Simulator Assessment of Alternative Lane Grouping at Signalized Intersections

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FOREWORD

The Federal Highway Administration (FHWA) is focused on improving highway design by increasing knowledge of how intersection design affects operational efficiency and safety. Two intersection configurations designed to increase capacity without adding lanes are the dynamic reversible left-turn lane at diamond interchanges and contraflow left-turn lane at signalized intersections. These intersection configurations were explored in the project Simulator Assessment of Alternative Lane Grouping at Signalized Intersections. This project consisted of two studies, both conducted in FHWA's Highway Driving Simulator, that assessed driver behavior and comprehension in response to signs and symbols used to convey reversible-lane operations.

This report is of interest to engineers, planners, and transportation professionals concerned with implementing signs and pavement treatments for alternative intersections and responsible for highway design and public safety.

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16. Abstract
Throughput during peak-period traffic at signalized intersections with high left-turn demand commonly creates a bottleneck. Two intersection configurations designed to increase the capacity at locations without adding lanes are the dynamic reversible left-turn (DRLT) lane at diamond interchanges and contraflow left-turn (CLT) lane at signalized intersections. The DRLT design replaces back-to-back left-turn bays with reversible lanes that span the distance between interchange nodes. The direction of flow alternates within a signal cycle. Signals and changeable-message signs control the direction of flow. The DRLT configuration may result in drivers intending to make a left turn at the downstream ramp viewing opposing traffic in the lane they are to use in a subsequent signal phase. In a CLT intersection, a gap in the median allows drivers turning left to queue in a lane that is normally used by opposing through traffic. The CLT design allows for an additional left-turn lane without widening the roadway. Two experiments, conducted in a highway driving simulator, evaluated driver comprehension and lane usage in DRLT and CLT intersections compared to conventional intersections, which were also simulated. Data were obtained from 96 participants in each experiment. The results of the DRLT interchange experiment showed that up to 25 percent of participants made inappropriate lane changes when first encountering the DRLT lane and observing opposing traffic in their lane prior to receiving a green signal. Early signs of confusion dissipated in later trials, such that only 4 percent of participants made more than 1 inappropriate lane change in the DRLT interchange. Participants in the CLT-intersection experiment used the CLT lane more frequently after the first encounter, with probability of use rising to 58 percent during the second exposure when there was a long queue in the nonreversible left-turn lane. Lane changes in the CLT intersection were uncommon and occurred in only 5 percent of trials. Under some circumstances, however, acceleration- and brake-release delays were longer in the CLT intersection than in the conventional intersection configuration. These delays did not improve during the second exposure. Findings show that signs and markings used in both studies will work well in a real-world environment. Recommendations are provided for additional and modified signs and markings on the approach sides of DRLT and CLT intersections to improve comprehension and comfort of drivers who may see opposing traffic in their lane while waiting for a green signal.

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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

CLT	contraflow left-turn
CMS	changeable-message sign
DRLT	dynamic reversible left-turn
FHWA	Federal Highway Administration
GEE	general estimating equations
I	Interstate
MUTCD	*Manual on Uniform Traffic Control Devices for Streets and Highways*
SR	State Route
SSQ	simulator sickness questionnaire
TCD	traffic control device

CHAPTER 1. INTRODUCTION

Increasing traffic can lead to congestion and bottlenecks at intersections and freeway interchanges. One solution to this problem is reversible-lane configurations. Reversible lanes require static and changeable-message signs to indicate lane assignment based on the time of day and traffic demand. Dynamic lane-grouping strategies offer cost-effective methods for increasing operational efficiency within existing rights of way. Where left-turn demand is high, dynamic reversible left-turn (DRLT) lanes could relieve congestion at signalized diamond interchanges, and contraflow left-turn (CLT) lanes could relieve congestion at signalized intersections.

Previous traffic simulations suggested that reversible left-turn lanes can significantly increase throughput at interchanges where left-turn demand is high.[(1,2)] However, the operational benefits offered by reversible-turn-lane designs depend upon safe and proper use by drivers. Because reversible lanes make use of existing infrastructure and are time-of-day dependent, they require clear and adaptive signs and signals to indicate the active or closed status of the lane and control alternative lane assignment during active periods. Reversible-lane designs may also expose drivers to novel or unfamiliar situations, such as sharing a lane with opposing traffic waiting at the far side of the intersection. In these cases, appropriate signs can mitigate unsafe driving behaviors caused by driver discomfort or confusion. In addition, improved signs and markings may aid in minimizing issues observed at existing reversible-lane interchanges, such as incorrect or missed turns and lane changes within the intersection.

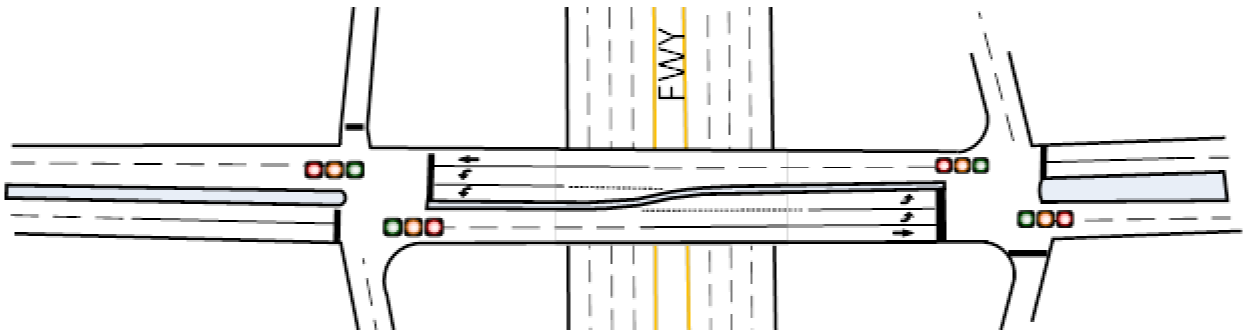
This report documents and discusses the designs and results of two driving simulator studies that assessed driver behavior and comprehension in response to signs and symbols used to convey reversible lane operations. The signs employed in these simulations had previously undergone rigorous behavioral evaluation for comprehensibility and perceived meaning.[1] The results of the two studies are intended to support recommendations and guidance for sign design and placement at reversible interchanges.

[1]Inman, V. and Jackson, S. (2017). *Dynamic Reversible Lane Human Factors Laboratory Study*. Unpublished internal report.

CHAPTER 2. DRIVING SIMULATOR STUDY OF A DRLT INTERCHANGE

INTRODUCTION

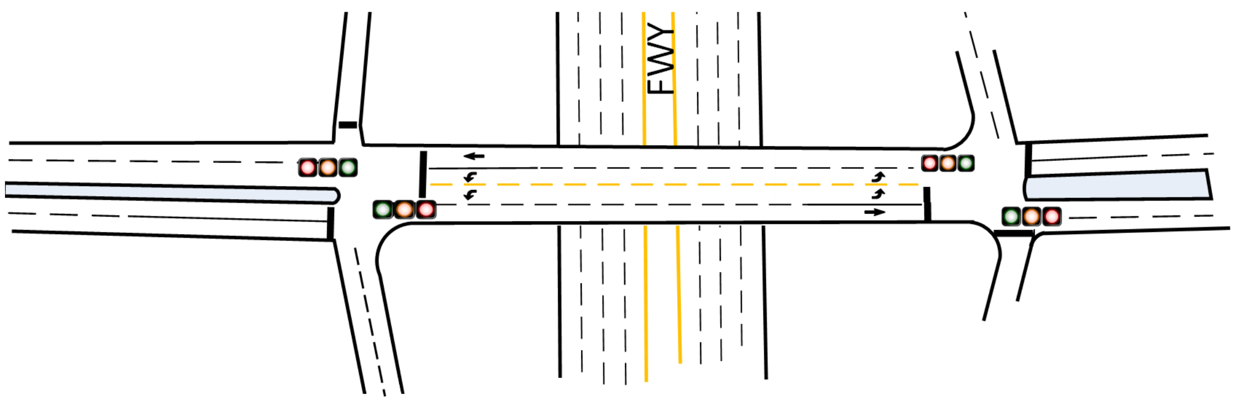
The diamond interchange is the most common design for intersections of controlled-access roadways and arterials.(3) Compared to conventional interchange designs, diamond interchanges have the advantages of requiring relatively low land use and only one bridge. A signalized, conventional diamond interchange is shown in figure 1. The capacity of the conventional diamond interchange is limited as the operational efficiency of the design is dependent on adequate storage capacity between intersections. High volumes of traffic turning left can rapidly saturate capacity.(4)



Source: FHWA.
FWY = freeway.

Figure 1. Illustration. Conventional diamond interchange.

Zhao et al. proposed a novel means of mitigating effects of high directional flows on left-turn demand at diamond interchanges.(5) The approach required dynamically reversing the direction of flow on the arterial between signalized intersections. Their modeling, as well as subsequent modeling by Krause et al., suggested replacing back-to-back left-turn bays with DRLT lanes to create substantial increases in capacity.(2) An example of a DRLT design is illustrated in figure 2.



Source: FHWA.
FWY = freeway.

Figure 2. Illustration. Initial DRLT design.

