Signing, in Combination with Lane Markings, in Advance of Lane-Reduction Transitions

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Research, Development, and Technology
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FOREWORD

The objective of the Transportation Pooled Fund Program's Traffic Control Device (TCD) Consortium is to assemble a consortium of regional, State, and local entities, other appropriate organizations, and the Federal Highway Administration to establish a systematic procedure to select, test, and evaluate existing and new TCDs that will support changes to the *Manual on Uniform Traffic Control Devices* and interim approvals.

The purpose of this study is to explore driver behavior when exposed to four warning signs: two advance warning signs, and two lane line transition markings. This study quantifies driver behavior by investigating when drivers recognize that the lane would end, prepare to change lanes, and execute a lane change. The goal of this work is to assess driver understanding and behavior when faced with new and traditional lane-reduction roadway markings and signing.

This report is of interest to engineers, planners, and other researchers and practitioners who are concerned with road users' ability to comprehend and follow lane-reduction transitions correctly.

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16. Abstract
Roadway lane-reduction transitions have long been reported to be problematic for drivers. Whether this problem is the result of a lack of understanding of lane-reduction signing or lane markings, a simple failure to comply with such markings, or other unidentified factors is unknown. This study, completed in 2019, explored driver behavior when exposed to four warning signs, two advance warning signs, and two lane line transition markings. The warning signs included traditional and new designs. Some of the new designs have currently been adopted by State departments of transportation. This study quantified driver behavior by investigating when drivers recognized that the lane would end, prepared to change lanes, and executed a lane change. The inclusion of advance warning signs resulted in earlier recognition of lane termination. Dotted-with-solid-white lane line transition markings resulted in earlier lane changes.

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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 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

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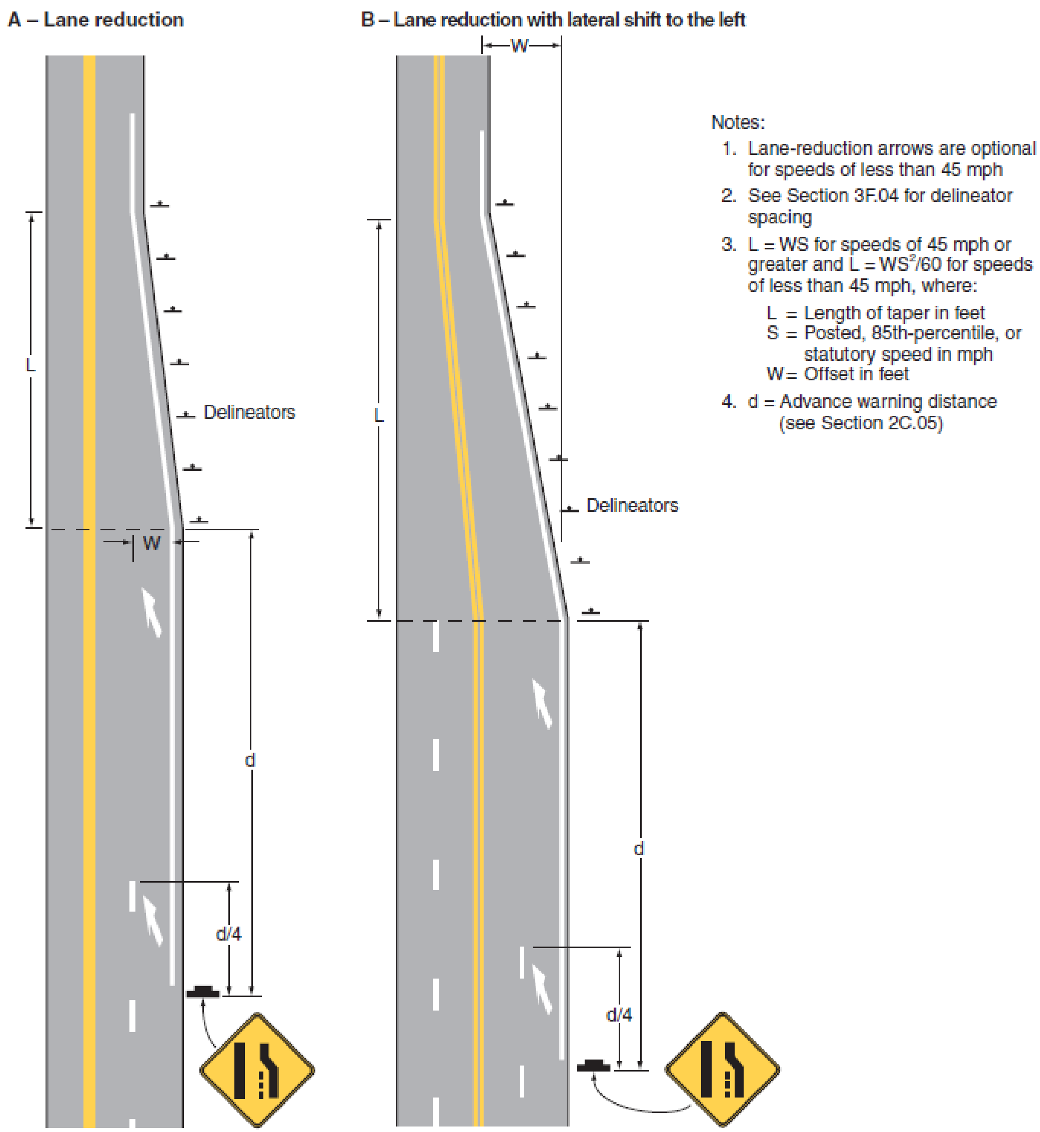
LIST OF ACRYNOMS

DOT	department of transportation
FHWA	Federal Highway Administration
MUTCD	*Manual on Uniform Traffic Control Devices for Streets and Highways*
TCD	Traffic Control Devices
PFS	Pooled Fund Study

CHAPTER 1. INTRODUCTION

The Traffic Control Device (TCD) Pooled Fund Study (PFS) addresses human factors and operations issues through the systematic evaluation of existing and new TCDs. As a part of this effort, the Federal Highway Administration (FHWA) Human Factors Team evaluated signing in advance of lane reductions. A lane-reduction transition occurs when the number of through lanes is reduced between interchanges or intersections. Where pavement markings are used, the *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) specifies in section 3B.09 that lane-reduction transition markings are used to guide traffic through the transition areas (FHWA 2009). Figure 1 shows two examples of lane-reduction transition markings from the MUTCD (FHWA 2009).



