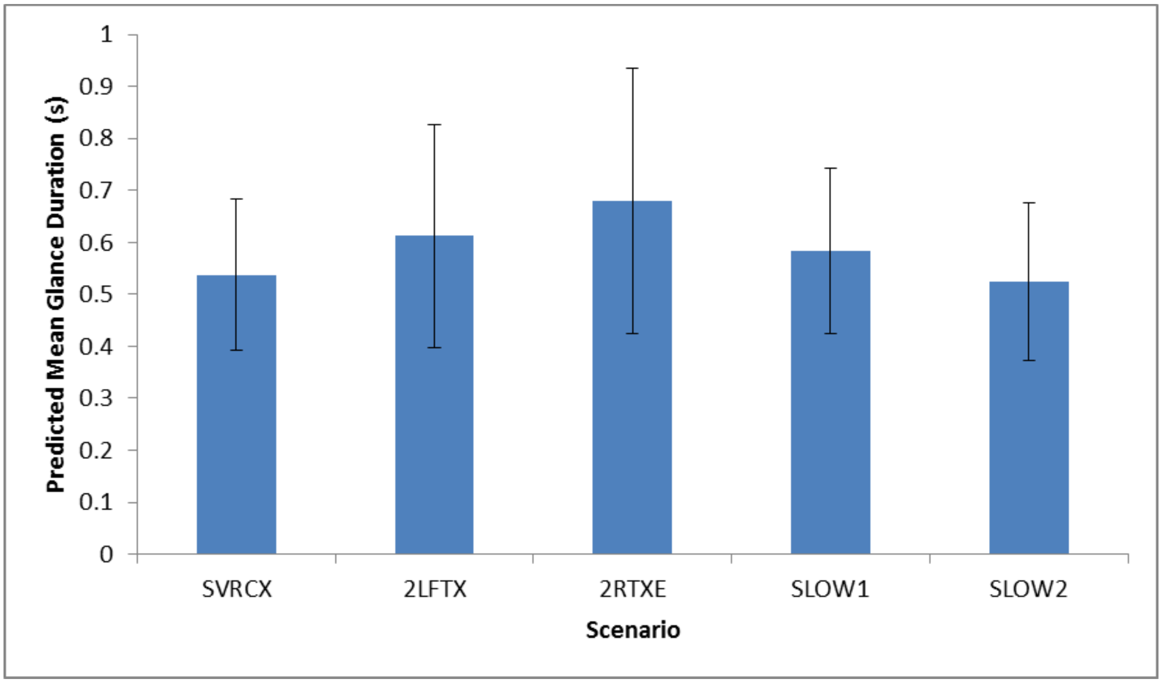


Figure 64. Graph. Predicted mean glance duration at ATM_RIGHT by scenario.

Look Behavior

A *look* was defined as 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.

Look Probability

Repeated measures logistic regression was used to determine whether there was a difference in the probability of at least one look across the different scenarios. Recall that scenario 5 (speed reduction) was viewed twice by each participant. However, data from each viewing was kept separate and analyzed as two independent scenarios (scenario 5a and 5b, respectively).

When considering only the overhead ATM signs (ATM_LEFT), results indicated there was no statistically significant difference in the probability of at least one look between the different scenarios. Overall, this probability was about 0.52. Figure 65 shows the probability of at least one look for each of the scenarios.

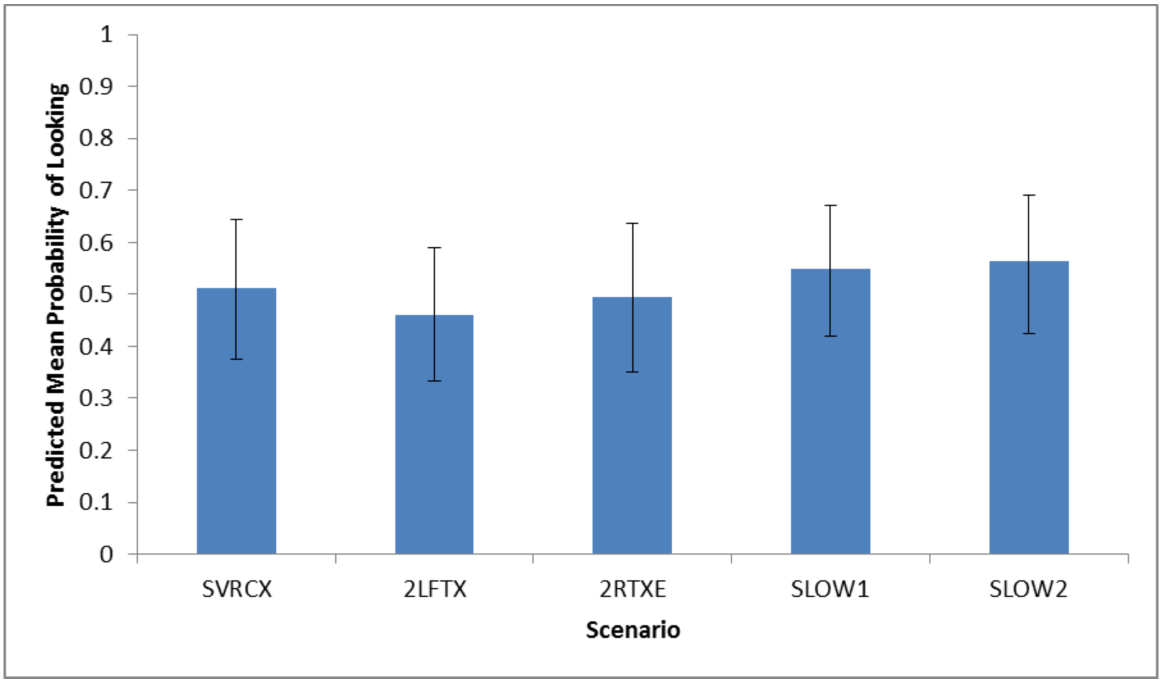


Figure 65. Graph. Predicted mean probability of at least one look at ATM_LEFT by scenario.

When considering only looks to ATM_RIGHT, results indicated there was no significant difference in the probability of at least one look between the different scenarios. Overall, this probability was about 0.44. Figure 66 shows the probability of at least one look for each of the scenarios.

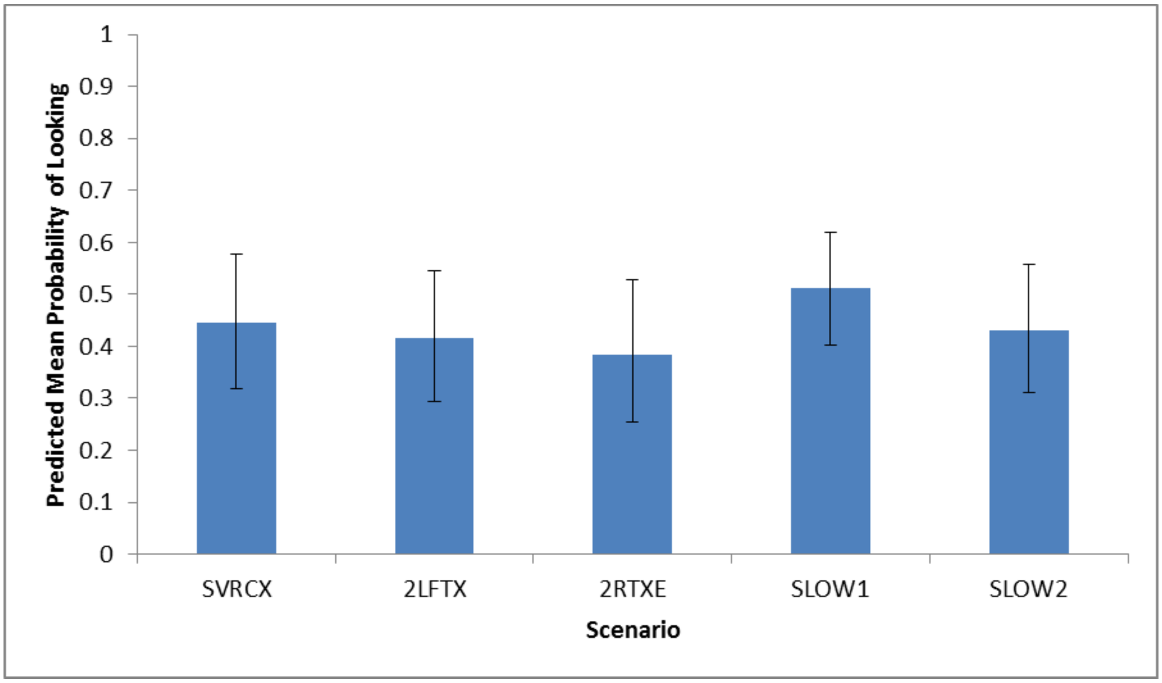


Figure 66. Graph. Predicted mean probability of at least one look at ATM_RIGHT by scenario.

Number of Looks

Repeated measures Poisson regression was used to determine whether the number of looks (assuming at least one look occurred) among between the different scenarios. Recall that scenario 5 (speed reduction) was viewed twice by each participant. However, data from each viewing was kept separate and analyzed as two independent scenarios (scenario 5a and 5b, respectively).

When considering only the overhead ATM signs (ATM_LEFT), results indicated there was a statistically significant difference in the number of looks across the scenarios (χ^2 (4) = 28.94, $p < 0.001$). Figure 67 shows the predicted mean number of looks by scenario. Despite having only three ATM signs (as opposed to five as in the other scenarios), scenario 4 (two right lanes blocked, take exit) resulted in the greatest number of looks. Scenario 5b (second speed reduction) yielded the fewest.

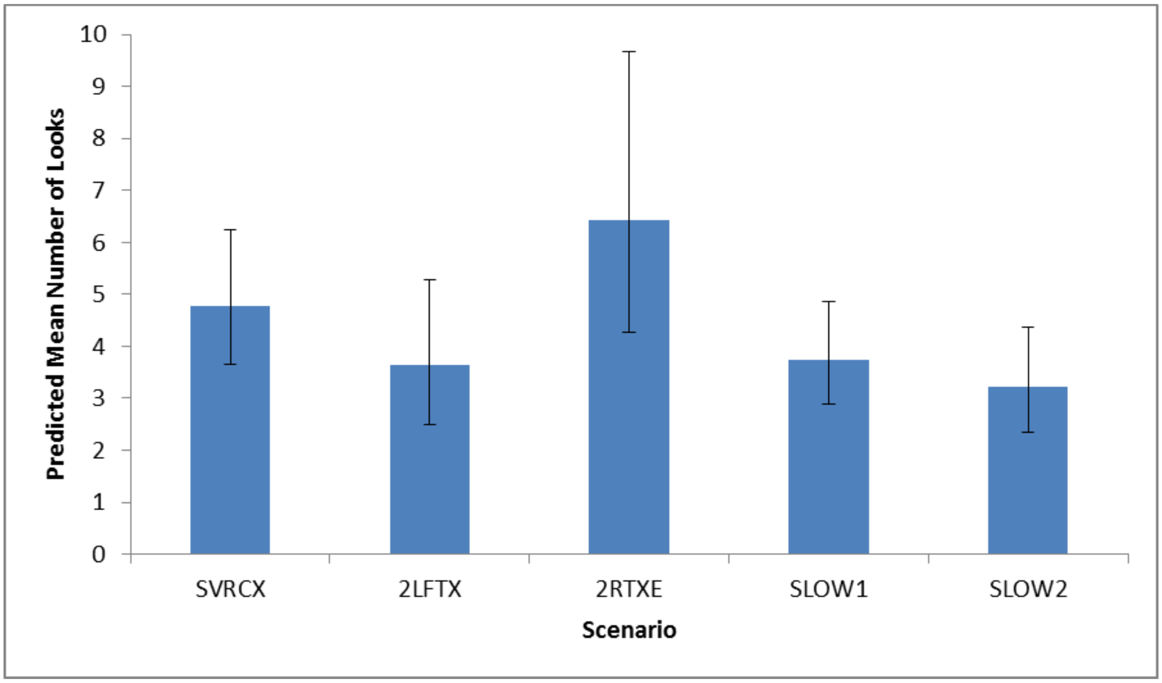


Figure 67. Graph. Predicted mean number of looks at ATM_LEFT by scenario.

When considering only ATM_RIGHT, results indicated there was a statistically significant difference in the number of looks across the scenarios (χ^2 (4) = 12.22, p = 0.016). There were generally fewer looks toward ATM_RIGHT than toward ATM_LEFT. However, the greatest number of looks to ATM_RIGHT was still in scenario 4 (two right lanes blocked, take exit; see figure 68). The fewest number of looks occurred during scenario 5b (second speed reduction).