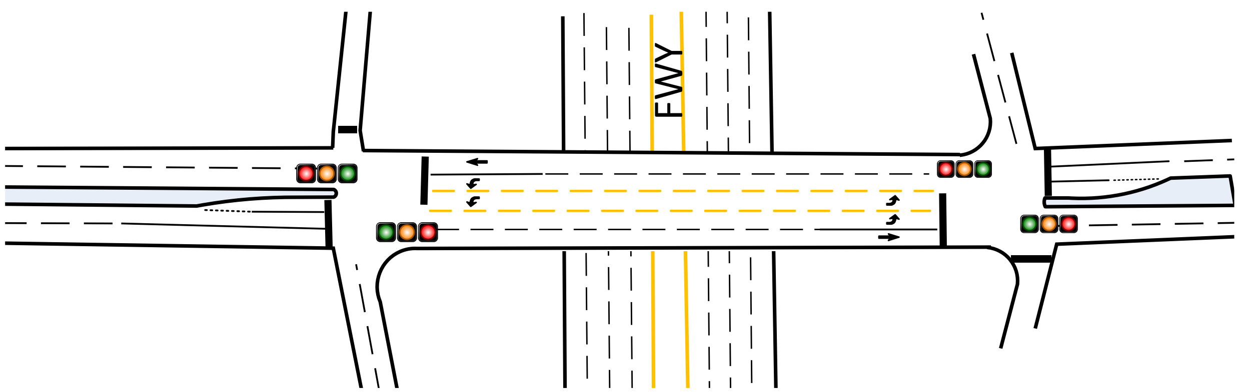
Human factors present a challenge in fielding such novel intersection designs. Signs and markings are needed to ensure drivers understand how to properly and safely navigate the intersection. Related challenges are anticipating the types of driver errors that may be associated with the design and proactively mitigating them.

This experiment was one part of a multistep process designed to address DRLT-related human-factors issues. The first step brought together an expert panel of subject-matter experts on human factors and traffic control devices (TCDs) and State traffic research engineers to review sign, marking, and geometric design options. The second step brought in drivers to provide feedback regarding their understanding of and preferences for visualizations of selected options.[2] The third step implemented the lessons learned from the first two steps into a driving simulation experiment. This experiment enabled the observation of lane use and performance of drivers unfamiliar with DRLT interchanges in both the conventional and DRLT configurations of the same interchange.

DESIGN

Microsimulation modeling of the DRLT interchange showed that capacity benefits are not achieved if traffic exiting the freeway is able to re-enter the freeway by turning left at the downstream signal (i.e., make a U-turn).[(6)] Thus, the modelers recommended that re-entry to the freeway should be prohibited when reverse lanes are open.

As the original design required a shift to the left within the approach intersection, the expert panel consulted during the first step of the study was concerned the geometric configuration shown in figure 2 would confuse drivers and cause sideswipes and merging problems. The suggested solution was to control driver behavior with geometry by adding left-turn bays at the upstream intersection approaches, as illustrated in figure 3.

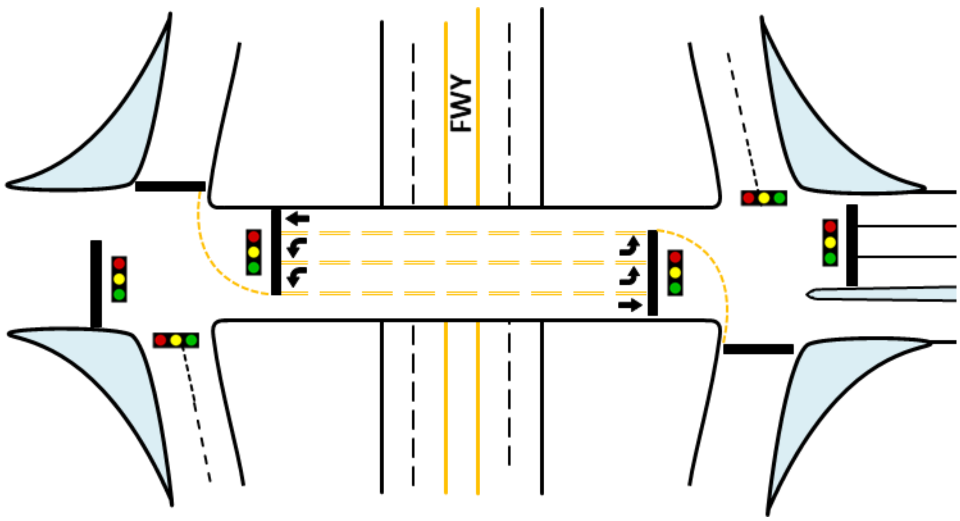


Source: FHWA.
FWY = freeway.

Figure 3. Illustration. Example of a DRLT design modified to align geometry with lane markings.

[2]Inman, V. and Jackson, S. (2017). *Dynamic Reversible Lane Human Factors Laboratory Study*. Unpublished internal report.

Historically, reversible-lane operations shift based on time of day.[1,7] Time-of-day operations have two purposes: adjusting to time-of-day directional flows and avoiding reversible-lane use during periods of low demand. Operations controlled based on time of day require peak-period and off-peak-period sign configurations, an option preferred by some expert panel members. Other panel members, however, favored using dynamic lanes at all times to avoid driver errors that may result from inconsistent operations and reduce the number of changeable-message signs (CMSs) required. This experiment tested peak-period and off-peak-period sign configurations. The final configuration of the DRLT interchange implemented in this experiment is illustrated in figure 4, and the conventional interchange, or control, is illustrated in figure 1.



Source: FHWA.
FWY = freeway.

Figure 4. Illustration. DRLT-interchange design used in this experiment.

GOAL

The goal of this experiment was to derive empirically supported recommendations for effective signs and markings at DRLT interchanges. To this end, a driving simulator experiment was conducted in which 96 participants drove through both a conventional diamond interchange and DRLT interchange.

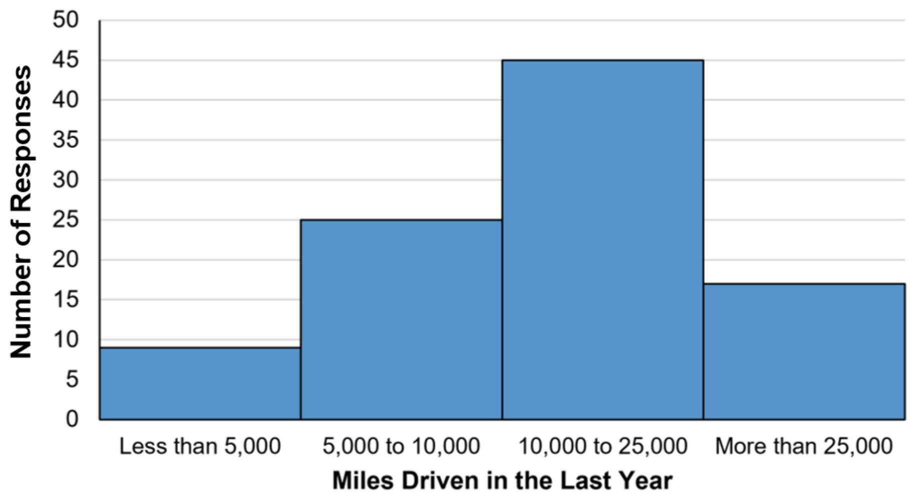
It was hypothesized that there would be few driver errors at either interchange; the signs and markings at the DRLT interchange were subjected to extensive development and review. All signs and markings were compliant with the *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD).[8] This study was expected to verify that the selected signs and markings at the DRLT interchange were adequate for safe operation of the interchange. The primary measures of effectiveness were drivers' navigational accuracy and appropriate lane use. The adequacy of the DRLT-interchange design was judged by comparing driver performance at the DRLT interchange to that at the equivalent conventional interchange. Any marked disparities in driver performance between the two interchange designs that favored the conventional design would suggest the need for additional efforts designing the DRLT interchange.

METHOD

The following sections describe the participants, research design, driving simulator, and post-task questionnaire used in this study. The post-task questionnaire focused on assessing participants' opinions of specific DRLT-interchange signs and symbols.

Participants

Participants included 96 licensed drivers from the Washington, DC, metropolitan area who were screened for binocular visual acuity of 20/40 or better. Participants were equally male and female, and within each group of sex, two age groups were equally represented: less than 47 yr of age and 47 yr of age or greater. Participants were asked to estimate how many miles they had driven in the last year by selecting one of four categories: less than 5,000 mi; 5,000 to 10,000 mi; 10,000 to 25,000 mi; or more than 25,000 mi. Figure 5 represents participant responses to this question. There were no significant trends in these estimates as functions of either age group or sex (all $p > 0.10$).



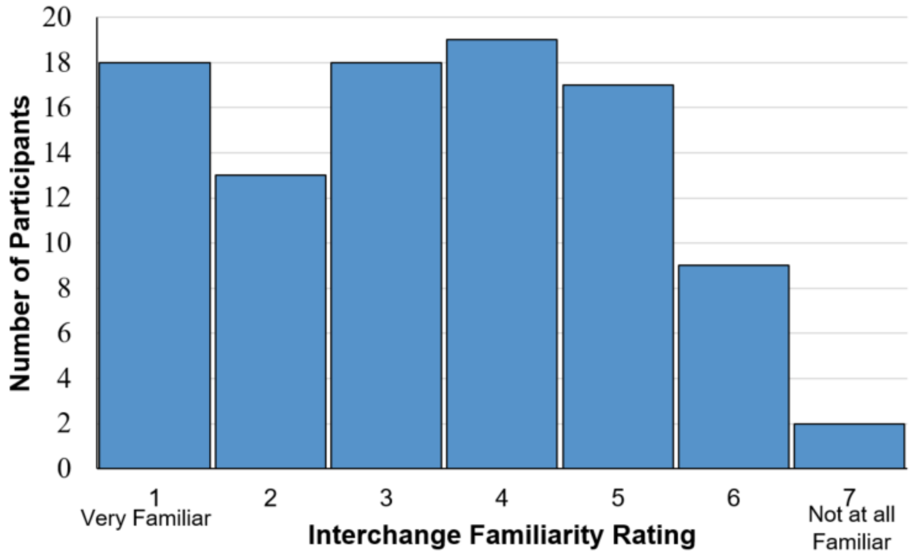
Source: FHWA.