Source: FHWA.

Figure 1. Illustration. Examples of lane-reduction transition markings (FHWA 2009).

The 2009 edition of the MUTCD recommends the placement of the Lane Ends (W4-2) sign (figure 2) or the text version LANE ENDS MERGE LEFT (RIGHT) (W9-2) sign (figure 3) for a lane-reduction transition (FHWA 2009). The recommended placement of either sign depends on the posted speed or the 85th percentile speed of the roadway. This advance placement distance (*d*) is provided in table 2C-4 of the MUTCD (FHWA 2009). For example, if the posted speed limit of a roadway is 40 mph, then it is recommended that the warning sign should be placed 670 ft before the beginning of the taper. Similarly, for a speed of 60 mph, *d* = 1,100 ft.

Source: FHWA.

Figure 2. Illustration. Symbolic lane-reduction warning sign, W4-2 (FHWA 2009).

Source: FHWA.

Figure 3. Illustration. Text lane-reduction warning sign, W9-2 (FHWA 2009).

The 2009 edition of the MUTCD provides an option to use the RIGHT (LEFT) LANE ENDS (W9-1) sign (figure 4) in advance of the W4-2 sign or the W9-2 sign (FHWA 2009). The purpose for using this additional sign is to provide more time for drivers to safely make the appropriate merging maneuver. It is recommended that the RIGHT W9-1 sign be placed adjacent to the lane-reduction arrow pavement marking. For speeds less than 45 mph, lane-reduction arrows are optional per MUTCD provisions.

Source: FHWA.

Figure 4. Illustration. Optional additional advance lane-reduction transition sign, W9-1 (FHWA 2009).

Several studies have suggested that the W4-2 symbol has a relatively low comprehension rate. Researchers reported 61 percent comprehension rate among 489 drivers from either Texas, Idaho, or Alberta, Canada (Dewar et al. 1997). This study scored written responses to pictures of the 1988 MUTCD version of W4-2, which lacked the three dashes shown in figure 2. A "merge left" response was scored as partially correct in their protocol, and "road narrows" was scored as incorrect. Whether this scoring accurately reflects understanding of the W4-2 can be questioned; merging left is a correct response to the realization that a lane is ending, and if a driver merged into the adjacent lane after recognizing that the number of lanes will reduce, the same result (merging into the adjacent lane) would be appropriate. Thus, it is uncertain how many of the drivers that comprehended the sign "incorrectly" in the Dewar et al. (1997) study would have stayed in the terminating lane later than drivers who comprehended the sign "correctly."

Picha, Hawkins, and Womack (1995) reported on several studies conducted over a 5-yr period that examined driver comprehension of various lane-reduction signs. Participants were presented with eight lane-reduction signs and six forced-choice responses. Only one response was considered correct. Signs selected were a combination of standard W4-2 and W9-1 signs in addition to alternative designs similar to the MUTCD guidance provisions. The 1988 and 2000 MUTCD versions of W4-2 garnered correct selections from about 71 percent of respondents. The text versions of the right lane ends, W9-1, received significantly more correct selections (81 percent) than the W4-2 based signs, but about 20 percent of respondents still selected incorrect choices.

The MUTCD provides W4-2, W9-1, and W9-2 signs for lane-reduction transitions. W4-2 is used in place of W9-1 because it has greater legibility distance and does not require English literacy. Several States supplement the MUTCD with other warning signs. A few alternatives used by States are shown and discussed in the immediate, following paragraphs. These signs (shown in figure 5 through figure 7) do not comply with MUTCD provisions. State departments of transportation (DOTs) and local jurisdictions are required to use MUTCD-compliant signs. If a State DOT or local jurisdiction is interested in using a new TCD or a different application of an existing device, it must receive approval to experiment from FHWA using the MUTCD experimentation process (FHWA 2009).

The MERGE (W20-X3) warning sign shown in figure 5 is used mainly in Iowa, Minnesota, and Missouri. The LANE ENDS (W9-2L-DE) sign shown in figure 6 is used in Delaware and Maryland. The warning sign shown in figure 7 is a noncompliant variation of the W4-2-PI that is not currently in State or Federal MUTCD.

Figure 5. Illustration. Lane-reduction transition sign W20-X3 used in Iowa (Iowa DOT 2017).

Figure 6. Illustration. Lane-reduction transition sign W9-2L-DE used in Delaware and Maryland (Delaware DOT 2011).

Figure 7. Illustration. Americanized version of work zone sign from the Vienna Convention G12a (Shaw et al. 2017).