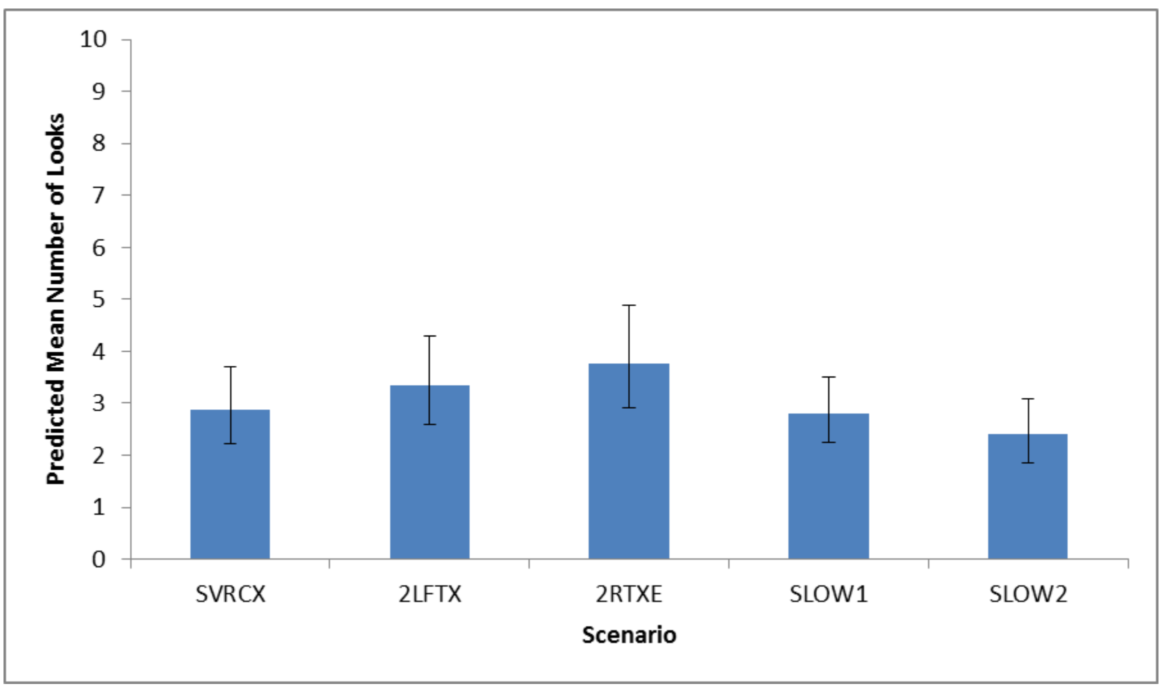


Figure 68. Graph. Predicted mean number of looks at ATM_RIGHT by scenario.

Look Duration

GEEs with a Gamma response distribution and identity link function were used to determine whether the duration of looks (assuming at least one look occurred) varied among the different scenarios. Recall that scenario 5 (speed reduction) was viewed twice by each participant. However, data from each viewing was kept separate and analyzed as two independent scenarios (scenario 5a and 5b, respectively).

When considering only the overhead ATM signs (ATM_LEFT), results indicated there was no statistically significant difference in the duration of looks across the scenarios. Overall, the mean look duration was 0.14 s. Figure 69 shows the predicted mean look duration for each scenario.

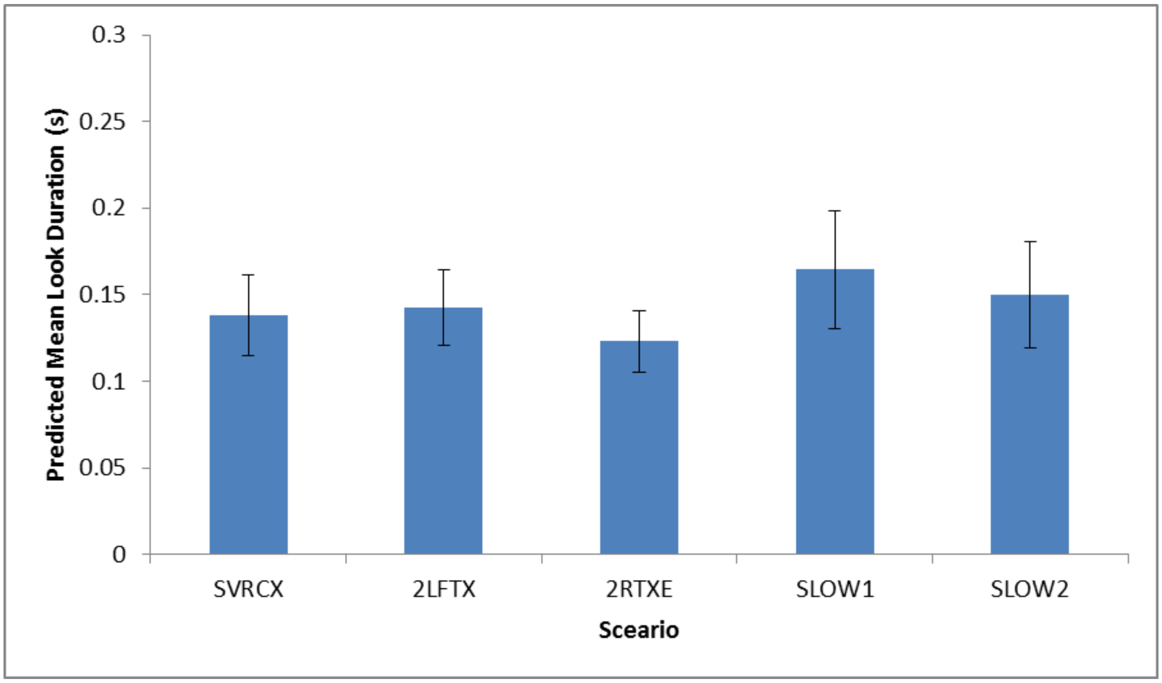


Figure 69. Graph. Predicted mean look duration at ATM_LEFT by scenario.

When considering only ATM_RIGHT, results indicated there was a statistically significant difference in look duration between the different scenarios ($\chi^2(4) = 12.34$, $p = 0.015$). Figure 70 shows the predicted mean look duration for each scenario. Although scenario 5b (second speed reduction) yielded the fewest looks to ATM_RIGHT (see figure 68), these looks were the longest in duration. Scenario 2 (stalled vehicle) resulted in the shortest look durations.

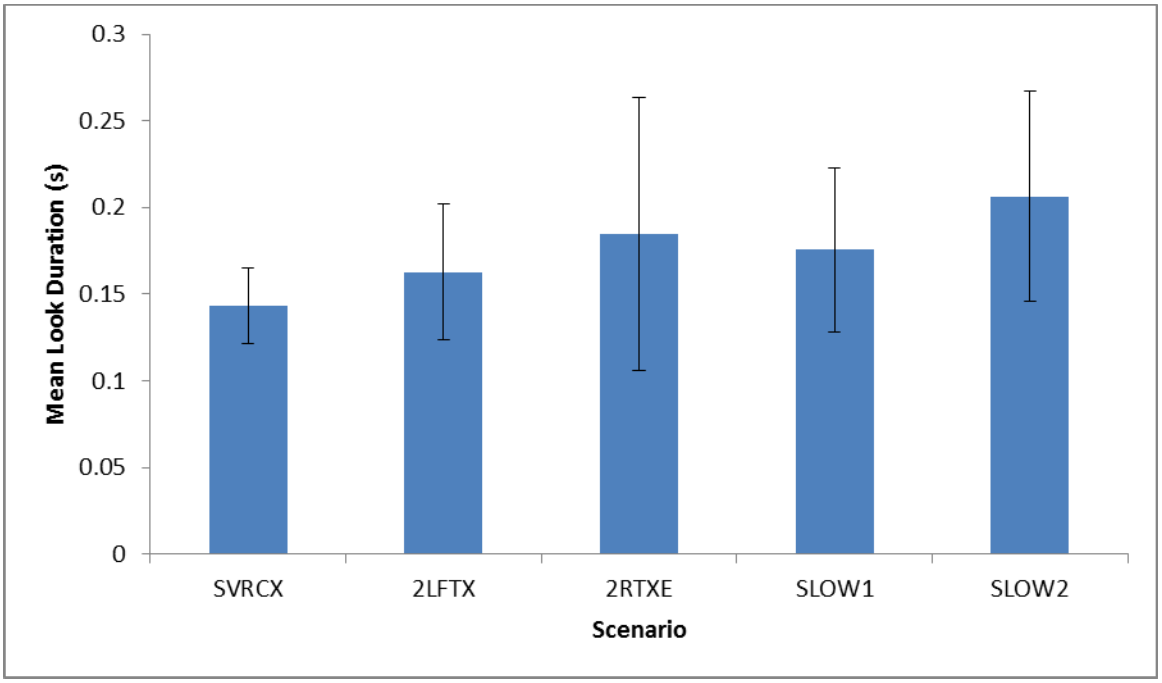


Figure 70. Graph. Predicted mean look duration at ATM_RIGHT by scenario.

Fixation Behavior

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., 15 pixels on the 372-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.

Fixation Probability

Repeated measures logistic regression was used to determine whether there was a difference in the probability of at least one fixation across the different scenarios. Recall that scenario 5 (speed reduction) was viewed twice by each participant. However, data from each viewing was kept separate and analyzed as two independent scenarios (scenario 5a and 5b, respectively).

When considering only the overhead ATM signs (ATM_LEFT), results indicated there was a statistically significant difference in the probability of at least one fixation between the different scenarios (χ^2 (4) = 13.46, p = 0.009). Figure 71 shows the probability of at least one fixation for each of the scenarios. Scenario 2 (stalled vehicle) and scenario 5b (second speed reduction) resulted in the highest probability of at least one fixation, while scenario 3 (two left lanes closed) yielded the lowest corresponding probability.

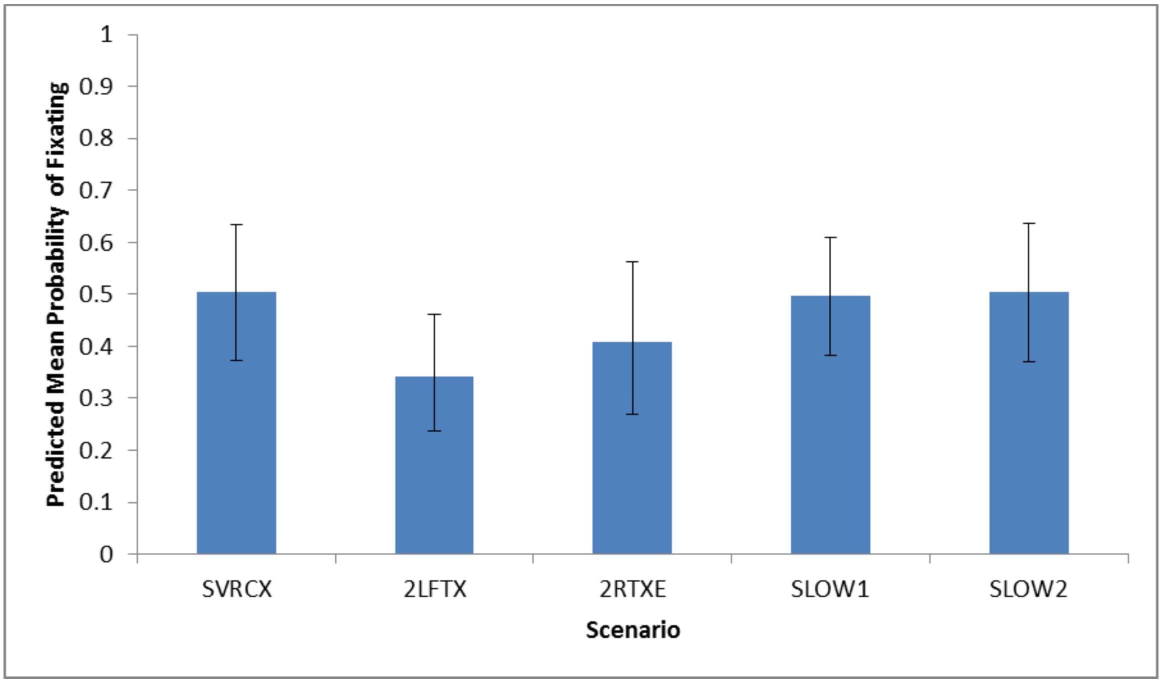


Figure 71. Graph. Predicted mean probability of at least one fixation on ATM_LEFT by scenario.