Figure 5. Graph. Participant self-estimation of miles driven in the last year.

Research Design

Both conventional and DRLT interchanges were modeled on a square tile (predefined sections of the simulated driving model) that measured approximately 0.53 mi on each side. The tiles were designed to allow the participant to drive seamlessly from one tile to the next while keeping the next approach consistent (e.g., from Interstate (I)-495 South to I-495 North). This tile configuration allowed the order of conditions to remain unaffected even if the participant made a navigational error.

Because the interchange simulations were based on a model of the conventional diamond interchange at I-495 and Georgetown Pike in McLean, VA, about 1.9 mi from the laboratory where the experiment was conducted, participants were asked to rate their familiarity with that interchange before starting the simulation. On a scale from 1 to 7, where 1 was "very familiar" and 7 was “not at all familiar,” the mean rating was 3.4, indicating that most participants were at least somewhat familiar with the interchange. The response distribution is shown in figure 6.

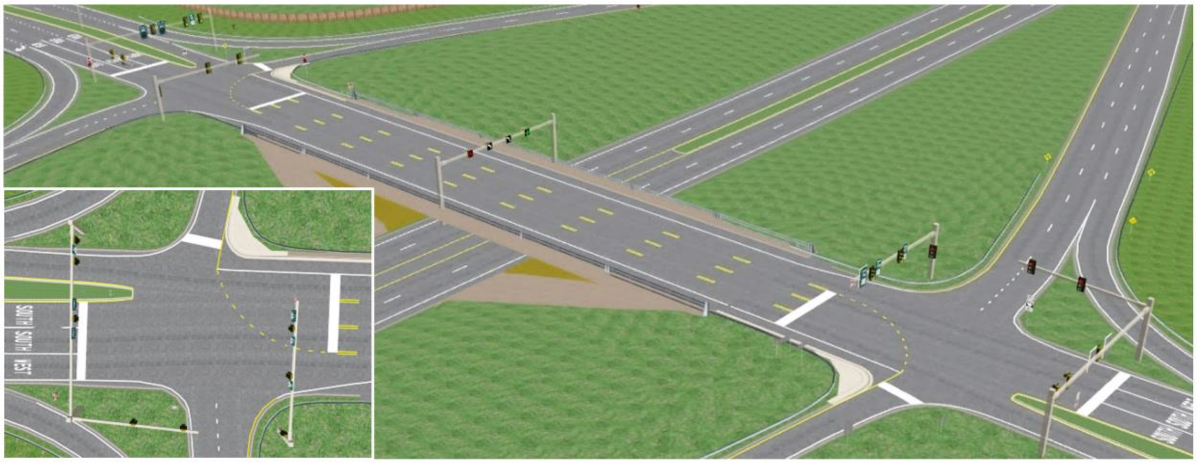


Source: FHWA.

Figure 6. Graph. Familiarity ratings for the interchange that served as the model for the simulation.

Participants first drove through the simulation of the conventional diamond interchange four times (trials) to provide baseline driving-performance data. The first and third drives through the interchange required participants to approach the arterial. During those trials, participants were instructed to follow the signs to I-495 North and South, respectively (destination names “Rockville” and “Richmond” were also provided). These instructions, if followed correctly, resulted in participants driving through the interchange and turning left at the second intersection. No instructions were given as to which of the two left-turn lanes should be used. On the second and fourth drives through the interchange, participants were instructed to follow signs to State Route (SR) 193 East and West, respectively (destination names “McLean” and “Great Falls” were also provided). These movements consisted of left turns from the interstate off-ramp onto the arterial.

Next, participants drove through the DRLT interchange (figure 7) 14 times. Instructions were the same as those for the conventional diamond interchange (e.g., “follow the signs to I-495 South, Richmond”).



Source: FHWA.

Figure 7. Illustration. DRLT-interchange scenario used in this study with an overhead view of the signalized intersection.

The 14 trials, comprised of the following four scenarios, were conducted:

- Scenario 1 consisted of four trials with the arterial configured for peak-period traffic conditions (contraflow lane open). The interchange consisted of two left-turn lanes and one through lane in the participant’s direction of travel. The participant arrived at the first intersection during the red signal phase and observed opposing traffic turning left from the lanes to be used for accessing the freeway (figure 8). At the second intersection, the participant was intended to turn left.

- Scenario 2 consisted of four trials with the arterial configured for peak-period traffic conditions (contraflow lane open). The interchange consisted of two left-turn lanes and one through lane in the participant’s direction of travel. The traffic signals were green for the participant’s direction of travel. Vehicles ahead of the participant used both left-turn lanes (i.e., the participant could follow the vehicles ahead using the reversible lanes). At the second intersection, the participant was intended to turn left.

- Scenario 3 consisted of four trials with the arterial configured for off-peak-period traffic conditions (contraflow lane closed). The interchange consisted of one left-turn lane and one through lane in each direction. The participant arrived at the first intersection during the red signal phase while opposing traffic was turning left (figure 9). At the second intersection, the participant was intended to turn left.

- Scenario 4 consisted of two trials from the one-lane freeway off-ramp configured for peak-period traffic conditions (contraflow lane open). The participant arrived at the ramp terminal during a green signal phase. The participant was intended to make a left turn onto the arterial.

Source: FHWA.

A. Scenario 1 overhead signs.

Source: FHWA.

B. Scenario 1—participant’s point of view from the first intersection stop bar: peak-period traffic, arrival on red.

Figure 8. Illustrations. Scenario 1.

Source: FHWA.

A. Scenario 3 overhead signs.

Source: FHWA.

B. Scenario 3—participant's point of view from the first intersection stop bar: off-peak-period traffic, arrival on red, "This Lane Closed" sign indicating the DRLT lane should not be used.

Figure 9. Illustrations. Scenario 3.

In total, participants approached the interchange from the arterial 12 times. In half of the 12 arterial approaches, participants were instructed to start from the right lane, and on the other half they were instructed to start from the left lane. These instructions were intended to control in which lane the participant would be when reading the first navigational sign at the approach. It was hypothesized that participants might be more likely to use the turn bay and leftmost reversible lane if they approached the first navigational sign from the left lane.

Highway Driving Simulator

Federal Highway Administration's (FHWA's) Highway Driving Simulator consisted of a sedan mounted on a six-degree-of-freedom motion base. A floor-mounted cylindrical screen hosted a projected 200-degree-horizontal by 40-degree-vertical field of view of the driving environment.

The screen cylinder had a radius of 8.9 ft. Drivers' eye points varied with the seat position and ranged from 0 to 23 cm to the rear of the cylinder's center. The vehicle steering had a force-feedback controller. The accelerator pedal provided spring-loaded resistance. The brake resistance was provided by a hydraulic brake system. All instrument displays were programmable. Images on the cylindrical screen were provided by three projectors, and each projector image consisted of 4,096 horizontal by 2,400 vertical pixels and updated at 60 Hz. The vehicle dynamics model was tuned to simulate a generic compact sedan. A bass shaker simulated roadway vibrations, and the generation of wind, engine, and road noise was linked to the vehicle dynamics.

Procedure

Upon arriving at the testing site, participants were asked to review and sign a record of informed consent. They were then asked a few questions about their current state of health to ensure that they were not at increased risk of simulator sickness. Next, participants were asked to read a Bailey–Lovie LogMAR eye chart and provide a valid driver's license. Participants were asked to estimate the number of miles they drove in the last year and the number of years since they first received a driver's license. They were then asked to complete a simulator sickness questionnaire (SSQ) to provide a baseline for comparison to subsequent SSQ administrations.

Next, participants were seated in the driving simulator and briefed on the controls and display. A short practice scenario was run in which participants were asked to accelerate to 35 mph, stop at a red signal, make a left turn, and change lanes at least twice. When participants indicated they were comfortable handling the simulated vehicle, they were asked to exit the simulator and complete another SSQ. The instructions for the next drive were read to participants before they were reseated in the simulator.

The main simulation experiment began with the instruction to accelerate to 35 mph and follow signs to I-495 South. Conditions for the first four trials for each participant were the same: two passes through the conventional diamond interchange on the arterial and two passes through the interchange beginning at the freeway off-ramp. The order of the next 14 trials was counterbalanced across participants, such that the order of each peak-period, off-peak-period, and traffic-signal condition occurred equally across participants.

After the main drive, which lasted about 38 min, a final SSQ and the post-task questionnaire were administered. Participants were then debriefed with a verbal explanation of the study's goals and paid $60.

Post-Task Questionnaire

A post-task questionnaire was presented to participants on a laptop computer after completing the driving simulation. The questionnaire showed pictures of signs on the arterial and queried participants regarding their understanding of those signs. Pictures from the driver's viewpoint showed peak-period and off-peak-period sign configurations at four locations: the beginning of the taper of the left-turn bay, the first intersection stop bar, the sign bridge over the middle of the interchange overpass, and the second intersection. Participants were shown a picture at each location and were asked questions, such as, "Did you understand these signs?" "Was the meaning of these signs clear?" or a question with similar wording. If the answer was "yes," then participants were queried on their understanding of the signs in the next picture. If the answer was "no," then a followup question asked for an explanation of what was unclear. When shown the picture of the first location, participants were also asked whether they would use the lane under the green-arrow CMS (figure 10) if there were less traffic in that lane than in their current lane.