The use of lane-reduction signing practices that deviate from MUTCD guidance is an indication of a perceived need for more effective signing. However, inconsistent and nonstandard signing and marking across and within States may lead to problems in driver comprehension, especially for drivers travelling outside of their local jurisdictions. A few recent studies have evaluated noncompliant, alternative lane-reduction transition signs for work zones. One study sponsored by the Smart Work Zone Deployment Initiative and FHWA evaluated various signs used in work zones in the United States, Canada, United Kingdom, Europe, and other countries (Shaw et al. 2017). Following a process that used survey data to select lane transition signs from a plethora of alternatives, the authors selected three sign alternatives to evaluate in a driving simulation. Those signs were W4-2, as shown in figure 2; W20-X3, as shown in figure 5; and an Americanized version of the Vienna Convention G12a sign similar to that shown in figure 7.

The three sign configurations were presented in a driving simulation. The results of the study were inconclusive. Although the authors asserted that the W4-2 sign was less well understood, they had some validity concerns regarding the design of the questionnaire conducted after the test. It offered four, forced-choice responses for two of the signs and only three responses for the other. Also, one of the responses was at least partially correct: "[T]raffic in the [through] lane should yield to [drivers in the terminating] lane." This response was always presented before the more correct response: "[T]raffic in the [terminating] lane should merge into the [through] lane."

The former alternative was not offered as a response to W20-X3. The driving behavior measures were merge location, average speed, difference between entry speed, and speed at the time the participant changed lanes. Most of the participants changed lanes before reaching the signs that were the subject of the experiment. In other words, most of the subjects changed lanes before coming into proximity of the advance warning sign, which read, "[RIGHT/LEFT] LANE

CLOSED AHEAD," or they changed lanes at the beginning of the trial, presumably because they preferred the other lane. Of those participants who changed lanes after arriving within sight distance of the subject signs, there was no significant difference in speed or merge location. After reporting no significant differences in merge location, the authors asserted that the nonsignificant difference that showed W4-2 as having a later mean merge location than the other two signs indicated that W4-2 was less effective than the other two signs.

It should be noted that there is no general agreement on whether late or early merges are better. When traffic is heavy, late merges resulted in better operations. In regard to safety, the differences observed between late and early merge were within the bounds of chance. The only significant difference between the three sign configurations was in the amount of speed reduction observed among drivers who changed lanes after arriving within sight of the subject signs. The W4-2 and W20-X3 signs resulted in a significantly larger speed reduction than for the Americanized G12a. The authors interpreted the larger speed reduction as an indication that W4-2 presents a greater safety risk than the other two signs. Maximum deceleration, which would provide an indication of abrupt braking that poses a safety risk, was not reported.

A field evaluation of driver reactions to the W20-X3 sign compared with driver reactions to the W4-2 sign was conducted at a work zone in Missouri (Edara, Zhu, and Sun 2014). The data came from 1.5 h of observation at the same work zone on two different days. On the first day, the W20-X3 sign was placed on the terminating-lane side, and the left/right lane closed sign was placed on the through-lane side. On the second day of observation, W4-2 signs were placed on both sides of the road. The study measured driver speed and open-lane occupancy. The "MERGE" text and arrow symbol configuration of W20-X3 sign resulted in 6 percent more vehicles (11 percent more light vehicles) being in the through lane upstream of the merge signs. Mean speeds remained consistent between sign configurations or speed measurement locations (at test-sign configuration location and at the beginning of the taper). The authors concluded that the W20-X3 configuration was an acceptable alternative to W4-2 sign recommendations. They also concluded that the W20-X3 configuration resulted in earlier merges by passenger vehicle drivers (but not trucks), which might suggest a safety advantage. The authors did not indicate which lane was closed on the different days, which were 2 days apart. If different lanes were closed on each day (which would seem likely), then this difference in lane closures could have influenced differences in lane occupancy.

The previous literature on lane-reduction signing suggests valuable insights for the evaluation of alternatives to W4-2 at lane-reduction transitions.

1. The behavioral objective for each sign configuration needs to be made explicit before testing begins.

2. If a sign or configuration of signs is intended to replace configurations that implement W4-2, as recommended in the MUTCD, because the W4-2 is thought to be poorly comprehended, then the evaluation should assess comprehension of the entire configuration (i.e., advance signs, W4-2 or alternatives, and lane-reduction arrows).

3. Comprehension tests should reflect what participants would do in response to a sign rather than whether they can express the sign's meaning in a way acceptable to the

examiner. If the participant would merge into the through lane before the taper in response to the sign, then it should not matter whether the participant said the sign meant merge left or road narrows.

In a previous study conducted for the TCD PFS (Balk and Jackson 2016), researchers recommended using dotted lines to mark the lane reduction. In addition, the authors recommended further testing of the inclusion of a solid white line to the left of the dotted line transition markings, because there was some evidence that the solid line discouraged drivers in the through lane from moving into the terminating lane. Although the solid white line resulted in slightly better comprehension of the transition markings, there was some concern that it might discourage drivers from early merges. Because lane lines and signs are intended to work synergistically, they should be tested together. The researchers tested the dotted line markings without signs or arrow pavement markings to ensure that participants were responding to the dotted lines and not other environmental cues (i.e., arrows or signs). The current study attempted to isolate comprehension of the signs in a similar manner, and researchers also tested the signs in complete context, with arrow markings and the dotted line markings recommended in the previous PFS.

OBJECTIVES

The current research expands on Balk and Jackson's 2016 study by evaluating existing lane line marking patterns in combination with standard signs as well as potential new designs for lane-reduction transitions. The goal of this project was to determine the effects of specific signs, in combination with markings, in terms of:

- Merging behavior (i.e., early merging) before lane-reduction transitions.
- Understanding and time of comprehension of the intended message conveyed at lane-reduction transitions (from both the terminating lane and the left-adjacent lane).