When considering only fixations to ATM_RIGHT, results indicated there was a statistically significant difference in the probability of at least one fixation between the different scenarios (χ^2 (4) = 13.02, p = 0.011). Figure 72 shows the probability of at least one fixation for each of the scenarios. Overall, this probability was less than the corresponding probability for ATM_LEFT. Scenario 5a (first speed reduction) resulted in the greatest probability of at least one fixation while scenario 2 (stalled vehicle) yielded the lowest probability.

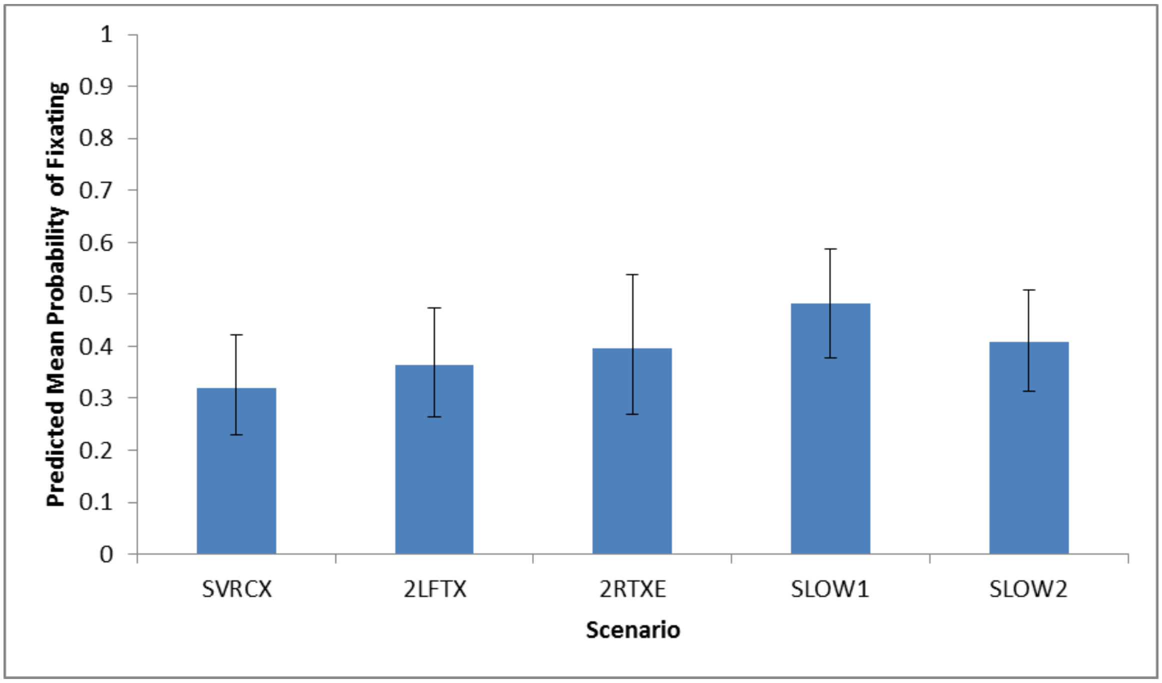


Figure 72. Graph. Predicted mean probability of at least one fixation on ATM_RIGHT by scenario.

Number of Fixations

Repeated measures Poisson regression was used to determine whether the number of fixations (assuming at least one fixation occurred) varied among the different scenarios. Recall that scenario 5 (speed reduction) was viewed twice by each participant. However, data from each viewing was kept separate and analyzed as two independent scenarios (scenario 5a and 5b, respectively).

When considering only the overhead ATM signs (ATM_LEFT), results indicated there was a statistically significant difference in the number of fixations across the scenarios (χ^2 (4) = 11.52, p = 0.021). Figure 73 shows the predicted mean number of fixations by scenario. Despite having only three ATM signs (as opposed to five as in the other scenarios), scenario 4 (two right lanes blocked, take exit) resulted in the greatest number of fixations. Scenario 5b (second speed reduction) yielded the fewest.

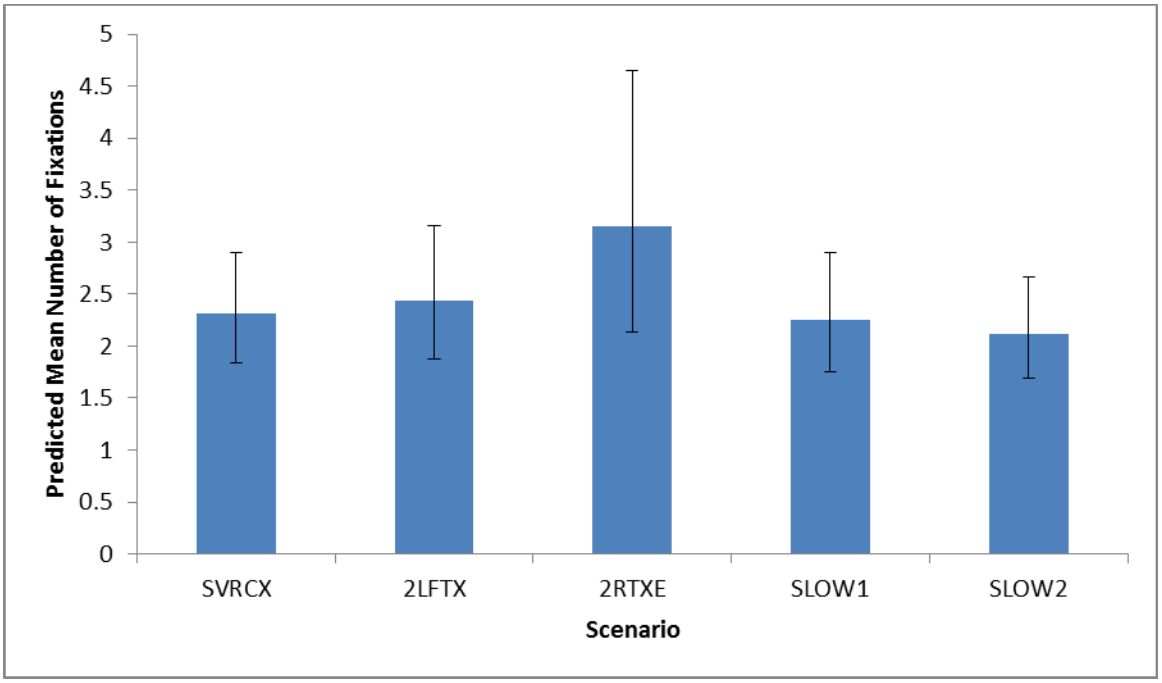


Figure 73. Graph. Predicted mean number of fixations on ATM_LEFT by scenario.

When considering only ATM_RIGHT, results indicated there was a statistically significant difference in the number of fixations across the scenarios (χ^2 (4) = 14.07, p = 0.007). There were generally fewer fixations toward ATM_RIGHT than toward ATM_LEFT. However, the greatest number of fixations on ATM_RIGHT was still in scenario 4 (two right lanes blocked, take exit; see figure 74). The fewest number of fixations occurred during scenario 5b (second speed reduction).

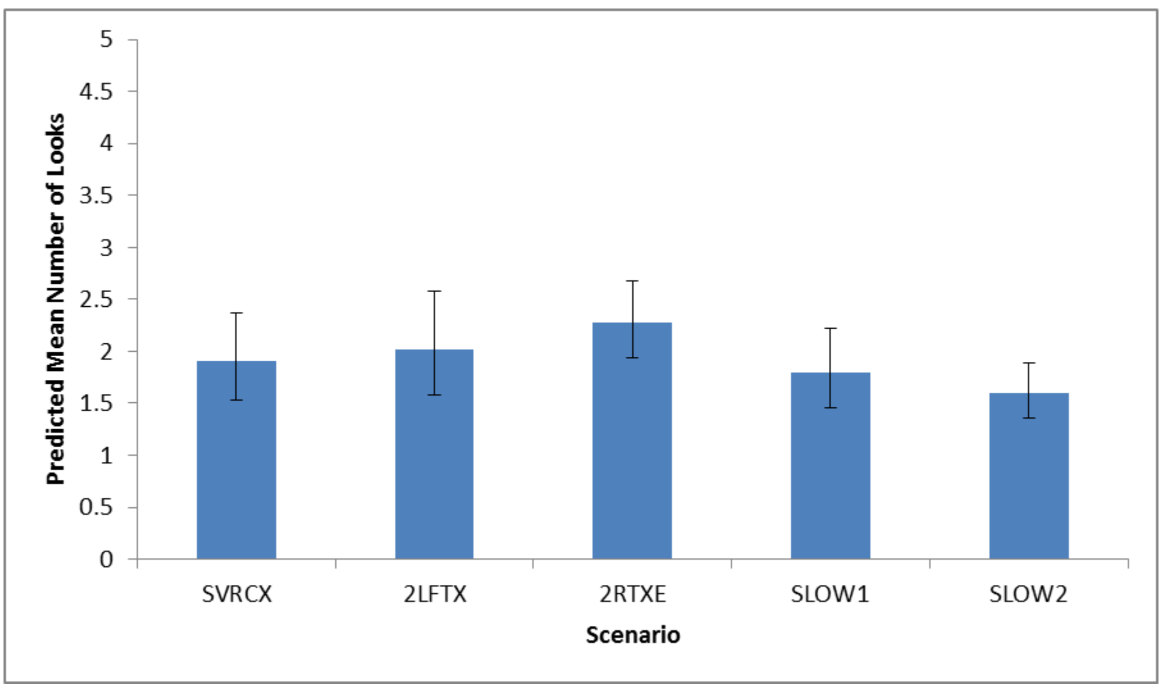


Figure 74. Graph. Predicted mean number of fixations on ATM_RIGHT by scenario.

Fixation Duration

GEEs with a Gamma response distribution and identity link function were used to determine whether the duration of fixations (assuming at least one fixation occurred) varied among the different scenarios. Recall that scenario 5 (speed reduction) was viewed twice by each participant. However, data from each viewing was kept separate and analyzed as two independent scenarios (scenario 5a and 5b, respectively).

When considering only the overhead ATM signs (ATM_LEFT), results indicated there was a statistically significant difference in the duration of fixations across the scenarios (χ^2 (4) = 15.18, p = 0.004). Figure 75 shows the predicted mean fixation duration for each scenario. Scenario 2 (stalled vehicle) resulted in the longest fixation duration while scenario 5b (second speed reduction) yielded the shortest.

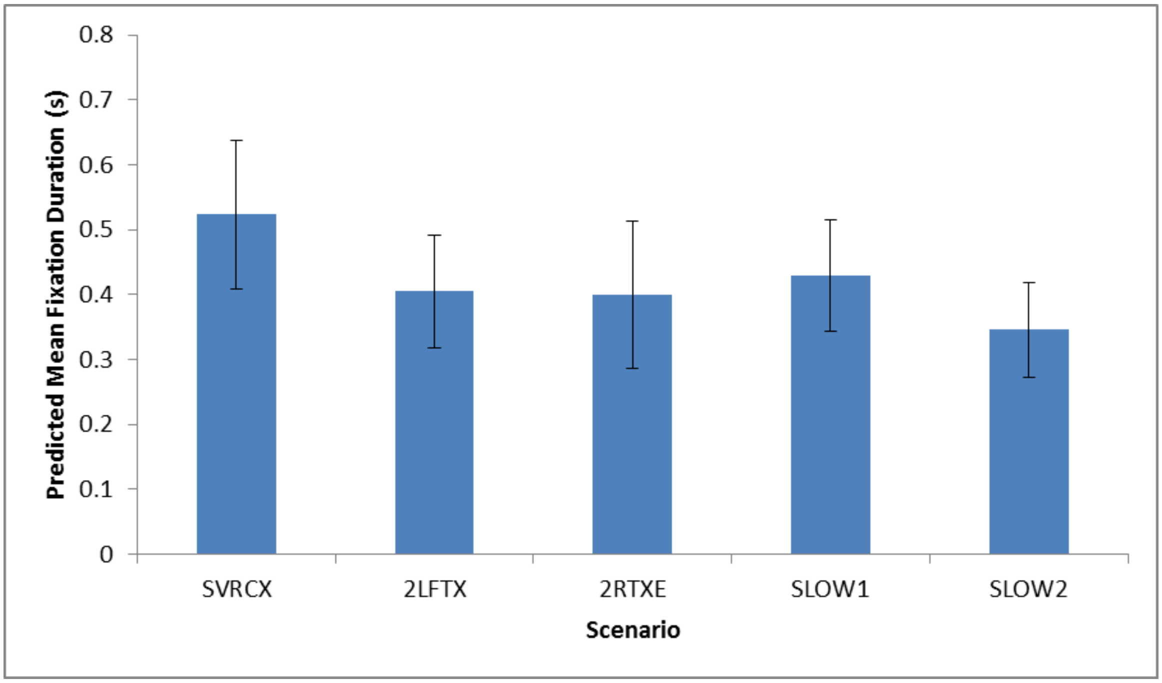


Figure 75. Graph. Predicted mean fixation duration on ATM_LEFT by scenario.