Source FHWA.

Figure 10. Illustration. Green-arrow CMS above the left-turn bay.

RESULTS

Each participant was intended to partake in 18 trials that consisted of 4 passes through the conventional interchange followed by 14 passes through the DRLT interchange of which 2 were left turns from the freeway off-ramp and 12 were left turns from the arterial. Data from the 18th trial were lost for 20 participants due to a procedural error. For one participant, data for the final two trials were lost due to a simulator failure. Because the order of trials was randomly assigned and counterbalanced, the small amount of data lost is unlikely to invalidate results.

Lane Choice

Lane Used at the Approach Guide Sign

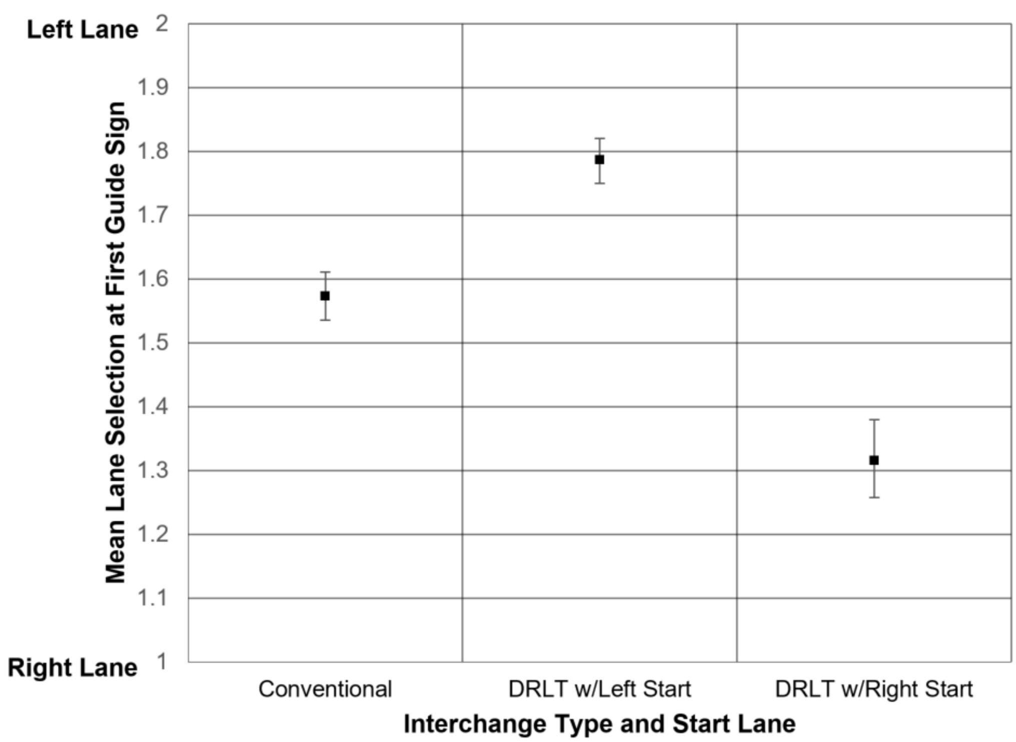
The first research question examined was the effect of the instruction to begin in the left or right lane on subsequent participant lane use. For DRLT trials that began on the arterial, participants were instructed to begin driving in the left lane for half of the trials and the right lane for the other half. This instruction was intended to ensure that, for at least half the trials, use of the leftmost lane would make using the left-turn bay convenient.

The effect of the lane-use instruction was tested using a general estimating equations (GEE) model with three independent factors: interchange type, start-lane instruction, and novelty (table 1). A trial was defined as novel if it was one of the participant's first three passes through the interchange. The factors novelty and start-lane instruction were nested within DRLT; novelty was undefined for the conventional interchange, and no start-lane instructions were given for conventional interchange trials. The GEE model used a multinomial distribution and a cumulative logit link function. Each factor in the model was analyzed at a 95-percent confidence level using the Wald χ^2 test.

Table 1. Corresponding levels for factors used in the GEE models.

Factor	Levels
Interchange type	Conventional, DRLT
Start-lane instruction	Left, right
Novelty	Novel (DRLT passes 1–3), nonnovel (DRLT passes 4–11)
Traffic	Leading, opposing
Period	Peak, off-peak

As participants passed the first navigational sign, 680.1 ft upstream of the first stop bar, the lane-use instruction had a strong effect, Wald $\chi^2(1) = 194.6$, $p < 0.0001$. Interchange type and novelty were not significant, Wald $\chi^2(1) < 1.0$. The first navigational sign was legible from at least 600.4 ft; participants had ample opportunity to change lanes before reaching it. Figure 11 depicts the average lane position for the conventional interchange and DRLT interchange with left (denoted as 2) and right (denoted as 1) start lanes. When participants reached the first guide sign, those instructed to start in the right lane were, on average, still in the right lane, whereas participants instructed to start in the left lane were, on average, still in the left lane. Participants given no instruction had a slight preference for the left lane.



Source: FHWA.
Note: Error bars represent the 95-percent confidence limits of the means.

Figure 11. Plot. Average lane choice at the first guide sign.

Lane Use at the Beginning of the Taper of the Left-Turn Bay

The same model used to evaluate lane-use instruction was applied to examine the effect of the start-lane instruction at the beginning of the taper of the left-turn bay. At the start of the taper of the left-turn bay, participants were in the left lane in over 90 percent of trials regardless of start lane or interchange type; overall, the probability of being in the left lane was 0.95. There was a small but statistically significant difference in lane use as a function of novelty with being in the right lane more likely during the first three DRLT trials, Wald $\chi^2(1) = 7.7$, $p < 0.006$. There was no difference in lane use as a function of interchange type ($p > 0.05$).

As participants were already in the left lane in 95 percent of trials in which their destination required a left turn at the second signal, it is unlikely that the start-lane instruction had any effect on participants' lane choice beyond the beginning of the taper of the left-turn bay.

In trials where the interchange was configured for peak-period traffic conditions (i.e., when the left-turn bay was open), use of either the left lane (lane 2 from right to left, excluding the exit lane; see figure 12) or the turn bay (lane 3) was appropriate. When queues were present ahead of participants, the queues were of equal length, and participants could use either lane just as they could when no queues were present. Lane choice was examined to gain a sense of willingness to use the turn bay and, subsequently, the leftmost reversible lane.

A model with three independent factors—start-lane instruction, traffic, and novelty—was tested. The start-lane instruction and novelty factors are defined as in table 1. Leading traffic consisted of three vehicles each in the left lane (lane 2) and turn bay (lane 3) (figure 12). Opposing traffic consisted of two lanes of traffic turning left from reversible lanes that also functioned as receiving lanes for the participants' lanes (figure 13). The GEE model included main effects and all two-way interactions, a binomial response distribution, and a logit link function. Each factor in the model was analyzed at a 95-percent confidence level using the Wald χ^2 test.

Source: FHWA.
Note: Lane numbers are for reference.

Figure 12. Illustration. Beginning of the turn-bay taper with leading traffic.

Source: FHWA.

A. Overhead signs at the first intersection.

Source: FHWA.

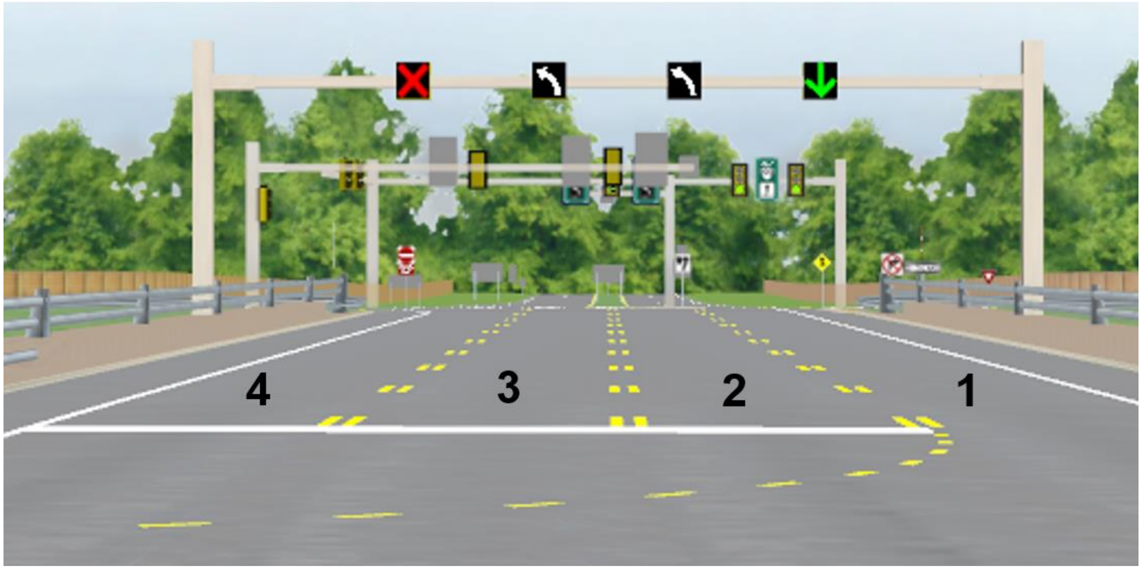
B. Vehicles turning left from the participant's receiving lane at the first intersection.

Figure 13. Illustrations. Opposing traffic turning left from the reversible lanes at the first intersection.