CHAPTER 2. METHOD

STIMULI

Drafting and three-dimensional modeling software were used to generate virtual four-lane, undivided highways with reasonably realistic surrounding environments using real roadway geographic information system (known as "GIS") data. On completion of the roadway and environment, "fly-through" videos, which create the illusion of moving through the environment, were created. To reduce the possibility of a participant's response being influenced by repeated exposure to identical surrounding environments, four surrounding environments were used: a dense urban environment, a moderate urban environment, a rural environment, and a wooded environment. Driving environments were strictly superficial and had no impact on traffic flow.

Simulated traffic was used in the oncoming lane to mimic a more realistic driving environment. Traffic was absent from the participant's direction of travel to simulate free-flow conditions. These conditions ensured that the participant's response was influenced only by the roadway's lane markings and signing.

PARTICIPANT GROUPS AND VARIABLES

Each participant was assigned to one of two lane-reduction transition marking groups. Within each group, there were four variables: lane transition markings—two conditions; warning signs—eight conditions; advance warning signs—three conditions; and lane assignment—two conditions. The result was a total of 56 trials for each participant in each group. See the appendix for a complete list of trial combinations.

Lane Transition Markings

The lane markings selected for the participant groups were dotted line (figure 8) and dotted lines with solid line to the left of the dotted line (figure 9). Balk and Jackson (2016) recommended these two selected lane line groups. The taper and lane transition marking length were based on a posted speed limit of 45 mph (See MUTCD table 2C-4) (FHWA 2009).

Source: FHWA.

Figure 8. Screenshot. Dotted line lane-reduction transition marking.

Source: FHWA

Figure 9. Screenshot. Dotted-line-plus-solid-white-line lane-reduction transition marking.

Sign Combinations

Four lane-reduction warning signs and two advance warning signs were used. Of the six warning and advance warning signs used, three were from the FHWA MUTCD (W4-2, W9-2, and W9-1) (FHWA 2009). The remaining are not compliant with MUTCD provisions, such that if a State DOT or local jurisdiction is interested in using these signs, it must first receive approval to experiment from FHWA. Of the three noncompliant signs, two were from State MUTCDs (W20-X3 and W9-2L-DE), and one was a proposed custom design not currently found on roadways (W4-2-PI).

Warning sign and advance warning sign placement were based on a posted speed limit of 45 mph (See MUTCD table 2C-4) (FHWA 2009).

To ensure active participant engagement, four non-lane-reduction signs were used twice, once for each lane assignment (See table 1, conditions 13–16). These trials had no lane reduction and were not used in the analysis. Participants who incorrectly responded to at least 50 percent of the non-lane-reduction trials were excluded from analysis and replaced by another participant of the same age group and gender. See the Stimuli Response section following in this chapter for an explanation of what is considered a correct response for the non-lane-reduction trials. All 16 sign configurations were within-subject tested (i.e., all participants saw all sign configurations). The 16 sign configurations can be seen in table 1. Note that signs W20-X3, W9-2L-DE, and W4-2-PI do not comply with MUTCD provisions.

Table 1. Sign configurations (Delaware DOT 2011; FHWA 2009; Iowa DOT 2017; Shaw et al. 2017).

Sign Configuration Condition	Lane Reduction	Advance Warning Sign	Advance Warning Sign Image	Warning Sign	Warning Sign Image
1	Yes	None	None	W4-2	
2	Yes	None	None	W9-2	
3	Yes	None	None	W20-X3	 © 2017 Iowa DOT.
4	Yes	None	None	W9-2L-DE	 © 2009 Delaware DOT.
5	Yes	W9-1		W4-2	
6	Yes	W9-1		W9-2	

Sign Configuration Condition	Lane Reduction	Advance Warning Sign	Advance Warning Sign Image	Warning Sign	Warning Sign Image
7	Yes	W9-1		W20-X3	
8	Yes	W9-1		W9-2L-DE	
9	Yes	W4-2-PI	 © 2017 Shaw.	W4-2	
10	Yes	W4-2-PI		W9-2	
11	Yes	W4-2-PI		W20-X3	
12	Yes	W4-2-PI		W9-2L-DE	
13	No	None	None	W23-2	

Sign Configuration Condition	Lane Reduction	Advance Warning Sign	Advance Warning Sign Image	Warning Sign	Warning Sign Image
14	No	None	None	W19-1	
15	No	None	None	W1-10b	
16	No	None	None	W1-10c	

Note: Unless indicated otherwise, all illustrations source: FHWA (2009).

Lane-Reduction Arrow Markings and Lane Assignment

Sign configuration conditions 1–12 had trials with and without lane-reduction arrow markings. Sign configuration conditions 13 and 14 did not have lane-reduction arrow markings for all four sign configurations because of the absence of lane reduction. All sign configurations and lane-reduction arrow marking combinations had trials with lane assignments in the right merge lane and left through lane. Trials in the right merge lane experienced a lane reduction, but trials in the left through lane did not. Trials were blocked in groups of 14 (14 right merge, 14 left through, 14 right merge, 14 left through) and then were randomized within each block (table 2).

Table 2. Arrow markings and lane-assignment conditions.

Condition	Lane Assignment	Lane Arrows Used
1	Right merge lane	Yes
2	Right merge lane	No
3	Left through lane	Yes
4	Left through lane	No

STIMULI RESPONSES

Participants were instructed to imagine they were driving in the lane pictured in the provided stimuli. Using high-precision stimulus presentation and response-recording software, participants were asked to respond appropriately and in sequential order using three predefined responses. If responses were selected out of sequential order, those trials were excluded from analysis.