When considering only ATM_RIGHT, results indicated there was no statistically significant difference in fixation duration among the different scenarios. The average fixation duration was 0.50 s. Figure 76 shows the predicted mean fixation duration for each scenario. In general, fixation durations on ATM_RIGHT were greater than the fixation durations on ATM_LEFT.

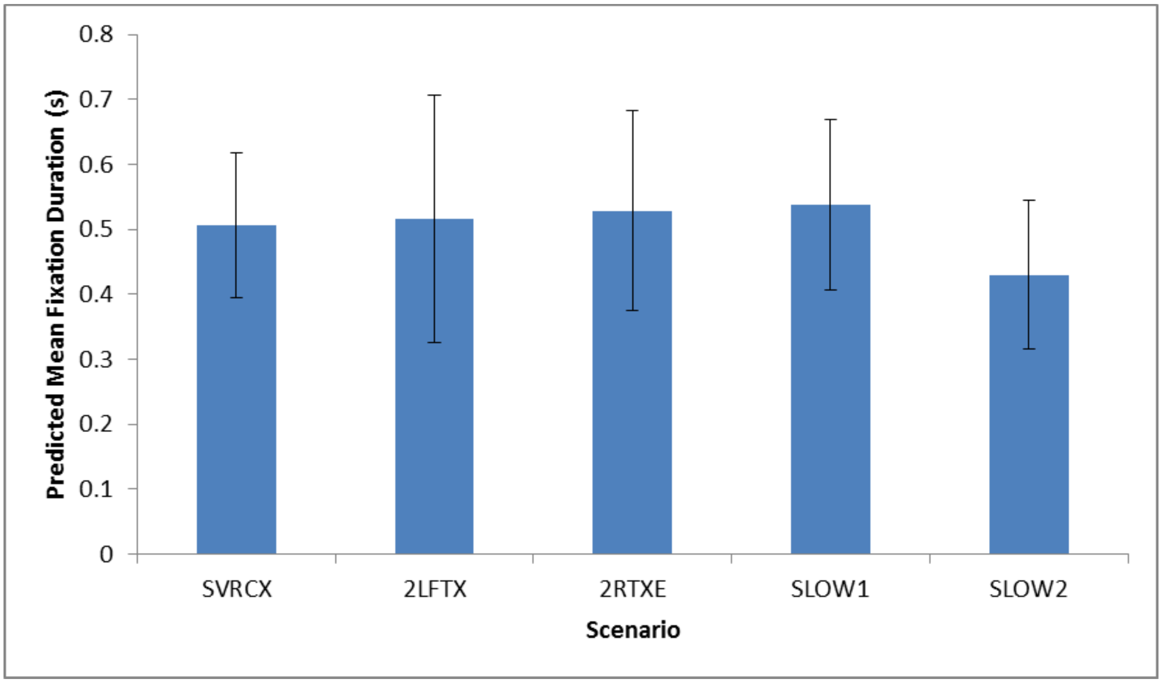


Figure 76. Graph. Predicted mean fixation duration on ATM_RIGHT by scenario.

DISCUSSION

In an unintentional departure from the original experiment design, a subset of participants was not presented with the second exit sequence sign for Holt Ave (HOLT2). For that subset of participants, the observed glance probabilities were 0.40, 0.00, and 0.60 for the first, second, and third exit signs, respectively. Inclusion of the second exit sequence sign resulted in an increase in all of the observed glance probabilities, i.e., 0.41, 0.64, and 0.73 for the first exit sign, second exit sign, and third exit sign, respectively. The data suggest that inclusion of the second advanced guide sign resulted in a higher probability of glances to the last exit sign in the sequence. The MUTCD does not specify the requirement for a 1-mi (1.61-km) and a 0.5-mi (0.8-km) exit sign.[8] However, the present study suggests that the addition of the 0.5-mi (0.8-km) advance guide sign will increase the likelihood that drivers will glance at the last exit sign in the series and perhaps be more likely not to miss the exit.

Drivers experienced five different scenarios during the simulated drive. However, data from the resting condition was not analyzed. The following summarizes behavioral results (i.e., speed maintenance, lane choice) for the other four scenarios:

- **Scenario 2—Stalled vehicle closing 1 lane (right-center lane—lane 3):** Participants exited their travel lane upon encountering the stalled car, and no participant collided with the vehicle. Most of the participants exited their lane when shown the lane closed ahead sign well in advance of when the lane actually closed. The participants made these early decisions while in the driving environment where the side-mounted ATM displayed a message that there was a stalled vehicle ahead. From a safety perspective, this may prove to be effective behavior. However, early exiting of the lane by a large volume of traffic might not be optimal behavior from a traffic flow perspective. On average, participants slowed down to about 5 mi/h (8 km/h) below the speed limit while approaching the stalled vehicle.

- **Scenario 3—Vehicle crash closing two left lanes (lanes 1 and 2):** Most of the drivers remained in their lane or moved to the rightmost lane, both of which were correct responses. Speed selection behavior was very similar to that observed for the stalled vehicle scenario.

- **Scenario 4—Vehicle crash closing two right lanes (lanes 3 and 4 with exit ramp open):** Drivers were instructed at the start of the simulation to exit at Holt Ave (the exit in this scenario). The side-mounted CMS indicated that the right lanes were for exit only. Results showed that the majority of the participants successfully exited at Holt Ave. Participants slowed a few miles per hour (less than 5 mi/h (8 km/h)) until they approached the exit and then significantly decreased their speeds as they took the exit.

- **Scenario 5—Message in the event of slow-moving traffic in all lanes (reduce speed):** The VSL signs showed lower speed limits every 0.5 mi (0.8 km). Although the simulated background traffic did not decelerate until it passed the VSL signs, the participants did decreased their speeds after they encountered the signs. The data showed they complied with a given VSL sign about 314 ft (99 m) after passing that sign. Although the drivers slowed down in response to the VSL sign, they were, by and large, speeding by about 10 mi/h (16 km/h).

The following summarizes eye-tracking results for each of the four scenarios that were analyzed:

- **Scenario 2—Stalled vehicle closing 1 lane (right-center lane—lane 3):** Participants fixated on the per-lane CMSs about two times, on average. The mean fixation duration was more than 0.5 s, which was significantly longer compared with the other scenarios. Similarly, participants fixated on the side-mounted CMS an average of two times. The corresponding average fixation duration (0.5 s) was not significantly different from the other scenarios.

- **Scenario 3—Vehicle crash closing two left lanes (lanes 1 and 2):** Participants fixated on the per-lane CMSs about two times, on average, and the corresponding mean fixation duration was about 0.4 s. Similarly, participants fixated on the side-mounted CMS an average of two times. The corresponding average fixation duration (0.5 s) was not significantly different from the other scenarios.

- **Scenario 4—Vehicle crash closing two right lanes (lanes 3 and 4 with exit ramp open):** Despite having only three ATM signs (as opposed to five as in the other scenarios), this scenario resulted in the greatest number of fixations (about three) on the per-lane CMSs. The corresponding average fixation duration was about 0.4 s. Similarly, this scenario also resulted in the greatest number of fixations (about two) on the side-mounted CMS. However, the corresponding average fixation duration (0.5 s) was not significantly different from the other scenarios.

- **Scenario 5—Message in the event of slow-moving traffic in all lanes (reduce speed):** Participants fixated on the per-lane CMSs an average of two times for each viewing of this scenario. The overall predicted mean fixation duration was about 0.4 s, and this duration decreased from the first viewing of the scenario to the second. Participants fixated on the side-mounted CMS, which indicated there was slow traffic ahead, an average of two times for each viewing of this scenario. The overall predicted mean fixation duration was about 0.5 s, and this duration also decreased (although not significantly) from the first viewing of the scenario to the second.

In summary, participants garnered useful information from the per-lane and side-mounted CMSs without long (greater than 2 s) fixations. In conjunction with the speed and lane choice behavioral data, results suggest that these ATM signs are easily understood.

CHAPTER 5. DRIVER DECISIONMAKING UNDER VISUAL CLUTTER

This second simulation study used the same scenarios as the previous simulation study. The gantries for the per-lane ATM signs contained guide signs, but no side-mounted CMSs with supplemental roadway messages. The arrangement of the signs in this study was similar to the arrangement in the Minnesota deployment. In addition, two different levels of roadway clutter (low and moderate) were included on the sides of the road. The focus of this study was driver behavior and decisionmaking under different scenarios and varying levels of clutter.

METHODS

The Simulator

The experiment was conducted using the FHWA Highway Driving Simulator. In the previous simulator experiment described in this report, the simulator's out-of-vehicle display consisted of a horizontal projection of 240 degrees onto a 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. Two of the original projectors were used to complete the side portions of the 240 degrees horizontal display. The LCD monitors were mounted in the windshield area of the late model compact sedan as shown in figure 77.

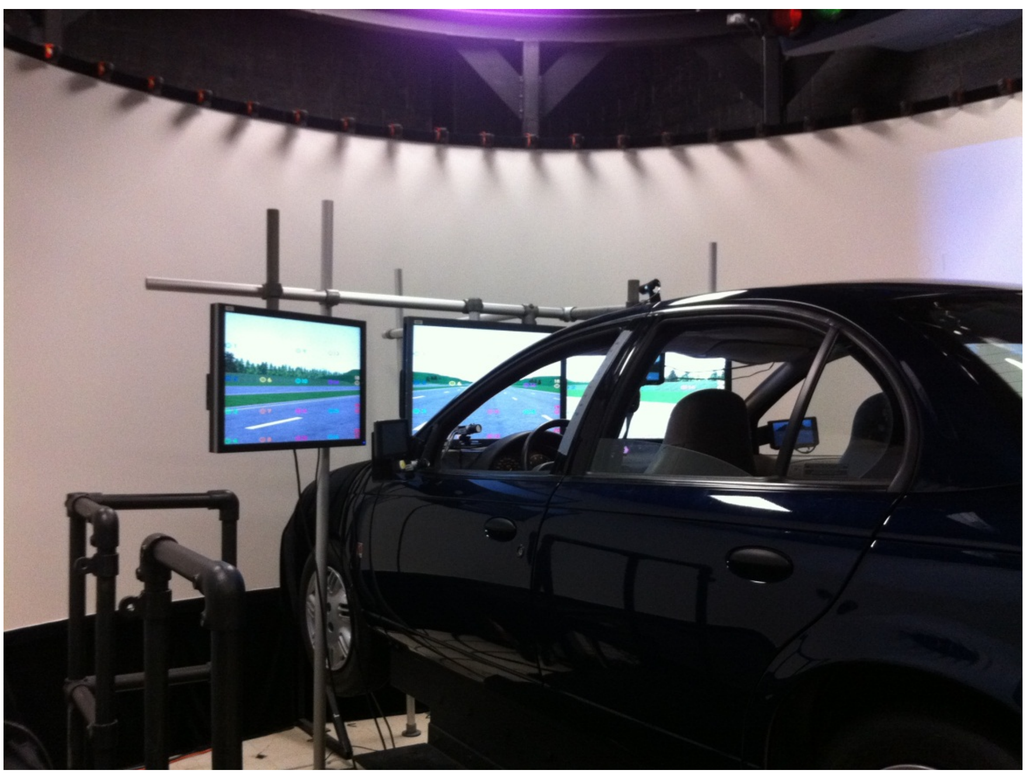


Figure 77. Photo. The FHWA Highway Driving Simulator with LCD monitors.

Each of the LCD displays was 30 inches (76 cm) on the diagonal with a 16:10 aspect ratio. The LCD monitor resolutions were 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 (91 cm). The right and left monitors were 39 and 49 inches (99 and 124 cm), respectively, from the design eye point. 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 displays was 8 ms.