Only the effect of the start-lane instruction was significant, Wald $\chi^2(1) = 22.1$, $p < 0.0001$. Participants who started in the left lane had a higher probability of using the turn bay (mean = 0.35; confidence limits = 0.28–0.43) than participants who started in the right lane (mean = 0.18; confidence limits = 0.13–0.24). Thus, regardless of start lane, the probability of using the turn bay when it was open was less than 0.5.

Reversible-Lane Use

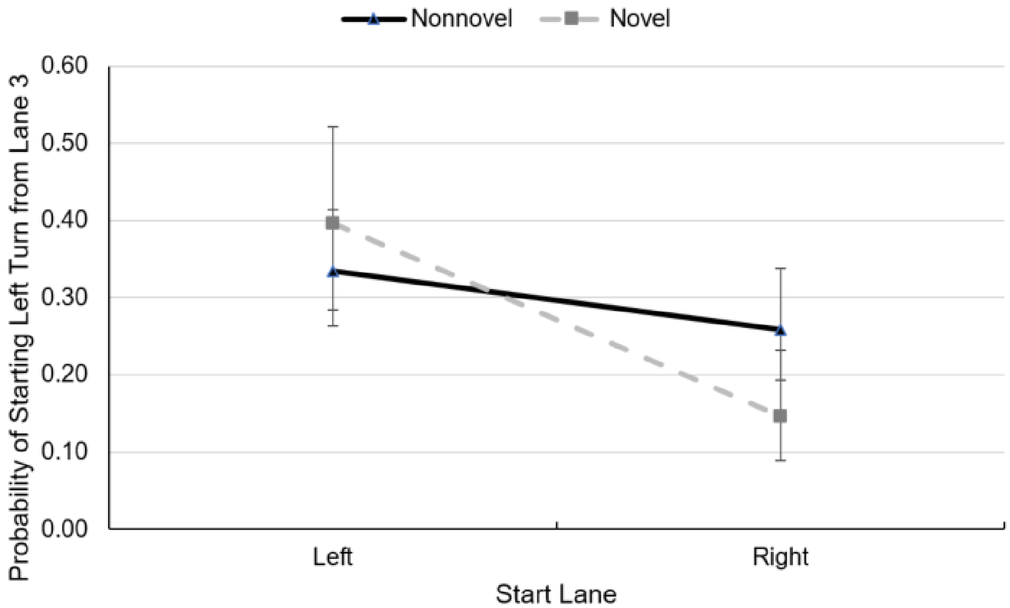
During scenarios 1 and 2 with peak-period traffic conditions, participants had the opportunity to properly use lanes 2 and 3 (figure 14) to turn left onto the freeway on-ramp at the second traffic signal. Lane use was evaluated at the stop bar for the second signal. During some trials, a few participants began their turn before the stop bar and were classified as turning from lane 4. There were 23 cases out of 742 trials in which participants crossed into lane 4 before reaching the stop bar. There were six cases in which participants turned left from the right lane (lane 1).



Source: FHWA.
Note: Lane numbers are for reference.

Figure 14. Illustration. Reversible lanes at the second signal during the peak period.

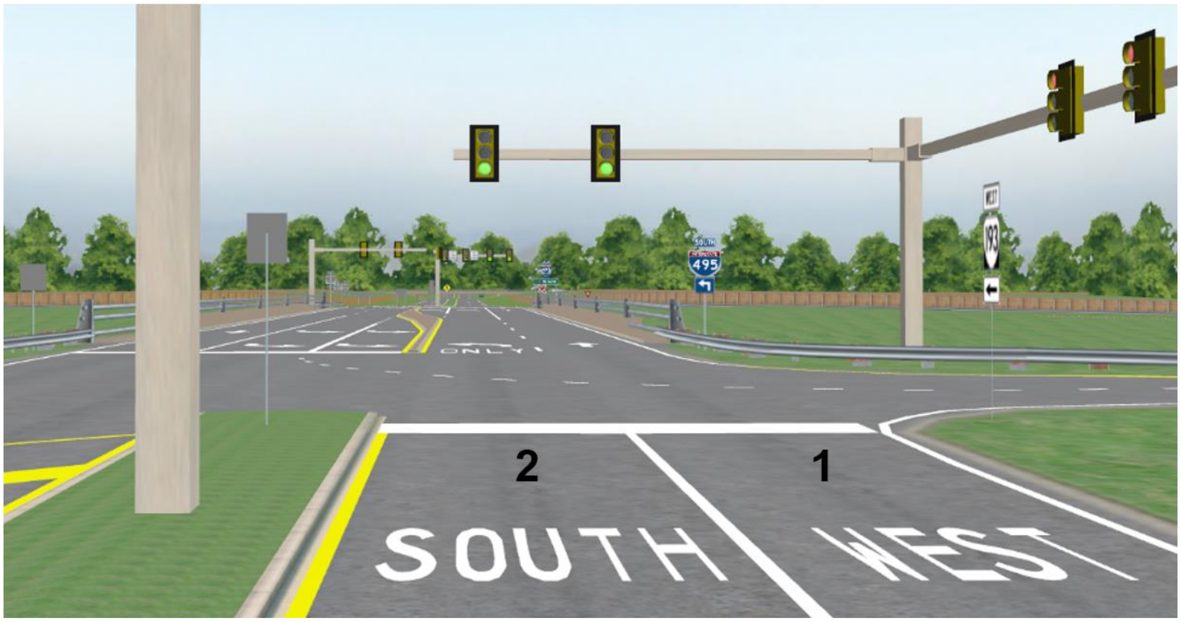
A GEE model using start-lane instruction, traffic, novelty, all two-way interactions as independent factors, and a binomial response distribution and a logit link function was computed. Each factor in the model was analyzed at a 95-percent confidence level using the Wald χ^2 test. Only cases in which the driver began in lanes 2 or 3 at the first intersection (figure 12) were included in the analysis. Participants who started in the left lane (lane 3) had a 0.35 probability of using lane 4 (confidence limits = 0.28–0.42), whereas those who started in the right lane (lane 2) had a 0.23 probability of using lane 3 (confidence limits = 0.17–0.29). This difference was statistically significant, Wald $\chi^2(1) = 14.7$, $p < 0.0001$. As seen in figure 15, the interaction between start-lane instruction and novelty was significant. Participants who started in the left lane (lane 2) on the first three trials were more likely to use lane 4 on novel trials than they were in later trials; however, the novelty effect was reversed for participants who started in the right lane.



Source: FHWA.

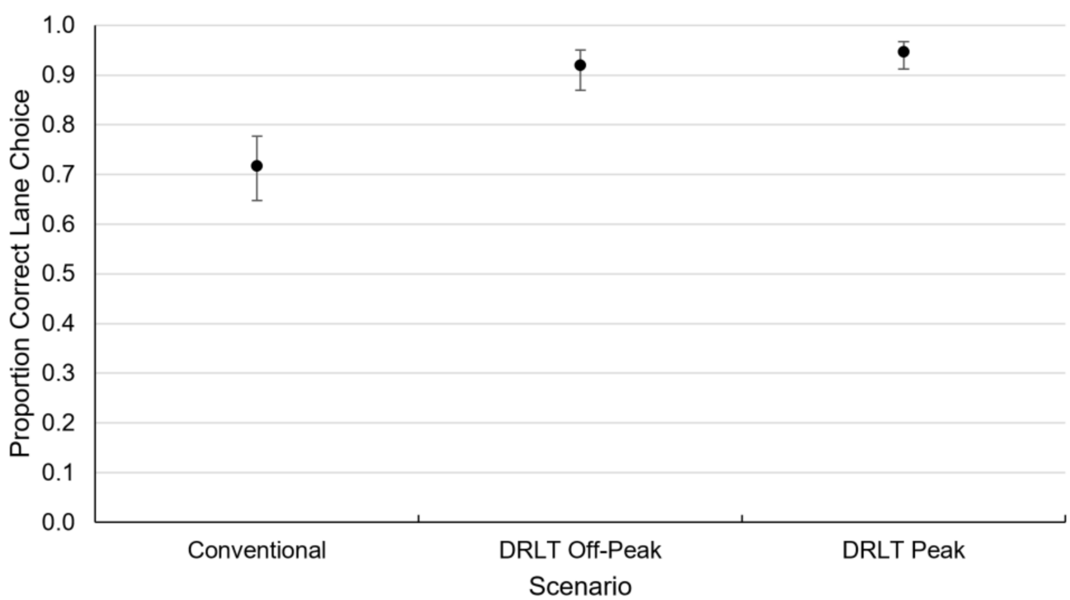
Figure 15. Graph. Probability of beginning a left turn to the freeway on-ramp in the third lane from the right as a function of start-lane instruction and novelty.

In the off-peak-period DRLT scenarios that called for a turn from the arterial to the freeway, participants should have been in lane 2 (figure 12), which was indeed the case in 174 of 190 opportunities. In eight trials, the closed left-turn bay (lane 3) was used, and in another eight trials, the right through lane (lane 1) was used. These outcomes were comparable to participants' performance in the conventional interchange in which they correctly used lane 2 (figure 16) in 139 of 190 opportunities for the same left-turn movement. A main-effects GEE model, which included interchange type, period nested within DRLT, and novelty also nested within DRLT, showed that only interchange type had a significant effect on correct lane choice at the first stop bar; the number of incorrect lane choices at the first stop bar was greater in the conventional interchange than in the DRLT interchange, Wald $\chi^2(1) = 37.0$, $p < 0.0001$. Figure 17 shows the probability of a correct lane choice using this model.