Right Merge Lane Trials

In right merge lane-assignment trials, the participant's viewpoint was from a lane that may eventually end. Participants were asked to respond, when appropriate and in sequential order, using the three labeled buttons in front of them:

1. Right lane ends.
2. Prepare to change lanes.
3. Change lanes.

The research team instructed participants to press the "Right lane ends" button when the participants determined the lane they were traveling in (the right lane) would eventually terminate. The team instructed participants to press the "Prepare to change lanes" button when the participants would begin lane-change preparations, such as when checking mirrors and engaging turn signals. Finally, the team instructed participants to press the "Change lanes" button when the participants would normally execute the lane change. Participants were also instructed to respond only if necessary, and responses may not be necessary on some trials. Any response for nonlane-reduction trials was considered incorrect.

Left Through Lane Trials

In left through lane-assignment trials, the participant's viewpoint was adjacent to a right lane that may eventually end. Participants were asked to imagine there was a vehicle in the right lane about 10 ft ahead. Unlike during the right merge lane trials, participants were instructed to anticipate the other vehicles' maneuvers and not their own. The responses were the same as for the right merge lane scenarios:

1. Right lane ends.
2. Prepare to change lanes.
3. Change lanes.

The research team instructed participants to press the "Right lane ends" button when the participants determined the adjacent lane would eventually terminate. The team instructed participants to press the "Prepare to change lanes" button when the participants estimated that the vehicle in the adjacent lane would begin lane change preparations (e.g., check their mirrors, engage turn signals). The team instructed participants to press the "Change lanes" button when the participants estimated that the other vehicles would begin the lane change. The participants were instructed to only respond if they determined that the right lane would end, and they were told that responses may be unnecessary for some trials. Responses for non-lane-reduction trials were considered incorrect.

PARTICIPANTS

In total, 112 licensed drivers participated: two groups of 56 participants with equal numbers of males and females older and younger than 45 yr. Each was paid $40 for his or her participation.

PROCEDURE

On arrival, participants were greeted and asked to review and sign a record of informed consent. Participants' visual acuity was checked to ensure a minimum 20/40 vision in at least one eye (i.e., the minimum to obtain a driver's license in most States). Next, participants were seated approximately 8 ft from a 60-inch LCD monitor used for video presentations. A table in front of the participant supported a three-button response pad. Instructions read as follows:

> The purpose of this study is to identify the best way to indicate to drivers when they need to change lanes because of roadway conditions ahead. We are going to show you a series of videos of a four-lane highway. Each video shows a driver's view of the roadway as it would appear when traveling at 45 mi/h. Sometimes the view will be from the left lane, sometimes from the right.
>
> In videos from the right lane your task is to imagine you are driving in a lane that may end and you need to decide if you need to change lanes. You should NOT decide to change lanes unless it is necessary. If you detect that a lane change will be required ahead, press the left button, which is labeled "Right lane ends." At the location where you would start to check your mirrors or engage your turn signals, press the button labeled "Prepare to change lanes." When you are at the point where you would make the lane change, press the button labeled "Make lane change." If you determine that there is no lane change, do not respond. When all three buttons are pressed or the video ends with no recorded input, the trial will end and continue to the next one.
>
> Videos in the left lane are like the right lane videos in that you have the same three responses. However, the left lane will NEVER end. Instead of imagining that you need to make the lane change, you will be trying to anticipate how a vehicle in the right lane may behave. For example, imagine there is a vehicle in the right lane about 10 feet in front of you. Your task is to first (1) determine that the right lane ends, then (2) estimate when the vehicle would prepare to change lanes, and finally (3) estimate when the vehicle would begin a lane change. If the right lane does not end, do not enter any responses.
>
> Prior to starting the experiment, you will be given 6 practice videos, 3 from the right lane and 3 from the left lane. Do you have any questions?

After each participant completed the six practice trials and was comfortable with the task, the 56 experimental trials began. Total participation time ranged from 25 to 50 min, depending on participant response speed and breaks between trials.

MEASURES

The two dependent measures were the time stamps indicating when the participants selected each of the three buttons and the response times between button presses. The time stamps indicating when the participant pressed the buttons served as the primary measure and provided an indication of sign recognition and early versus late merge tendencies as a function of the TCD. The response time between the first and second button press served as a secondary measure that provides an indication of early- versus late-merge tendencies as a function of the TCD.

ANALYSIS APPROACH

A generalized estimating equation model was used to test the associations between the independent variables and the dependent variables (i.e., three response time stamps). When the reaction times were analyzed, the normal distribution was specified. The repeated statement was specified to account for variability associated with each participant because there were multiple responses per participant.

All independent variables and their pairwise interactions were included in the initial model for each analysis. The most nonsignificant effects were removed, and the model was rerun. This procedure was repeated until the effects remaining in the model were all significant. Nonsignificant main effects were kept in the model if there was a significant interaction with that effect. The following independent variables were used in the initial model: gender, age group, lane line transition markings, lane assignment, lane-reduction arrows, warning sign, and advance warning sign.

CHAPTER 3. RESULTS

Incorrect responses (i.e., responding out of sequential order, not responding when appropriate) were removed from analysis, resulting in 44 to 48 trials per participant. The analysis was completed by using the Wald Chi-Squared test.

RESPONSE TIMES—RIGHT LANE ENDS

The "right lane ends" response was the first in the sequence of responses. Its intent was to signify the point at which participants recognized the right lane was ending.

Warning Sign

Overall, type of warning sign significantly affected "right lane ends" response times, $\chi^2(3) = 59.1$, $p < 0.001$. Trials during which warning sign W4-2 (mean [M] = 18.7 s) was present and trials during which W20-X3 were present (M = 18.9 s) had mean response times that were significantly faster than trials with W9-2 (M = 19.5 s) or W9-2L-DE (M = 19.5 s).