Rearview mirrors were simulated using 7.8- by 4.8-inch ((20 by 12-cm) color LCDs 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 rearview LCD was placed as near as possible to the location of the vehicle's original mirror.

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.

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 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 well-being.

ATM Signs

The ATM signs used in this experiment were those shown in figure 43 through figure 49. These signs represented a selection of signs that were being used in ATM test deployments in Washington and Minnesota at the time of this study. Selection of these signs was based on the result of sign comprehension and preference testing done in a laboratory setting (see chapter 2). The sign gantries and mounting of the per-lane ATM signs were similar to that employed in the Minnesota field deployment.

Simulation Scenarios

The participants drove on a simulated eight-lane highway approximately 23 mi (37 km) in length. A 1-mi (1.61-km) section of freeway without overhead signs preceded the first overhead ATM sign. The ATM signs (gantries) were spaced every 0.5 mi (0.8 km) along the roadway. 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 1.25 times the size of their real-world equivalents. Figure 78 shows an example of an ATM sign at the start of an area in scenario 5 (speed reduction).

Figure 78. Screen capture. Example ATM signs for a speed reduction zone.

Each drive was composed of the following scenarios:

1. Resting condition for the signs (normal operations for all lanes).
2. Stalled vehicle closing 1 lane (right-center lane—lane 3).
3. Vehicle crash closing two left lanes (lanes 1 and 2).
4. Vehicle crash closing two right lanes (lanes 3 and 4 with exit ramp open).
5. Message in the event of slow-moving traffic in all lanes (speed reduction).

The traffic in this simulation was generated in the same manner as for the previous simulation experiment (see chapter 4).

Eye-Tracking System

The eye-tracking system and its setup was the same as for the previous simulation experiment (see chapter 4).

To quantify when and for how long participants looked at each ATM sign, a researcher used analysis software to indicate a ROI on individual frames of the recorded video image. An example of an ROI is shown in figure 78 (the halo around the signs). ROIs were created between the point a sign began to pass out of the driver's view and 10 s upstream of that point. Only one ROI for this experiment was created, which encompassed the four per-lane CMSs as well as the overhead guide signs.

PARTICIPANTS

Fifty-three participants successfully completed the simulation. However, only 43 participants (22 males and 21 females) produced usable eye-tracking data. Of these 43 participants, the mean age for males was 39 years old (range 18 to 73 years old) and the mean age for females was 44 years old (range 18 to 76 years old).

Participants experienced low or medium levels of clutter depending on the clutter level. Of the participants who had usable eye-tracking data, 19 participants experienced the low clutter simulation, and 24 participants experienced the medium clutter simulation.

RESULTS

In all figures, error bars indicate 95-percent confidence limits. Also, for ease of understanding, the scenarios have been coded in the figures as the following. There are two codes for scenario 5 (speed reduction) because participants viewed this scenario twice.

1. **REST:** Resting condition for the signs (normal operations for all lanes).
2. **SVRCX:** Stalled vehicle closing 1 lane (right-center lane – lane 3).
3. **2LFTX:** Vehicle crash closing two left lanes (lanes 1 and 2).
4. **2RTXE:** Vehicle crash closing two right lanes (lanes 3 and 4 with exit ramp open).
5. **SLOW1/SLOW2:** Message in the event of slow-moving traffic in all lanes (reduced speed).

Clutter Effect

First, all participants were included to analyze whether the level of clutter altered a driver's ability to successfully exit at the end of the drive (see table 29). Of these participants, 24 experienced the low clutter level and 29 experienced the medium clutter level. Chi-squared test results indicated there was no significant difference in exit-taking behavior for the two groups.

Table 29. Distribution (row percentages) for exit-taking behavior by clutter level for all participants (N = 53).

	Exit-Taking Behavior (percent)	
Clutter Level	Did Not Take Exit	Took Exit
Low	38	62
Medium	41	59

Next, only the 43 participants who produced usable eye-tracking data were included in a similar analysis of the effect of clutter (see table 30). Chi-squared test results indicated there was no significant difference in exit-taking behavior for the two groups.

Table 30. Distribution (row percentages) for exit-taking behavior by clutter level for all participants with usable eye-tracking data (N = 43).

	Exit-Taking Behavior (percent)	
Clutter Level	Did Not Take Exit	Took Exit
Low	37	63
Medium	42	58

Lane Choice and Speed Behavior

During data collection, researchers observed a participant's lane position following each gantry in the scenario. In scenario 1 (resting condition), three observations were recorded, one for each gantry. This scenario was presented to each participant at the beginning of the drive and then in between each of the other scenarios. Table 31 shows the distribution (row percentages) of lane choice across participants for each recorded observation. Chi-squared test results indicated there was no significant association between the observation in the scenario and lane choice. Overall, participants tended to stay in lane 3 as initially instructed by the researcher.

Table 31. Distribution (row percentages) of lane choice by DCZ for scenario 1 (resting condition).

DCZ	Lane Choice (percent) Lane 1	Lane 2	Lane 3	Lane 4
1	—	3	96	1
2	—	2	98	—
3	—	2	98	—

— Indicates 0 percent.

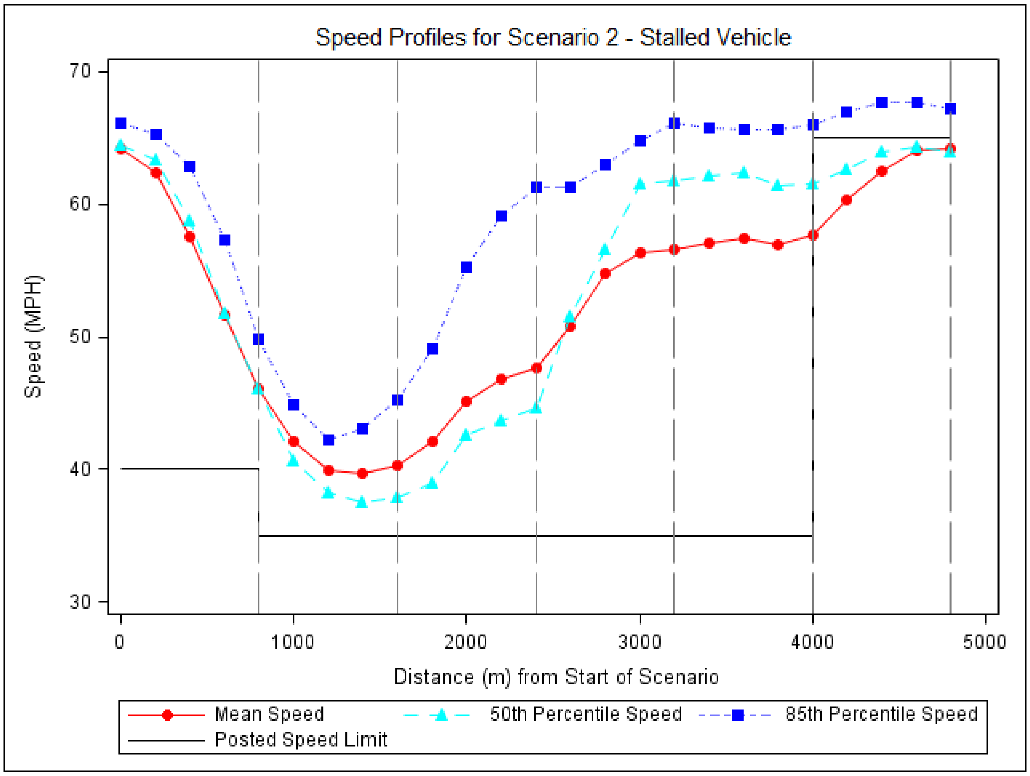
In scenario 2 (stalled vehicle), six observations were recorded, one for each of the gantries. Table 32 shows the distribution (row percentages) of lane choice for each recorded observation. Chi-squared test results indicated there was a significant association between the observation in the scenario and lane choice (χ^2 (10) = 130.82, $p < 0.001$). The data suggest that the participants exited lane 3 in accordance with the instructions on the ATM signs. Once the stalled vehicle was encountered (between the fifth and sixth gantries), participants reentered lane 3.

Table 32. Distribution (row percentages) of lane choice by DCZ for scenario 2 (stalled vehicle).

DCZ	Lane Choice (percent) Lane 1	Lane 2	Lane 3	Lane 4
1	—	—	100	—
2	—	—	100	—
3	—	21	60	19
4	—	40	23	37
5	—	46	7	47
6	—	17	60	23

— indicates 0 percent.

Figure 79 shows the speed profile for this scenario. Unlike the previous experiment (see chapter 4), VSL signs were used in this experiment to slow the traffic down as it approached the stalled vehicle. Also, in contrast to the previous experiment, participants were not presented supplemental roadway information messages on a side-mounted CMS in this experiment. The speed profile shows that the participants initially decreased their speeds in response to the VSL signs but then sped up throughout the scenario as they approached the stalled vehicle. By the time the stalled vehicle was encountered, the participants were driving about 10 mi/h (16 km/h) slower than the facility posted speed limit (65 mi/h (105 km/h)) but significantly faster than the posted speed limits shown on the last VSL sign (shown on gantry 2).



1 mi/h = 1.61 km/h.
1 ft = 0.305 m.

Figure 79. Graph. Speed profile for scenario 2 (stalled vehicle).

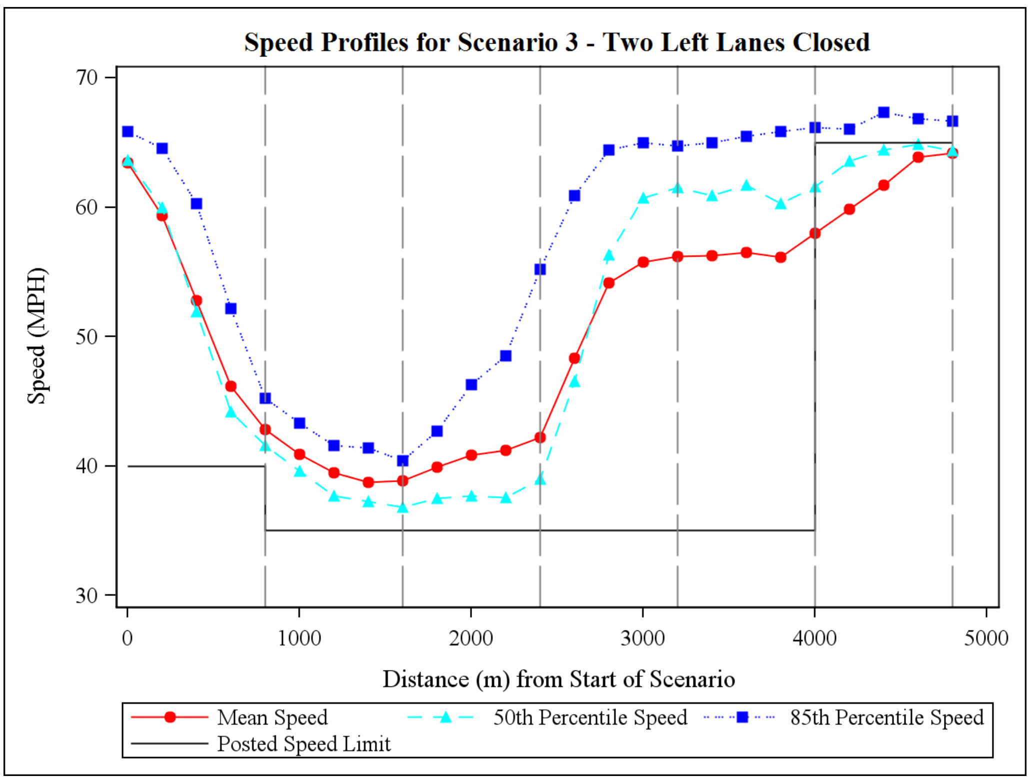
In scenario 3 (two left lanes closed), six observations were recorded, one for each of the gantries. Table 33 shows the distribution (row percentages) of lane choice for each recorded observation. Chi-squared test results indicated there was no significant association between the observation in the scenario and lane choice. The data suggest that participants exited the two left lanes (lanes 1 and 2) in accordance with the instructions on the ATM signs.

Table 33. Distribution (row percentages) of lane choices by DCZ for scenario 3 (two left lanes closed).

DCZ	Lane Choice (percent) Lane 1	Lane 2	Lane 3	Lane 4
1	—	2	98	—
2	—	2	98	—
3	—	2	95	3
4	—	—	93	7
5	—	—	93	7
6	—	—	95	5

— Indicates 0 percent.