Source: FHWA.
Note: Lane numbers are for reference.

Figure 16. Illustration. Conventional intersection at the first signal.



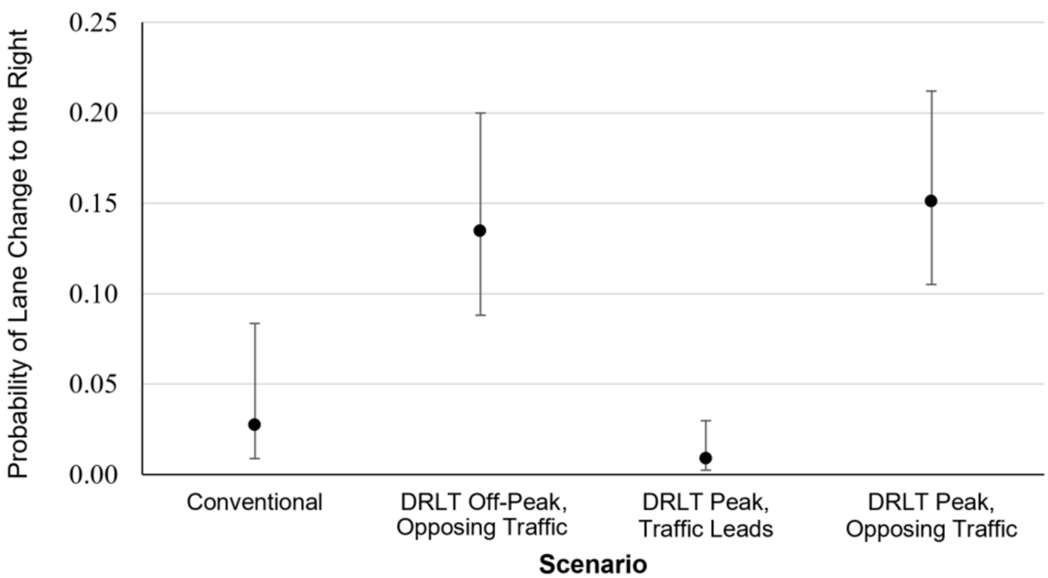
Source: FHWA.

Figure 17. Plot. Correct lane use at the first stop bar when instructed to turn left from the arterial onto the freeway on-ramp.

Lane Changes

As participants may have seen opposing traffic in their lanes during peak-period scenarios, the possibility existed that participants would conclude they were in the wrong lane and make an inappropriate lane change to the right. To examine the probability of this type of error, a GEE model examined the probability of one or more changes to the right from a correct lane within the first intersection. Factors in the model were interchange type, period nested within DRLT, traffic nested within DRLT, and novelty nested within DRLT. The dependent measure of lane-change error was binary (whether there were one or more lane changes to the right). Each factor in the model was analyzed at a 95-percent confidence level using the Wald χ^2 test.

Interchange type was not a significant factor (p = 0.07). Period had a significant effect as did traffic and novelty, Wald $\chi^2(1) = 20.2$, $p < 0.0001$; Wald $\chi^2(1) = 22.2$, $p < 0.001$; and Wald $\chi^2(1) = 20.7$, $p < 0.0001$, respectively. The tested model did not include interactions, although the results of DRLT scenarios indicated a possible interaction between the probability of a lane change to the right and traffic conditions. Figure 18 shows the probability of a lane change to the right within the first intersection. When there was no opposing traffic, the probability of a lane change to the right was near 0 (i.e., conventional interchange or DRLT interchange with leading traffic). When opposing traffic was turning left during the signal phase before the participant received a green signal (i.e., DRLT interchange at off-peak period and DRLT interchange at peak period with opposing traffic scenarios), the probability of a lane change to the right was nontrivial: over 0.15 for the DRLT peak-period scenario. During the DRLT trials, the majority of erroneous lane changes to the right occurred in the first three (novel) trials. During novel trials, the probability of a lane change to the right was 0.13, whereas, during later trials, it was 0.04.

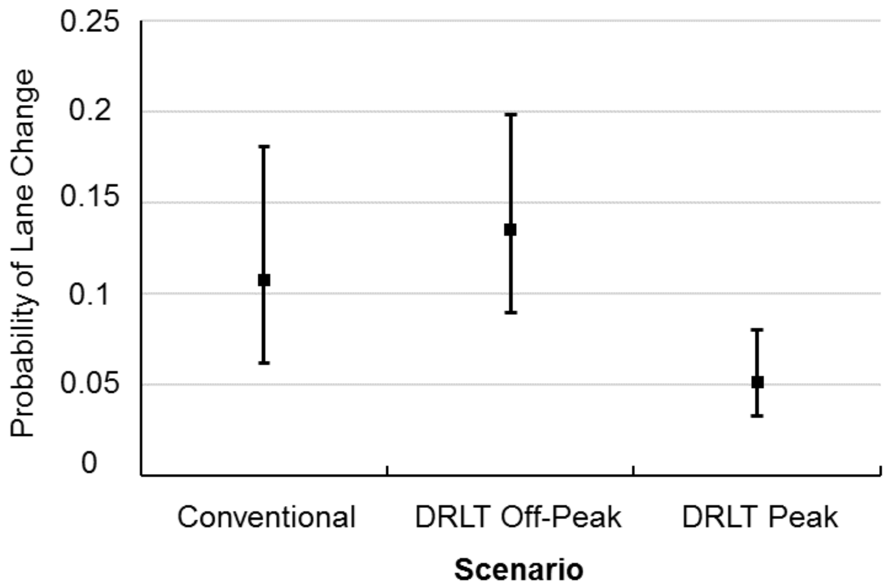


Source: FHWA.

Figure 18. Plot. Probability of a lane change to the right at the first intersection by moving from a correct lane at the first stop bar.

As expected, lane changes to the right were relatively high when participants first encountered opposing traffic in the lane ahead while waiting at the first stop bar. There should have been no lane changes to the left or right in the intersection. Therefore, the analysis addressed the probability of lane changes in the intersection. There was no significant difference in the probability of at least one lane change between conventional and DRLT interchanges (p = 0.88).

As seen in figure 19, the probability of at least one lane change was lowest in the DRLT interchange during peak-period traffic conditions, Wald $\chi^2(1) = 26.4$, $p < 0.0001$. However, this effect was the result of the probability of a lane change being close to 0 (mean = 0.018) when following other vehicles, which was about the same for the off-peak-period DRLT and conventional configurations (mean = 0.135) when facing opposing traffic in the same lane while waiting for a green signal. Most inappropriate DRLT lane changes occurred during the first three passes through the interchange and were significantly less likely thereafter, Wald $\chi^2(1) = 27.1$, $p < 0.0001$.



Source: FHWA.

Figure 19. Graph. Probability of at least one lane change between the first and second intersections.

Lane changes within an intersection are considered unsafe in the majority of the United States. Therefore, it was hypothesized that some participants would be tempted to change lanes but might delay their lane change until they make it through the first intersection. Would Furthermore, it was expected that participants who changed lanes within the first intersection might change back to the left to make the correct movement at the second intersection. Table 2 shows the overall count of lane changes made between the first and second intersections.

Table 2. Number of lane changes between the first and second intersections.

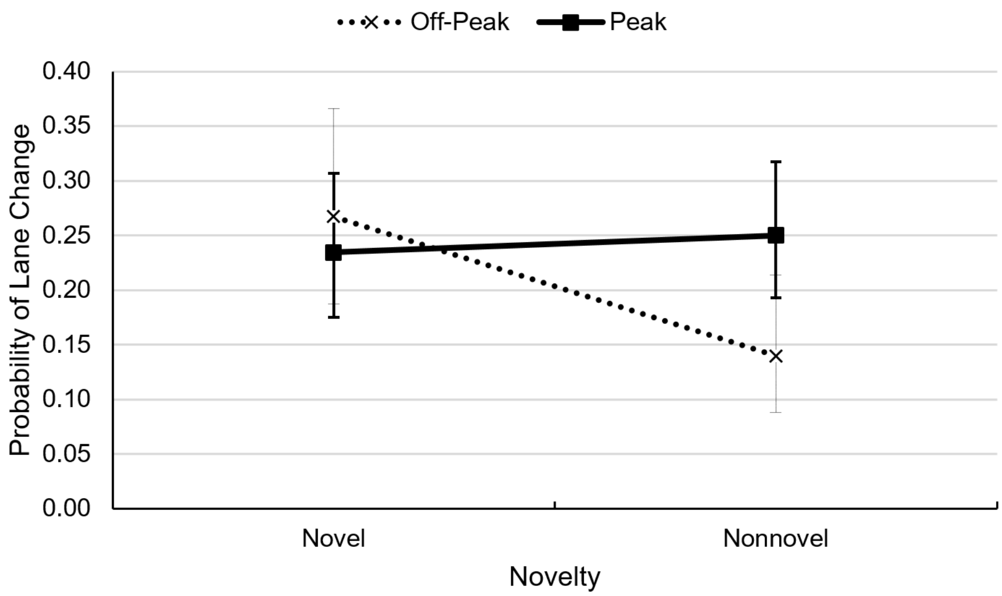
Number of Lane Changes	Frequency	Percent of Total
0	909	77.49
1	214	18.24
2	46	3.92
4	4	0.34
Cumulative total	1,173	100

A GEE model was used to analyze the probability of one or more lane changes between the first and second intersections. This model included both through and left-turn movements that began on the arterial but did not include movements that began on the freeway off-ramp. The model used a binomial response distribution and a logit link function. Each factor in the model was analyzed at a 95-percent confidence level using the Wald χ^2 test. The binary dependent measure was whether a lane change was made. The conventional interchange was not included in the model. Independent factors were period, start-lane instruction nested within peak, traffic nested within peak, novelty, and the interaction of period and novelty.