Advance Warning Sign

Overall, the presence and type of advance warning sign significantly affected "right lane ends" response times, $\chi^2(2) = 172.1$, $p < 0.001$. Trials with W4-2-PI (M = 17.4 s) had a mean response time that was significantly faster than the mean response time of trials with W9-1 (M = 19.5 s), and trials with advance warning sign W9-1 had a mean response time that was significantly faster than the mean response times of trials having no advance warning signs present (M = 20.6 s).

Interaction: Lane Line Transition Markings and Advance Warning Sign

The interaction between lane transition markings and advance warning signs significantly affected "right lane ends" response times, $\chi^2(2) = 8.3$, $p = 0.016$. When there was no advance warning sign present, dotted-with-solid-line transition markings had response times that were 1.4 s faster than the mean response times of trials with only dotted lane line transition markings. No difference in response time was found between lane line transition markings when either of the advance warning signs was present.

Interaction: Warning Sign and Advance Warning Sign

The interaction between warning sign and type of advance warning sign significantly affected "right lane ends" response times, $\chi^2(6) = 89.5$, $p < 0.001$. The warning signs' effects on "right lane ends" response times were significant only when there were no advance warning signs present. When no warning signs were present, trials with W4-2 (M = 19.9 s) and trials with W20-X3 (M = 20.1 s) had mean response times that were significantly faster than trials with W9-2 (M = 21.5 s) or W9-2L-DE (M = 21.4 s). However, when either of the advanced warning signs was present, there were no significant differences in mean response time to any of the four warning signs.

Nonsignificant Results

Gender, age group, lane assignment, and lane-reduction arrows were found to have had no significant effect on "right lane ends" response times.

RESPONSE TIMES—PREPARE TO CHANGE LANES

The "prepare to change lanes" response was the second in the sequence of responses. Its intent was to signify the point at which the participant or the other vehicle (lane assignment: left through lane trials) would prepare to change lanes by checking their mirrors or engaging the turn signal.

Warning Sign

Overall, the warning signs had a significant effect on "prepare to change lanes" response times, $\chi^2(3) = 61.9$, $p < 0.001$. Trials during which warning sign W4-2 ($M = 22.5$ s) was present and trials during which W20-X3 ($M = 22.6$ s) were present had mean response times that were significantly faster than trials with W9-2 ($M = 22.9$ s) or W9-2L-DE ($M = 23.0$ s).

Advance Warning Sign

Overall, advance warning sign had a significant effect on "prepare to change lanes" response times, $\chi^2(2) = 120.7$, $p < 0.001$. Trials on which either W4-2-PI ($M = 21.9$ s) or W9-1 ($M = 22.9$ s) was present had mean response times that were significantly faster than trials when no advance warning signs present ($M = 23.6$ s).

Interaction: Lane Line Transition Marking and Advance Warning Sign

The interaction between lane transition markings and type of advance warning sign significantly affected "right lane ends" response times, $\chi^2(2) = 8.1$, $p = 0.018$. The results for this interaction were the same as the effect of "right lane ends" on response times. Only when there was no advance warning sign present did the dotted-with-solid lane line transition marking have a faster average response time on "prepare to change lanes" ($M = 22.9$ s) than dotted-only lane line transition markings ($M = 24.2$ s).

Interaction: Warning Sign and Advance Warning Sign

Overall, the interaction between warning sign and advance warning sign had a significant effect on "prepare to change lanes" response times, $\chi^2(6) = 40.3$, $p < 0.001$. When no warning signs were present, trials with W4-2 ($M = 23.0$ s) and trials with W20-X3 ($M = 23.2$ s) had mean response times that were significantly faster than trials with W9-2 ($M = 24.1$ s) or W9-2L-DE ($M = 24$ s). When the advanced warning sign W9-1 was present, trials with W4-2 ($M = 22.7$ s) and trials with W20-X3 ($M = 22.6$ s) had mean response times that were significantly faster than trials with W9-2L-DE ($M = 22.9$ s). When advanced warning sign W9-1 was present, there was no difference in mean response time for the four warning signs.

Nonsignificant Results

Age group, lane assignment, and lane-reduction arrows were found to have had no significant effect on "prepare to change lanes" response times.

RESPONSE TIMES—CHANGE LANES

The "change lanes" response was the third in the sequence of responses. Its intent was to signify the point at which the participant or the other vehicle (lane assignment left through lane trials) would execute the lane change.

Lane Line Transition Markings

Lane line transition markings had a significant effect on "change lanes" response times, $\chi^2(1) = 4.2$, $p = 0.043$. Trials that had dotted-with-solid lane line markings had "change lanes" response times that were on average significantly faster ($M = 25.3$ s) than those trials with dotted-line-only lane line markings ($M = 26.7$ s).

Warning Sign

Overall, the presence of a warning sign had a significant effect on "change lanes" response times, $\chi^2(3) = 28.5$, $p < 0.001$. Trials during which warning sign W4-2 ($M = 25.8$ s) was present and trials during which W20-X3 ($M = 225.9$ s) were present had mean response times that were significantly faster than trials with W9-2 ($M = 26.1$ s) or W9-2L-DE ($M = 26.2$ s).

Advance Warning Sign

Overall, the presence of an advance warning sign had a significant effect on the "change lanes" response times, $\chi^2(2) = 58.4$, $p < 0.001$. The response times were fastest on average when trials had W4-2-PI present ($M = 25.5$ s). Trials with W4-2-PI had response times that were on average significantly faster than those response times of trials with W9-1 present ($M = 26.0$ s) and when there was no advance warning sign present ($M = 26.5$ s).