Figure 80 shows the speed profile for this scenario. VSL signs were used in this experiment to slow the traffic down as it approached the lane closure. Participants initially decreased their speeds in response to the VSL signs but then increased their speeds throughout the scenario. By the time they reached the crashed vehicles, participants were on average traveling about 10 mi/h (16 km/h) slower than the facility posted speed limit (65 mi/h (105 km/h)) but faster than the posted speed limits shown on the last VSL sign (shown on gantry 2).



1 mi/h (MPH) = 1.61 km/h.
1 ft = 0.305 m.

Figure 80. Graph. Speed profile for scenario 3 (two left lanes closed).

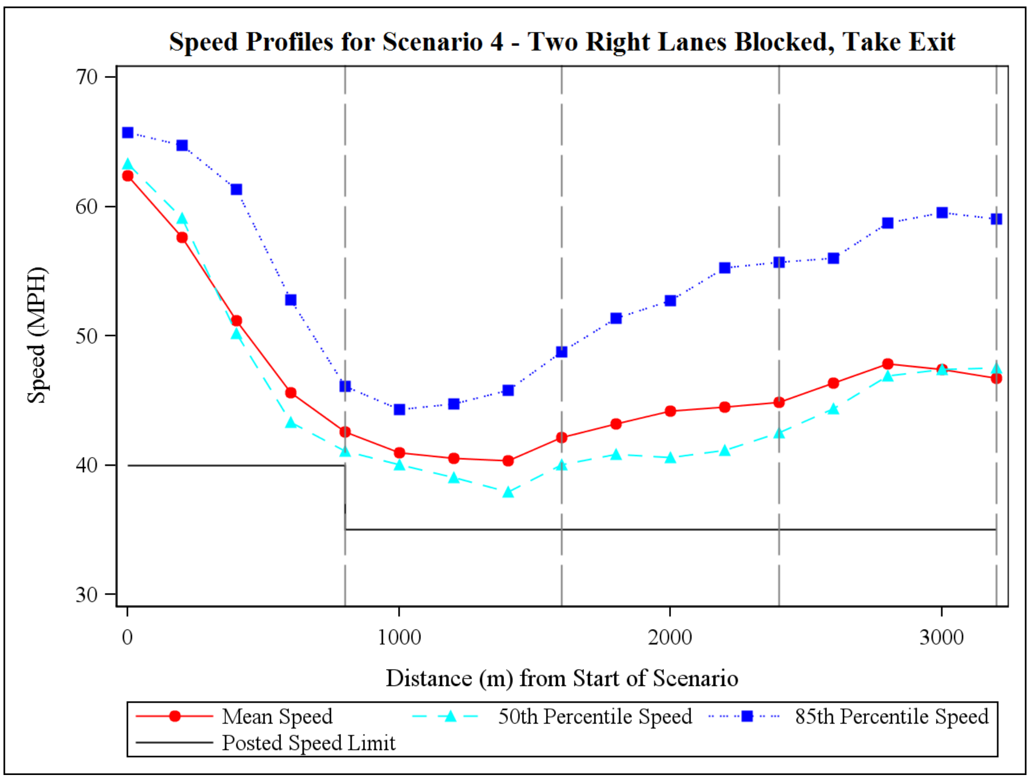
In scenario 4 (two right lanes blocked, take exit), four observations were recorded, one for each of the four gantries. Table 34 shows the distribution (row percentages) of lane choice for each recorded observation. Chi-squared test results indicated there was a significant association between the observation in the scenario and lane choice (χ^2 (4) = 89.63, $p < 0.001$).

Table 34. Distribution (row percentages) of lane choices by DCZ for scenario 4 (two right lanes blocked, take exit; empty cells indicate 0 percent).

DCZ	Lane Choice (percent) Lane 1	Lane 2	Lane 3	Lane 4
1	—	2	95	3
2	—	2	95	3
3	—	27	56	17
4	—	43	12	45

— Indicates 0 percent.

Figure 81 shows the speed profile for this scenario. VSL signs were used in this experiment to slow the traffic down as it approached the lane closure. Participants responded to the VSL signs by lowering their speeds. By the time the participants reached the exit, they were, on average, traveling about 10 mi/h (16 km/h) faster than the posted speed limit on the last VSL sign (shown on gantry 2) and 20 mi/h (32 km/h) slower than the facility posted speed limit (65 mi/h (105 km/h)).



1 mi/h (MPH) = 1.61 km/h.
0.3 m = 1 ft = 0.305 m.

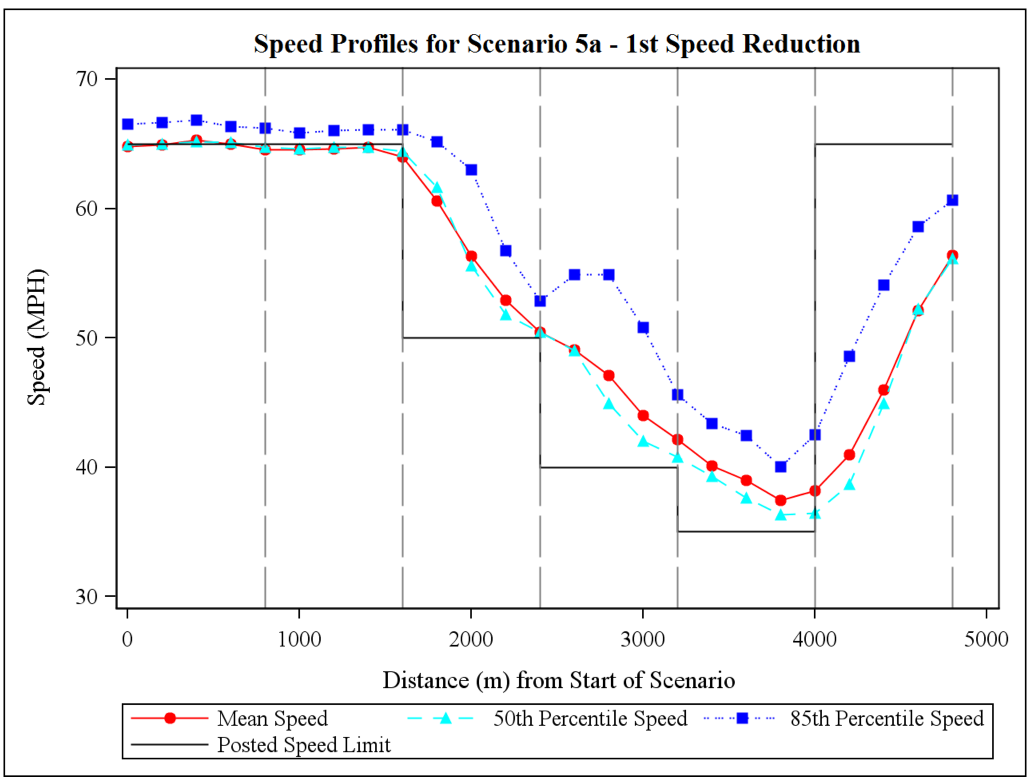
Figure 81. Graph. Speed profile for scenario 4 (two right lanes blocked, take exit).

Scenario 5 (speed reduction) was viewed twice by each participant (scenarios 5a and 5b, respectively). In scenario 5a (first speed reduction), six observations were recorded, one for each of the gantries. Table 35 shows the distribution (row percentages) of lane choice across participants for each recorded observation. Chi-squared test results indicated that there was no significant association between the observation in the scenario and lane choice. Overall, participants tended to stay in lane 3 as initially instructed by the researcher. Figure 82 shows the speed profile for this scenario. On average, the participants complied with the VSL signs.

Table 35. Distribution (row percentages) of lane choices by DCZ for scenario 5a (first speed reduction).

DCZ	Lane Choice (percent)			
	Lane 1	Lane 2	Lane 3	Lane 4
1	—	—	100	—
2	—	—	100	—
3	—	—	100	—
4	—	—	100	—
5	—	2	98	—
6	—	2	98	—

— Indicates 0 percent.



1 mi/h = 1.61 km/h.
1 ft = .305 m.

Figure 82. Graph. Speed profile for scenario 5a (first speed reduction).

In scenario 5b (second speed reduction), six observations were recorded, one for each of the gantries. Table 36 shows the distribution (row percentages) of lane choice across participants for each recorded observation. Chi-squared test results indicated that there was no significant association between the observation in the scenario and lane choice. Overall, participants tended to stay in lane 3 as initially instructed by the researcher. As with the first viewing, there was also high compliance with the VSL signs in this viewing of the scenario, and therefore the speed profile not shown.

Table 36. Distribution (row percentages) of lane choices by DCZ for scenario 5b (second speed reduction).

	Lane Choice (percent)			
DCZ	Lane 1	Lane 2	Lane 3	Lane 4
1	—	2	98	—
2	—	2	98	—
3	—	2	98	—
4	—	2	98	—
5	—	2	98	—
6	—	2	98	—

— Indicates 0 percent.

Glance Behavior

A *glance* toward an ROI was defined as when a participant registered 12 or more hits toward the ROI during a DCZ. If a glance occurred, then the number of hits was multiplied by 120 (the advertised sampling rate of the eye-tracking system) to calculate the duration.

Glance Probability

The overall probability of glancing, regardless of scenario, was 0.98. Thus, only descriptive statistics are reported in table 37.

Table 37. Probability of glancing by scenario.

Scenario	Probability
2—Stalled Vehicle	1.00
3—Two Left Lanes Closed	0.98
4—Two Right Lanes Blocked, Take Exit	1.00
5a—First Speed Reduction	0.99
5b—Second Speed Reduction	0.96

Glance Duration

GEEs with a Gamma response distribution and identity link function were used to analyze the duration of a glance, given that a glance had occurred. In other words, no durations of 0 s were included in the analysis.

Results indicated that there was a statistically significant difference in the duration of a glance among the scenarios (χ^2 (4) = 100.65, $p < 0.001$). As is shown in figure 83, scenario 4 (two right lanes blocked, take exit) yielded the longest glance duration, and scenario 5b (second speed reduction) yielded the shortest glance duration.

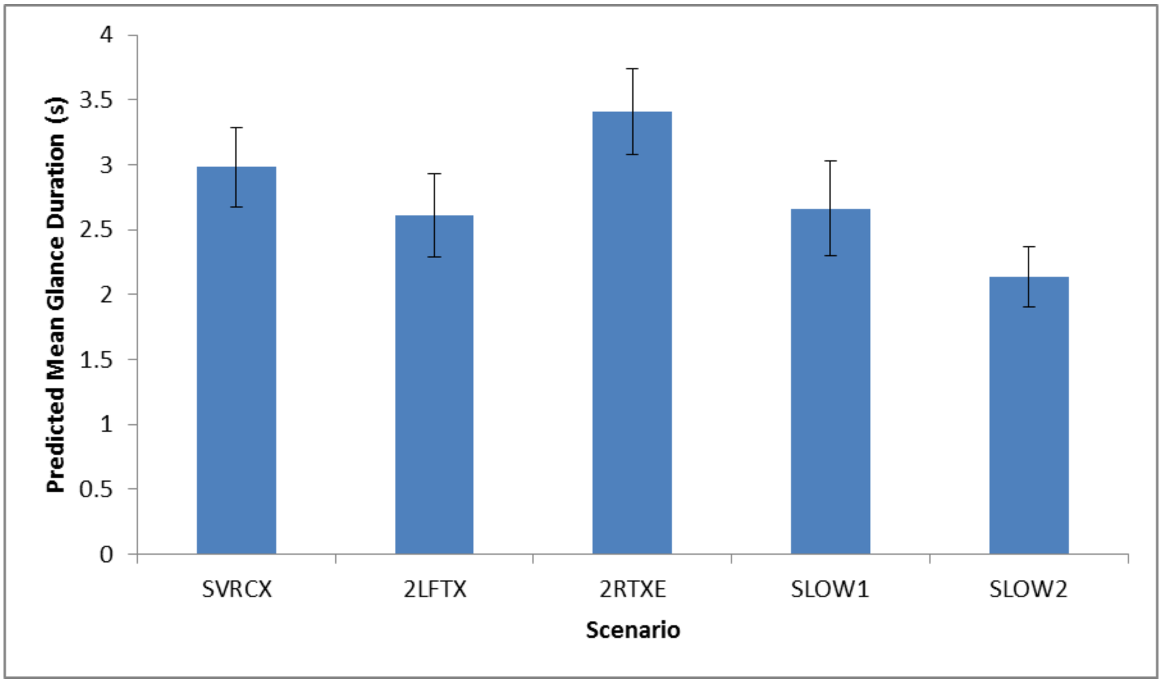


Figure 83. Graph. Predicted mean glance duration by scenario.