As summarized in table 3, the significant factors were period, novelty, and the interaction of period with novelty, Wald $\chi^2(1) = 10.14$, $p = 0.001$; Wald $\chi^2(1) = 4.09$, $p = 0.043$; and Wald $\chi^2(1) = 7.24$, $p = 0.007$, respectively. These effects are depicted in figure 20. The probability of one or more lane changes hovered around 0.25, except for the later off-peak-period trials for which the probability was less than 0.15. A separate analysis showed that there was only a probability of 0.05 regarding making more than one lane change between the first and second intersections. The probability of making a lane change between the first and second intersections in trials where participants were previously exposed to oncoming traffic in their lane was 0.30; the probability in trials where participants were not previously exposed to oncoming traffic was less than 0.20. However, most participants who made lane changes between the two intersections did so only once in 12 trials.

Table 3. Significant factors affecting the probability of one or more lane changes between the first and second intersections.

Independent Factor	**Wald χ^2**	***p***
Period	10.14	0.001
Novelty	4.09	0.043
Interaction of period and novelty	7.24	0.007



Source: FHWA.

Figure 20. Graph. Probability of at least one lane change between the two intersections as a function of novelty.

Navigational Errors

Participants committed few navigational errors. Overall, participants exited the interchange on the correct leg 99 percent of the time. The few navigational errors that did occur were not related to the type of interchange (i.e., conventional or DRLT).

Post-Task Questionnaire

Useable questionnaire responses were obtained from 95 of 96 participants. Questionnaire responses from one participant were not obtained due to a computer problem.

The first questionnaire item examined whether participants understood the meaning of the red-X CMS and green-arrow CMS that were intended to control whether or not the left-turn bay at the first intersection was to be used (figure 21). Most of the participants (89 of 95) indicated the meanings were clear. One participant was confused about which lanes in the intersection were closed. Two others said they were confused by the sight of oncoming traffic in their lanes on the far side of the intersection. Of the six who indicated the signs were unclear, two initially stated that they eventually understood how the red and green symbols related to the operation of the interchange.

The second question related to the red-X and green-arrow CMS asked, “Would you change to the lane under the green arrow if there was more traffic in your lane?” Most participants (86 of 95) said they would.

When participants were asked, “Is the meaning of these signs clear?” 89 of 95 said the red-X CMS was clear. Two participants commented that the red-X CMS and the pavement marking in the left-turn bay gave contradictory messages; the pavement marking “495 South” suggested to them that they should use that lane while the red-X CMS indicated they should not.

Source: FHWA.

A. Green-arrow CMS over the left-turn bay, indicating it is open to traffic.

Source: FHWA.

B. Red-X CMS over the left-turn bay, indicating it is closed to traffic.

Figure 21. Illustrations. Green-arrow CMS versus red-X CMS over the left-turn bay.

Of 95 participants, 90 understood the peak-period signs at the first intersection (figure 22). Two participants said they were confused by the no-left-turn sign adjacent to the navigational sign. To two participants, the stop bar for the two receiving lanes at the far side of the intersection seemed to contradict the overhead signs.

Source: FHWA.

A. Overhead signs at the first intersection.

Source: FHWA.

B. Participant's point of view from the stop bar of the first intersection.

Figure 22. Illustrations. Peak-period signs at the first intersection.

Participants indicated poorer comprehension of off-peak-period signs (figure 23) than peak-period signs; 8 of 95 participants found them difficult to understand. Four participants said they were not sure which lanes were closed. Others were confused by the far-side stop bar or seeing oncoming traffic in their lane while waiting for the green light.

Source: FHWA.

A. Overhead signs at the first intersection.

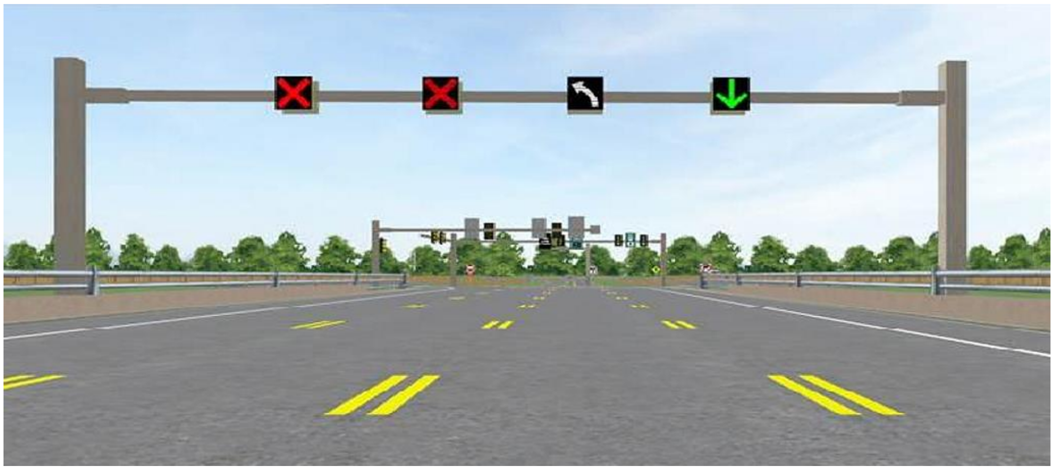
Source: FHWA.

B. Participant’s point of view from the stop bar of the first intersection.

Figure 23. Illustrations. Off-peak-period signs at the first intersection.

Between the first and second intersections of the DRLT interchange, 90 of 95 participants understood the markings and peak-period signs (figure 14). One participant asked what the yellow, dashed double lines meant. Another was confused by the red-X CMS over the far-left lane. One participant thought the white overhead turn-lane indications should be green-arrow CMSs.

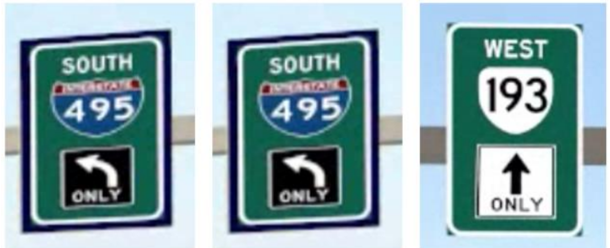
Of 95 participants, 90 also understood the markings and off-peak-period signs (figure 24). The remaining 5 participants questioned whether the red-X CMS was the best choice to mark the closed lane.



Source: FHWA.

Figure 24. Illustration. Off-peak-period signs between the first and second intersections.

When asked if they understood the peak-period signs at the second intersection (figure 25), 88 of 95 participants indicated they did. The yellow, dotted line intended to guide off-ramp traffic confused one participant. The "Do Not Enter" sign confused three participants. One participant thought there were too many signs. Other comments were not specific as to the sources of misunderstanding.



Source: FHWA.

A. Peak-period signs at the second intersection.

Source: FHWA.

B. Peak-period sign configuration at the second intersection.

Figure 25. Illustrations. Second intersection during peak period.

Of 95 participants, 93 also indicated they understood the off-peak-period signs at the second intersection (figure 26). These signs would only be displayed to drivers who exited the freeway at the first intersection. Left turns (i.e., returns to the freeway in the opposite direction) were prohibited so that the two opposing reversible lanes could operate during this movement. All 95 participants indicated they understood the pull-through sign for SR 193 East.

Source: FHWA.

A. Off-peak-period signs at the second intersection.

Source: FHWA.

B. Off-peak-period sign configuration at the second intersection.

Figure 26. Illustrations. Second intersection during off-peak period.

DISCUSSION

Overall, driver performance in the DRLT interchange was acceptable. Participants used all the available lanes and indicated in the post-task questionnaire that they would use the turn bay and leftmost reversible lane when it had the shortest queue. The researchers' main safety concern was the number of lane changes after participants arrived at the first intersection in the correct lane. When participants saw opposing traffic in the receiving lane on the far side of the intersection, the probability of making a lane change to the right within the intersection itself was 0.15. Because no vehicles were to the right of participants, this probability is higher than what is likely in a real-world environment; the friction of other traffic would probably reduce the propensity to change lanes as soon as the traffic signal turns green, and during peak periods, traffic would almost always be present. Furthermore, when participants were following other vehicles through the first intersection, the probability of a lane change in the intersection was close to 0. Nonetheless, the results suggest that some drivers will be intimidated, at least initially, by the sight of opposing traffic using their intended lane. Informational signs in advance of the intersection and perhaps at the stop bar (such as those used at time-of-day-controlled reversible lanes) might reduce the risk of driver confusion or intimidation. After some initial confusion, all participants adapted to the DRLT-interchange design so that the probability of lane change dropped to near 0.

Physical guides, such as low-profile raised curbs mounted along reversible-lane markers, may help to deter unnecessary lane changes. Additional lane markings that guide participants from DRLT lanes into their respective lane destinations may also reassure drivers that they are in the correct lane. Participants reported confusion related to the "This Lane Closed" sign when the reversible lane was not in operation. In the CLT study reported in chapter 3, this TCD was replaced with a blank CMS that was preceded by an advanced signal showing a red-X CMS over the contraflow lane. The results of the CLT study may illuminate whether a blank CMS eliminates the confusion reported in the DRLT study while efficiently informing drivers of useable lanes.