Interaction: Lane Line Transition Markings and Warning Sign

The interaction between lane line transition markings and type of warning sign significantly affected "change lanes" response times, $\chi^2(3) = 8.16$, $p = 0.043$. Trials that had dotted-with-solid lane line transition markings had response times that were on average significantly faster than trials with dotted-line-only lane line transition markings when warning signs W9-2L-DE ($M = 1.3$ s), W4-2 ($M = 1.5$ s), or W9-2 ($M = 1.4$ s) were present. Lane line transition markings did not make a significant difference when the W20-X3 warning sign was present. Trials with W9-2 had on average significantly slower response times than trials with W4-2 signs, regardless of lane line transition markings.

Interaction: Warning Sign and Advance Warning Sign

The interaction between type of warning sign and advance warning sign significantly affected "change lanes" response times, $\chi^2(6) = 21.3$, $p = 0.002$. When no warning signs were present, trials with W4-2 (M = 26.2 s) and trials with W20-X3 (M = 26.3 s) had significantly faster mean response times than trials with W9-2L-DE (M = 26.8 s). Warning signs did not make a significant difference for trials with an advance warning sign present.

Nonsignificant Results

Age group, lane assignment, and lane-reduction arrows were found to have had no significant effect on "change lanes" response times.

BETWEEN RESPONSE TIMES—RIGHT LANE ENDS AND PREPARE TO CHANGE LANES

Age Group

The average time between responses for older participants was significantly less than the time for younger participants, $\chi^2(1) = 6.1$, $p = 0.013$. On average, the older group (M = 2.9 s) took less time to prepare to change lanes after noticing the lane ends than the younger group (M = 4.1 s).

Advance Warning Sign

Overall, the presence of an advance warning sign had a significant effect on the time between responses, $\chi^2(2) = 68.0$, $p < 0.001$. Trials with no advance warning sign present had the least amount of time between recognizing the lane ends and preparing to change lanes (M = 2.9 s). Trials with the W9-1 advance warning sign had a mean response time (M = 3.2 s) that was significantly longer than the mean response time of trials with the W4-2-PI advance warning sign (M = 2.5 s).

Interaction: Gender and Advance Warning Sign

The interaction between gender and advance warning signs significantly affected time between "right lane ends" and "prepare to change" lanes responses, $\chi^2(2) = 10.6$, $p = 0.005$. The time between "right lane ends" and "prepare to change lanes" responses for females was significantly shorter than the time between responses for males only when W9-1 (M = 2.9 s, M = 3.6 s) or W4-2-PI (M = 3.6 s, 5.4 s) advance warning signs were present. The difference in time between responses between males and females was not significant when there was no advance warning sign present.

Interaction: Warning Sign and Advance Warning Sign

Overall, the interaction between warning sign and advance warning sign had a significant effect on time between responses, $\chi^2(6) = 54.2$, $p < 0.001$. When no advanced warning signs were present, trials with W9-2 (M = 2.5 s) and trials with W9-2L-DE (M = 2.7 s) had a smaller time between responses than trials with W4-2 (M = 3.6 s) and W20-X3 (M = 3.1 s). When either advance warning sign W9-1 or W4-2-PI was present, there was no significant difference in average time between responses between any of the tested warning signs.

CHAPTER 4. DISCUSSION

The goal of this work was to assess driver understanding and behavior when faced with new and traditional lane-reduction roadway markings and signing. Participants responded to various stimuli using button-press responses, and the timing of those responses was analyzed to determine the effects that lane-reduction signing in combination with lane line transition markings are expected to have on:

- Merging behavior (i.e., moving into the adjacent lane) at lane-reduction transitions.
- Understanding and time of comprehension of the intended message conveyed at lane-reduction transitions (from both the terminating lane and the left-adjacent lane).

When participants were presented with stimuli that contained advance warning signs, early merge behaviors were apparent across all measures, regardless of signing or lane markings. In some instances, recognition of lane termination was 3.2 s faster when an advance warning sign was present. At 45 mph, this speed provided the driver with an additional 211.2 ft to change lanes—just from the addition of an advance warning sign. The results also suggested that the effect of different warning signs on driver behavior is not significant when an advance warning sign is present.

Certain signs consistently encouraged early merge behavior, but others did not. When no advance warning sign was present, W4-2 frequently encouraged early merging across all three responses. In contrast, W9-2 had consistently slower response times across all measures when no advance warning sign was present. These results suggest different responses between symbol (W4-2) and text-based (W9-2) signing. Both the W9-2L-DE and W20-X3 warning signs, which include both symbols and text, had response times that fell between those response times found for W4-2 and W9-2. This claim is further supported by the advance warning sign results. W4-2-PI, a symbol-based and W4-2 derivative sign, had an average response time for "right lane ends" responses that was 2.1 s faster than the average response time for W9-1, a text-based advance warning sign. However, further research is required to fully substantiate these claims as it is difficult to isolate the ideal warning sign because of a myriad of other external factors that were not accounted for, such as familiarity with the signs or participants' native languages.

The intent of this study was to expand on the findings from the Balk and Jackson (2016) lane-reduction line markings study. From that study, two lane line marking suggestions were made, which were included as variables in the current study. Balk and Jackson (2016) found that the inclusion of a solid white line in combination with a dotted white line resulted in slightly better comprehension of a lane reduction, but there were concerns that the solid white line would discourage drivers from making early merges. The results of the current study suggest that this concern may be dismissed. Specifically, the significant interaction effects of lane line transitions markings and the warning sign on the "change lanes" responses reduced the concern that the solid white line would discourage drivers from making early merges. When warning signs W4-2, W9-2L-DE, or W9-2 were present, the average response time for "change lanes" was significantly faster when a dotted-with-solid line was present as opposed to the presence of a dotted-only lane line. It is possible that the inclusion of a solid line in combination with a warning sign created a sense of urgency, resulting in an earlier lane change.