Look Behavior

A look was defined as 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.

Look Probability

The overall probability of looking, regardless of scenario, was 0.98. Thus, only descriptive statistics are reported in table 38.

Table 38. Probability of looking by scenario.

Scenario	Probability
2—Stalled Vehicle	0.99
3—Two Left Lanes Closed	0.98
4—Two Right Lanes Blocked, Take Exit	1.00
5a—First Speed Reduction	0.98
5b—Second Speed Reduction	0.95

Number of Looks

Repeated measures Poisson regression was used to determine whether the number of looks (assuming at least one look occurred) varied among the different scenarios. Results indicated there was a statistically significant difference in the number of looks across the scenarios

(χ^2 (4) = 37.72, $p < 0.001$). As is shown in figure 84, scenario 4 (two right lanes blocked, take exit) resulted in the greatest number of looks, and scenario 5a (first speed reduction) yielded the smallest number of looks.

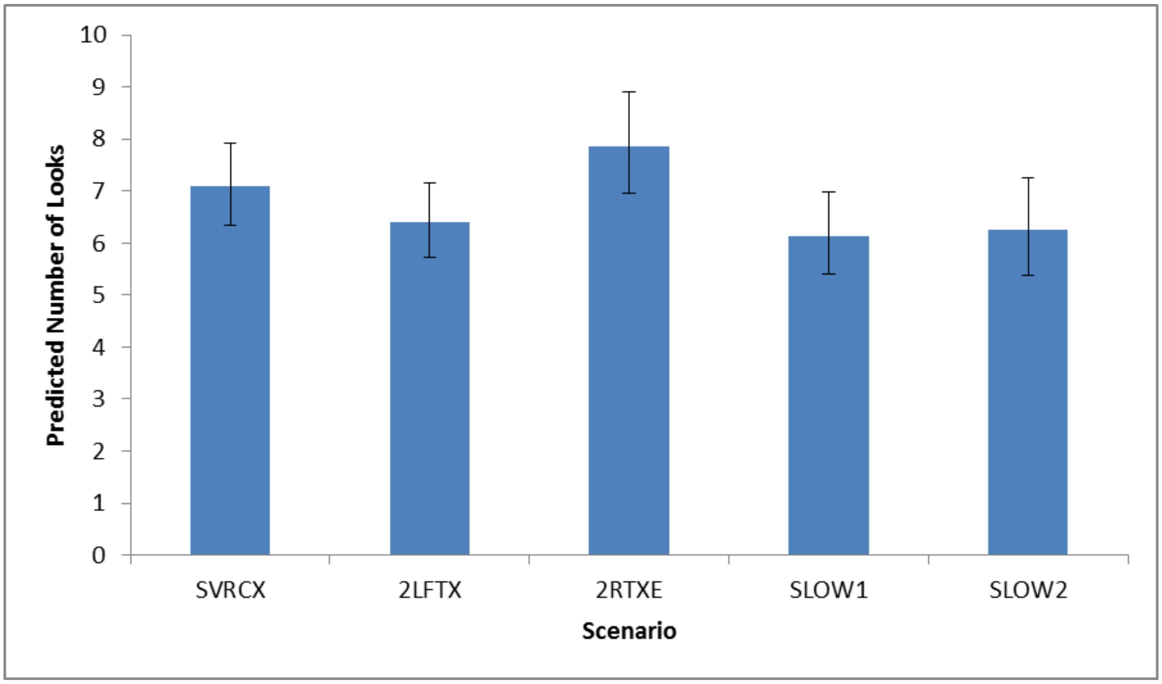


Figure 84. Graph. Predicted number of looks by scenario.

Look Duration

GEEs with a Gamma response distribution and identity link function were used to determine whether the duration of looks (assuming at least one look occurred) varied among the different scenarios. Results indicated there was a statistically significant difference in the number of looks across the scenarios (χ^2 (4) = 26.31, $p < 0.001$). As is shown in figure 85, scenario 4 (two right lanes blocked, take exit) resulted in the longest look duration, and scenario 5b (second speed reduction) yielded the shortest look duration.

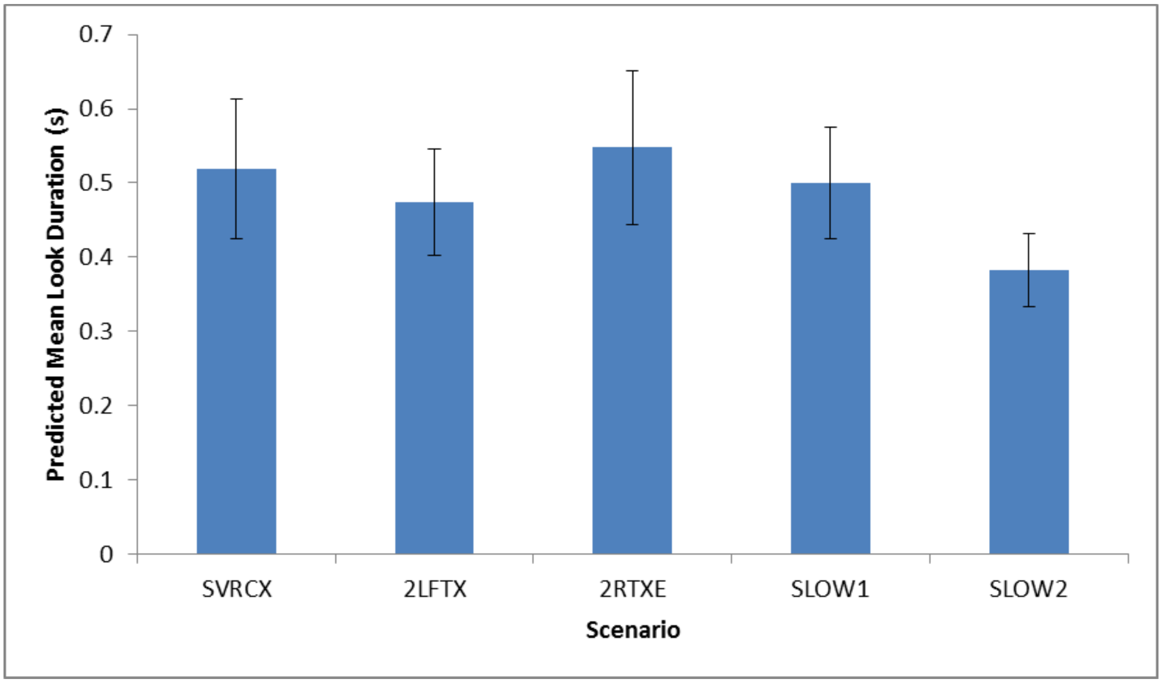


Figure 85. Graph. Predicted mean look duration by scenario.

Fixation Behavior

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., 15 pixels on the 372-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 (152.4 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.

Fixation Probability

The overall probability of looking, regardless of scenario, was 0.97. Thus, only descriptive statistics are reported in table 39.

Table 39. Probability of fixating by scenario.

Scenario	Probability
2—Stalled Vehicle	0.98
3—Two Left Lanes Closed	0.97
4—Two Right Lanes Blocked, Take Exit	0.99
5a—First Speed Reduction	0.97
5b—Second Speed Reduction	0.94

Number of Fixations

Repeated measures Poisson regression was used to determine whether the number of fixations (assuming at least one fixation occurred) varied among the different scenarios. Results indicated there was a statistically significant difference in the number of looks across the scenarios

(χ^2 (4) = 104.34, $p < 0.001$). As is shown in figure 86, scenario 4 (two right lanes blocked, take exit) resulted in the greatest number of fixations, and scenario 5b (second speed reduction) yielded the smallest number of looks.

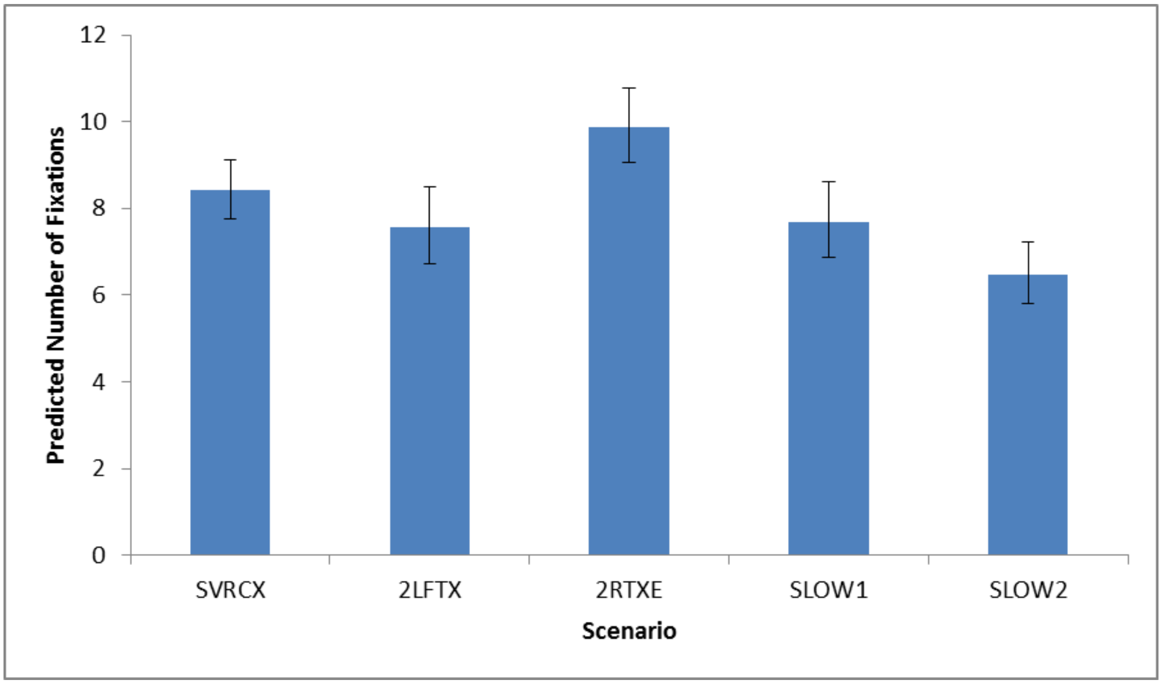


Figure 86. Graph. Predicted number of fixations by scenario.

Fixation Duration

GEEs with a Gamma response distribution and identity link function were used to determine whether the duration of fixations (assuming at least one fixation occurred) varied among the different scenarios. Results indicated there was no statistically significant difference in the duration of fixations across the scenarios. The overall fixation duration, regardless of scenario, was 0.33 s. Descriptive statistics are reported in table 40.

Table 40. Mean fixation duration (in seconds) by scenario.

Scenario	Mean Duration (s)
2—Stalled Vehicle	0.34
3—Two Left Lanes Closed	0.33
4—Two Right Lanes Blocked, Take Exit	0.33
5a—First Speed Reduction	0.33
5b—Second Speed Reduction	0.32

DISCUSSION

One objective of this study was to examine whether the amount of visual information/clutter on the sides of the road had an effect on driver behavior. This effect was examined for the exit-taking behavior at Holt Ave. Results showed there was no difference in the exit-taking behavior under low to moderate levels of clutter in the experiment. About 63 percent of the participants correctly exited at Holt Ave. The level of visual clutter did not vary in a dramatic way across the two levels of clutter that were tested. For the present experiment, varying the level of clutter on the sides of the road did not have a significant effect on the participants' compliance with directions and signs.

Drivers experienced five different scenarios during the simulated drive. However, data from the resting condition was not analyzed. The following summarizes behavioral results (i.e., speed maintenance, lane choice, etc.) for the other four scenarios:

- **Scenario 2—Stalled vehicle closing 1 lane (right-center lane—lane 3):** Participants exited their travel lane upon encountering the stalled car, and no participant collided with the vehicle. When shown the yellow X sign, the majority of the participants exited their lane well in advance of when they were requested to exit the lane. In this experiment, the participants were shown VSL signs that decreased the speed limit as they approached the stalled vehicle. Participants initially decreased their speeds in response to the VSL signs but then sped up throughout the scenario as they approached the stalled vehicle. By the time the stalled vehicle was encountered, the participants were driving about 10 mi/h (16 km/h) slower than the facility posted speed limit but significantly faster than the posted speed limits shown on the last VSL sign. The background simulated traffic did not slow in this scenario, and this may have had an effect on speed selection by the participants. Research by Weare, Robbins, and Blakeman that was discussed earlier showed that drivers in a simulator were affected by the speed of the background simulated traffic.[7] In busy traffic conditions, the speed of an individual driver might be greatly influenced by the speed of the surrounding traffic.

- **Scenario 3—Vehicle crash closing two left lanes (lanes 1 and 2):** Most of the drivers remained in their lane or moved to the right lane, both of which were correct responses. Speed behavior was very similar to that observed for the stalled vehicle scenario. Participants initially decreased their speeds in response to the VSL signs but then increased their speeds throughout the scenario. By the time they reached the crashed vehicles, participants were on average traveling about 10 mi/h (16 km/h) slower than the facility posted speed limit but faster than the posted speed limits shown on the last VSL sign.

- **Scenario 4—Vehicle crash closing two right lanes (lanes 3 and 4 with exit ramp open):** Drivers were instructed at the start of the simulation to exit at Holt Ave (the exit in this scenario). Results showed that the majority of participants successfully exited at Holt Ave. In this experiment, VSL signs were used to reduce the speed limit for the scenario. The data showed that the participants did respond to the decrease in speed limit. However, they still drove approximately 10 mi/h (16 km/h) faster than the new speed limits. As with the other scenarios, the participants' speed selection was affected by the simulated background traffic.

- **Scenario 5—Message in the event of slow-moving traffic in all lanes (reduce speed):** Participants generally followed the directions on the ATM signs. In the speed reduction scenario, the VSL signs showed lower speed limits every 0.5 mi (0.8 km). Although the simulated background traffic did not decelerate until passing the VSL signs, participants decreased their speeds after they encountered the signs. Results of this second simulation experiment were very similar to the results of the first experiment.

Eye-tracking results for each of the four scenarios that were analyzed are summarized below.

- **Scenario 2—Stalled vehicle closing 1 lane (right-center lane—lane 3):** The mean fixation duration on the per-lane CMSs was about 0.34 s, which was not significantly different from the other scenarios. However, there were multiple fixations on these signs (on average, about eight fixations). In this scenario, the fixations were of short duration but frequent.

- **Scenario 3—Vehicle crash closing two left lanes (lanes 1 and 2):** The average fixation duration on the per-lane CMSs was about 0.33 s, which was not significantly different from the other scenarios. The mean number of fixations was about eight. In this scenario, the fixations were of short duration but frequent, which was similar to what was observed in the stalled vehicle scenario.

- **Scenario 4—Vehicle crash closing two right lanes (lanes 3 and 4 with exit ramp open):** The mean fixation duration on the ATM signs in this scenario was 0.33 s, which was not significantly different from the other scenarios. However, the number of fixations on the ATM signs in this scenario was significantly greater (about 10 fixations on average) than for all of the other scenarios. Yet again, participants fixated on the per-lane CMSs often, but the fixations were of short duration.

- **Scenario 5—Message in the event of slow-moving traffic in all lanes (reduce speed):** Participants fixated on the VSL signs an average of seven times. This was more than in the first simulator experiment (in which participants fixated on the signs an average of only two times). The mean fixation duration on the signs was about 0.33 s for both viewings of this scenario. In comparison with the first simulator experiment, these values were shorter.

In comparison with the eye-tracking data from the first simulator experiment, fixations were more frequent but were also shorter in duration. However, across both studies, scenario 4 (two right lanes blocked, take exit), resulted in the greatest number of fixations. Similarly, the greatest fixation durations occurred in scenario 2 (stalled vehicle), although the difference among scenarios was not statistically significant in the second simulator experiment.

In summary, participants garnered useful information from the per-lane CMSs without long (greater than 2 s) fixations. In conjunction with the speed and lane choice behavioral data, results suggest that these ATM signs were easily understood.

CHAPTER 6. GENERAL DISCUSSION

Multiple studies were conducted to investigate the comprehension, legibility, and behavior in response to LCS and VSL ATM signs. Participants had no previous experience with the ATM signs as used in the experiments. For convenience, the current study describes the scenarios as emulating the Minnesota or Washington approaches. It is important to note that there was no intent to compare or evaluate the approaches taken in those States. Rather, the intent was to explore a range of content and contexts. The existing experimental deployments provided sources of content and contexts. Some of the sign content was novel and not used in either deployment.

A laboratory study showed that, in general, the signs were easy to interpret and would result in the actions requested (or required) by the signs. However, the following tested signs were not readily interpreted and are included in the subsequent discussion:

- Yellow arrow (flashing or steady), which was to indicate that the lane was open and to proceed with caution.
- Yellow X without text legend indicating that the lane was closed ahead. The yellow X sign with the 1 mile legend led to better performance.
- Advisory VSL signs were generally interpreted as regulatory speed limit signs.

The laboratory study also included an evaluation of sign preference by the participants. Signs that had high comprehension and were also preferred might be good candidates for deployment. These signs are the following:

- **Lane Open:** The participants preferred the sign as used in the Washington deployment, stating that the bolder and larger green arrow was more legible and easier to interpret from far away.
- **Merge:** The participants showed a preference for the streaming chevrons as deployed in Minnesota.
- **Lane Closed:** There was preference for the red X with the word "CLOSED" as deployed in Minnesota.

Legibility testing was done in the field using an actual CMS. This test included a subset of the ATM signs used in the laboratory experiment. Regulatory and advisory speed limit signs were tested, and the average legibility distances were approximately 1,225 ft (373 m) for all signs. These legibility distances were consistent across participants (small STDs in legibility distances were observed). The yellow X had the lowest average legibility distance at 1,040 ft (317 m). For the yellow X sign, there was a fair amount of variability in legibility distance across participants (STD of 305 ft (93 m)). The legibility distance ranged from 480 ft (146 m) to 1,250 ft (381 m), which was the maximum legibility distance because of the length of the test track. In this experiment, a response used to estimate legibility distance did not conclude until the participant finished reading the sign. The yellow X sign was shown to have poor comprehension in the laboratory experiment, and this effect was also evident in the field study. In other words, if a participant had difficulty interpreting a sign and did not respond quickly, then the estimated legibility distance was shorter. (They would be closer to the sign by the time they completed their response.)

Two driving simulator studies examined behavior in response to the ATM signs in the context of a driving situation. These studies employed signs that were shown to have the highest comprehension scores within a category of signs (e.g., lane closed signs, speed limit signs) in the laboratory study.

Side-mounted CMSs presented status information to the participants in the first simulator experiment. The eye-tracking data showed that participants fixated on these signs but not at the expense of looking at the forward roadway. Brief and direct messages appeared to be easy to understand and served as an aid in decisionmaking (e.g., lane changing behavior, reduced speed). In comparison, the second simulator experiment showed that drivers would make the correct maneuvers based on the LCS and VSL signs when no side-mounted CMS was present. The side-mounted CMS did appear to aid the drivers, but LCS and VSL signs on their own seemed to be sufficient.

The regulatory positive-contrast VSL signs were preferred in the laboratory study. In speed reduction zones, participants generally followed the posted changes in the speed limit. However, the speed reduction zones also entailed the reduction in speed for the simulated traffic. The data from the two simulator experiments showed a strong effect for the speed of the simulated (or background) traffic on participants' selected speed. In the second experiment, VSL signs were used in scenarios that entailed a lane closure (stalled vehicle or crash). In these scenarios, the VSL signs showed a reduction in the speed limit but the background traffic was not programmed to slow down. In this situation, participants initially responded to the VSL signs by slowing down but then sped up and closely matched the speed of the background traffic. These results are similar to those found by Weare, Robbins, and Blakeman where the speed of the participant driver was affected by the speed of the surrounding traffic in an ATM scenario tested in a driving simulator.[7]

The simulator experiments showed that the selected LCS and VLS signs resulted in effective behavior. These signs were tested in scenarios in which two left lanes, a center lane, or the two right lanes were closed. Use of the yellow X with the 1 mile text legend resulted in the desired behavior in the simulator experiments. The laboratory test indicated that this would be a more effective sign for indicating that a lane would be closing. The streaming chevrons resulted in appropriate behavior with respect to lane change behavior. Use of the streaming chevron signs resulted in the highest comprehension and preference in the laboratory study, and they were effective in the context of the driving task in the simulator.

The manipulation of visual clutter as implemented in the driving simulator experiments had no effect on driving or eye-glance behavior. In the second simulator study, the amount of clutter on the sides of the road was manipulated by varying the number and types of buildings.

Across the two simulator experiments, the amount of information on the sign gantries varied. In the first study, the sign gantries contained only per-lane ATM signs. However, in the second study, the gantries also contained guide signs. In these experiments, the amount information on the sign gantries did not have a significant effect on driving or eye-glance behavior.

The current study used a range of approaches to test different sign options for ATM. Numerous signs were screened using laboratory methods suitable for estimating sign comprehension and preference. In addition, field testing used an actual CMS for estimation of legibility distance because the high resolution and brightness of the CMS could not be modeled with a laboratory LCD. Use of a subset of ATM signs in the field allowed accurate estimation of the legibility distance of these signs. A driving simulator was used to evaluate different sign options under various driving conditions, which allowed the evaluation of responses to the signs in a dynamic environment. The combination of approaches used resulted in assessment of the signs' comprehension, legibility distance, and effect on driver decisionmaking.

REFERENCES

1. Mirshahi, M., Obenberger, J., Fuhs, C.A., Ho, C.E., Krammes, R.A., Kuhn, B.T., Mayhew, R.M., Moore, M.A., Sahebjam, K., Stone, C.J., and Yung, J.L. (2007) *Active Traffic Management: The Next Step in Congestion Management*, FHWA-PL-07-012. Federal Highway Administration, Washington, DC.

2. Papageorgiou, M., Kosmatopoulos, E., and Papamichail, I. (2008) "Effects of Variable Speed Limits on Motorway Traffic Flow." *Transportation Research Record 2047* (5), p. 37–48.

3. Lee, C. and Abdel-Aty, M. (2008) "Testing Effects of Warning Messages and Variable Speed Limits on Driver Behavior Using Driving Simulator." *Transportation Research Record 2069* (8), p. 55–64.

4. Datta, T., Schattler, K., Kar, P., and Guha, A. (2004) *Development and Evaluation of an Advanced Dynamic Lane Merge Traffic Control System for 3- to 2-Lane Transition Areas in Work Zones.* Transportation Research Group, Department of Civil & Environmental Engineering, Wayne State University, Detroit, MI.

5. Ullman, B.R., Trout, N.D., and Dudek, C.L. (2009) *Use of Graphics and Symbols on Dynamic Message Signs*. Technical Report Vol. 2009/05. Texas Department of Transportation, Austin, TX.

6. Blakeman, P. (2012) *Future Managed Motorways Concept Development—Task 3: Synthesis of Evidence*. Transport Research Laboratory, Highways Agency, Wokingham, England.

7. Weare, A., Robbins, R., and Blakeman, P. (2012) *Future Managed Motorways Concept Development—Task 1: Design Comparison Simulator Study*. Transport Research Laboratory, Highways Agency, Wokingham, England.

8. Federal Highway Administration. (2009) *Manual on Uniform Traffic Control Devices on Streets and Highways*. Available online at http://mutcd.fhwa.dot.gov/pdfs/2009/mutcd2009edition.pdf. Accessed April 21, 2016.

9. Empirisoft®. MediaLab® research software. Available online at http://www.empirisoft.com/medialab.aspx. Accessed April 21, 2016.

10. Washington State Department of Transportation (WSDOT) (2009) *Active Traffic Management Standard Operating Procedures*. WSDOT.

11. Perez, W.A., Bertola, M.A., Kennedy, J.F., and Miolino, J.A. (2012) *Driver Visual Behavior in the Presence of Commercial Electronic Variable Message Signs (CEVMS)*. Available online at http://www.fhwa.dot.gov/real_estate/practitioners/oac/visual_behavior_report/final/cevmsfinal.pdf. Accessed January 6, 2014.

12. PTV Group. PTV Vissim™. Available online at http://vision-traffic.ptvgroup.com/en-us/products/ptv-vissim/. Accessed February 12, 2014.

13. Smart Eye® AB. (2010) Smart Eye® Pro. Available online at http://www.http://smarteye.se/products/smart-eye-pro/. Accessed April 21, 2016.

14. EyesDX®. MAPPS™. Available online at http://www.eyesdx.com/products/mapps/. Accessed February 8, 2011.

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