Although lane-reduction arrow markings were a manipulated variable in this study, those markings had no significant effects on response times or times between responses. It is possible that these insignificant findings could be because of the experimental task and provided stimuli: The lane-reduction arrow markings were the final cue before the lane reduction. At that point, the participant had already been exposed to three to four other cues. However, this finding should not be interpreted as evidence for not using lane-reduction arrows in practice. In this study, participants were tasked with identifying lane reductions in an environment with little distraction. Lane-reduction arrow markings could still be a necessity in high-traffic-density or short-transition scenarios.

Taken together, these results lead to several conclusions:

- The addition of an advance warning sign resulted in earlier recognition of lane termination.
- There is some evidence that symbol-based warning signs encourage earlier recognition and execution of lane changes.
- In this study, driver behavior was evaluated in a low-traffic-density environment, making early lane changes the preferred behavior. However, in higher-traffic-density scenarios, early lane changes may not be preferred.
- The results of this study and Balk and Jackson (2016) suggest that the inclusion of a solid white line with a dotted lane line yields better lane-reduction recognition and encourages earlier lane changes.

APPENDIX

Table 3 includes the complete list of trial combinations used in the experiment.

Table 3. Trials

Trial	Sign Configuration Condition	Arrow Marking and Stimuli Condition	Advance Warning Sign	Warning Sign	Lane Assignment	Lane-Reduction Arrows Used
1	1	1	None	W4-2	Right merge lane	Yes
2	1	2	None	W4-2	Right merge lane	No
3	1	3	None	W4-2	Left through lane	Yes
4	1	4	None	W4-2	Left through lane	No
5	2	1	None	W9-2	Right merge lane	Yes
6	2	2	None	W9-2	Right merge lane	No
7	2	3	None	W9-2	Left through lane	Yes
8	2	4	None	W9-2	Left through lane	No
9	3	1	None	W20-X3	Right merge lane	Yes
10	3	2	None	W20-X3	Right merge lane	No
11	3	3	None	W20-X3	Left through lane	Yes
12	3	4	None	W20-X3	Left through lane	No
13	4	1	None	Delaware W9-2L-DE	Right merge lane	Yes
14	4	2	None	Delaware W9-2L-DE	Right merge lane	No
15	4	3	None	Delaware W9-2L-DE	Left through lane	Yes
16	4	4	None	Delaware W9-2L-DE	Left through lane	No
17	5	1	W9-1	W4-2	Right merge lane	Yes
18	5	2	W9-1	W4-2	Right merge lane	No
19	5	3	W9-1	W4-2	Left through lane	Yes
20	5	4	W9-1	W4-2	Left through lane	No
21	6	1	W9-1	W9-2	Right merge lane	Yes
22	6	2	W9-1	W9-2	Right merge lane	No
23	6	3	W9-1	W9-2	Left through lane	Yes
24	6	4	W9-1	W9-2	Left through lane	No
25	7	1	W9-1	W20-X3	Right merge lane	Yes
26	7	2	W9-1	W20-X3	Right merge lane	No
27	7	3	W9-1	W20-X3	Left through lane	Yes
28	7	4	W9-1	W20-X3	Left through lane	No
29	8	1	W9-1	Delaware W9-2L-DE	Right merge lane	Yes

Trial	Sign Configuration Condition	Arrow Marking and Stimuli Condition	Advance Warning Sign	Warning Sign	Lane Assignment	Lane-Reduction Arrows Used
30	8	2	W9-1	Delaware W9-2L-DE	Right merge lane	No
31	8	3	W9-1	Delaware W9-2L-DE	Left through lane	Yes
32	8	4	W9-1	Delaware W9-2L-DE	Left through lane	No
33	9	1	W4-2-PI	W4-2	Right merge lane	Yes
34	9	2	W4-2-PI	W4-2	Right merge lane	No
35	9	3	W4-2-PI	W4-2	Left through lane	Yes
36	9	4	W4-2-PI	W4-2	Left through lane	No
37	10	1	W4-2-PI	W9-2	Right merge lane	Yes
38	10	2	W4-2-PI	W9-2	Right merge lane	No
39	10	3	W4-2-PI	W9-2	Left through lane	Yes
40	10	4	W4-2-PI	W9-2	Left through lane	No
41	11	1	W4-2-PI	W20-X3	Right merge lane	Yes
42	11	2	W4-2-PI	W20-X3	Right merge lane	No
43	11	3	W4-2-PI	W20-X3	Left through lane	Yes
44	11	4	W4-2-PI	W20-X3	Left through lane	No
45	12	1	W4-2-PI	Delaware W9-2L-DE	Right merge lane	Yes
46	12	2	W4-2-PI	Delaware W9-2L-DE	Right merge lane	No
47	12	3	W4-2-PI	Delaware W9-2L-DE	Left through lane	Yes
48	12	4	W4-2-PI	Delaware W9-2L-DE	Left through lane	No
49	13	1	N/A	W23-2	Right merge lane	N/A
50	13	3	N/A	W23-2	Left through lane	N/A
51	14	1	N/A	W19-1	Right merge lane	N/A
52	14	3	N/A	W19-1	Left through lane	N/A
53	15	1	N/A	W1-10b	Right merge lane	N/A
54	15	3	N/A	W1-10b	Left through lane	N/A
55	16	1	N/A	W1-10c	Right merge lane	N/A
56	16	3	N/A	W1-10c	Left through lane	N/A

N/A = not applicable.

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