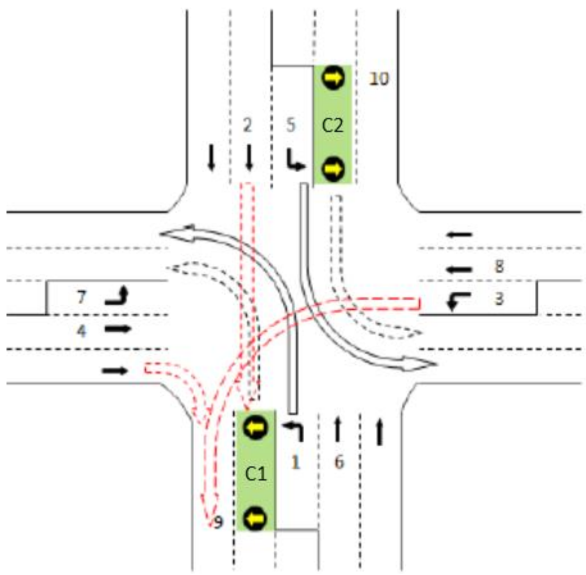
In addition to the sight of opposing traffic in their lane, at least two participants indicated they were bothered by the stop bar in their lane on the far side of the intersection. It is not clear if the stop bar influenced participants' lane choices. Researchers should consider options that reduce stop-bar visibility for drivers to whom that stop bar is not applicable.

The probability of at least one lane change between the two intersections was high, even in the off-peak period. Because the probability of any driver making more than one lane change between the intersections was low and the presence of traffic would likely reduce the actual number of lane changes, this phenomenon would likely be rare once drivers adapt to DRLT intersections. Note that, although the first three DRLT trials were used to assess the novelty effect, some drivers did not see opposing traffic in their lane in those first three trials due to the counterbalancing of trial conditions, which resulted because later trials included novel conditions.

CHAPTER 3. DRIVING SIMULATOR STUDY OF A CLT INTERSECTION

INTRODUCTION

The CLT-intersection design was introduced at the 2016 Transportation Research Board Annual Meeting by Hale et al.(9) The design concept, illustrated in figure 27, uses an opposing through lane to potentially double the queue space for left turns while minimizing or eliminating potential left-turn queue spillback. The treatment is intended for intersections with heavy left-turn demand, particularly where the existing left-turn lane spills back into through lanes during peak periods. In China, CLT intersections have been tested in a driving simulator and implemented on real roads.(10) However, safety performance requires further documentation, and human-factors concerns still need to be addressed.



Modified from FHWA.(9)

Figure 27. Diagram. Concept for the CLT-intersection design in which the highlighted left-turn lanes are shared with the opposing through movement.(9)

Hausknecht et al. describe computational methods for dynamically reversing through lanes at intersections.(11) They demonstrate, with modeling, throughput improvements of more than 70 percent under certain unbalanced flow conditions. However, the authors assume that benefits this large will await automated-vehicle developments because human error, such as unnecessary lane changes, may limit throughput benefits. The current effort was intended to support CLT-lane deployment by recommending design guidance based on human factors to minimize human error.

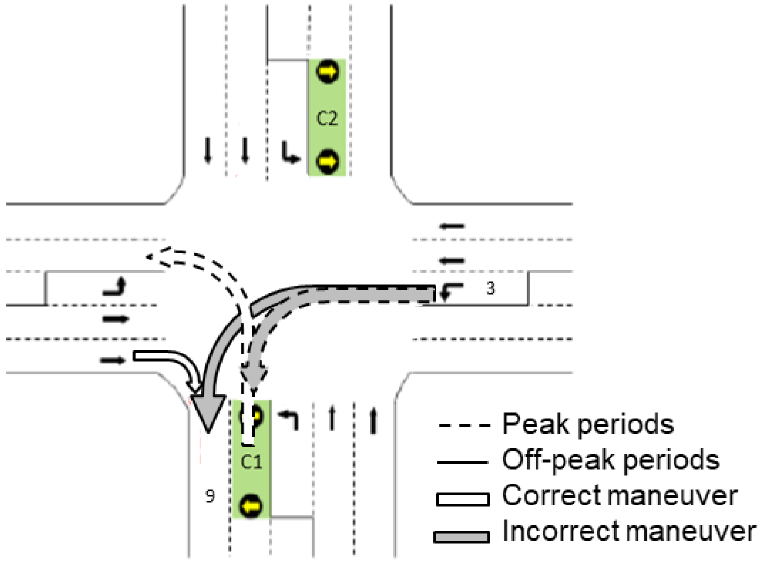
BACKGROUND

Although there have been no CLT intersections implemented in North America, there has been considerable experience with the more general case of reversible lanes. Agent and Clarke reported on a reversible-lane project in Lexington, KY (figure 28).(12) The relevant feature of that project is that it allowed left turns from reversible lanes. At intersections, this allowance requires a shifting of traffic signals. Blank-out signals (figure 29) were used for lane control. The biggest problem occurred at the terminals of the reversible-lane section where three lanes reduced to two. At those terminals, drivers in the rightmost lane were required to turn right at the terminal intersection, and the remaining two inner lanes were then shifted slightly to the right. However, many drivers who were required to turn right continued straight, causing a bottleneck and conflicts with vehicles in the left through lane. Some drivers in the reversible lane proceeded into oncoming traffic. Some drivers attempted to turn left from the middle lane, as was appropriate during off-peak periods. In this case, the reversible lane served as a two-way left-turn lane between intersections and a left-turn-only lane at five intersections. At the time the report was written, officials were trying to mitigate problems with additional signs; the reversible lanes appear to remain in operation at the time of this current report. The blank-out signals used in this installation are not compliant with the MUTCD and therefore were not an option for simulation in the current study.[8]

Figure 28. Map. Overhead view of reversible lanes at the intersection of Nicholasville Road and Southland Drive, Lexington, KY.

Figure 29. Map. Street view of a blank-out signal used to control a reversible lane on Nicholasville Road, Lexington, KY.

Wolshon and Lambert authored a Transportation Research Board synthesis that provided an extensive summary of reversible-lane experience in the United States.(13) Their document contains chapters on design, management, assessment, and the state of practice at the turn of the millennium. The safety assessment in that report was generally favorable of reversible lanes in that, at most locations, the crash rates were about the same as for other roadways of the same width. Crashes tended to increase when reversible lanes were first put into use. The biggest source of crashes appeared to be drivers who made left turns where they were prohibited and left turns from the incorrect lane (i.e., the lane from which a left turn was legal during off-peak periods, but not when the lane to the left was reversed). A driver-error problem observed at some reversible-lane installations was turning left into the wrong receiving lane from the cross street. This type of error may have two sources of confusion. One source of confusion could be the additional lanes that must be crossed when the contraflow lane is in operation, such as a left turn from location 3 into C1 instead of location 9 in figure 30. Similarly, during off-peak periods when C1 is a proper receiving lane, drivers might turn from location 3 to location 9 due to their experience during contraflow operations, and then collide with a right-turning vehicle whose driver expected the left turn to go to C1.



Modified from FHWA.[9]

Figure 30. Diagram. CLT intersection during peak and off-peak periods.[9]

Dey et al. reported on reversible lanes in Washington, DC, which has been using reversible lanes for more than 30 yr.[14] They compared crash rates during reverse-flow operations with those during off-peak periods and found that the rates were about the same, which suggested reverse-flow operations were not a problem. However, when they compared similar corridors without reversible lanes, the findings suggested that crash rates were higher than expected in reverse-flow corridors. Also, the frequency of head-on and side-swipe crashes was higher during peak periods, and these crashes were said to be associated with wrong-way incursions. Perhaps confounding Dey et al.'s peak-versus-off-peak-period comparisons was that on-street parking was banned during peak periods but allowed during off-peak periods.

Conflicts with parked vehicles are known to contribute to crashes such that off-peak-period crash rates may be inflated relative to peak-period crash rates for reasons not associated with reverse-flow operations.[15] A unique problem for reversible lanes of any type in Washington, DC, is that architectural regulations ban the use of overhead TCDs, so all reversible-lane signs are post-mounted, and lane-control signals are not feasible. This limitation means reversible-lane TCDs in Washington, DC, do not comply with MUTCD standards as the MUTCD specifies that post-mounted signs may only be used as supplements to overhead signs. The high rates of wrong-way incursions into reversible lanes observed by Dey et al. may be largely attributable to this restriction.[14]

The challenge of achieving adequate and efficient signs at intersections has been observed at other locations as well. Knoblauch et al. reported that drivers may become confused when lane-control signals are installed near traffic signals.[1] On Georgia Avenue in Montgomery County, MD, three sets of lane-control signs were removed to reduce driver confusion at intersections. Based on field observation, Knoblauch et al. suspected that similar confusion occurred at a reversible-lane installation in Manchester, ME. This issue may need to be addressed in CLT intersections. Forbes et al. reported what appears to be the earliest laboratory and field research into the effectiveness of various lane-control signals.[16] The authors found that the red-X CMS was most effective at communicating a closed lane when compared to other symbols they tested, which were often misunderstood as a "stop" indication. They also found that green, upward-pointing arrows were most effective at communicating that reverse-flow lanes were open. It does not appear that the authors tested a green, downward-pointing arrow.

METHOD

For this study, the intersection of Rockville Pike and Tuckerman Lane in North Bethesda, MD, (figure 31) was modeled using FHWA's Highway Driving Simulator.

Rockville Pike has three through lanes in each direction and one left-turn lane in each direction. The southbound approach has a dedicated right-turn lane with a pork-chop island. The northbound approach does not have a dedicated right-turn lane. Tuckerman Lane has two through lanes in each direction, as well as dedicated left- and right-turn lanes that are not relevant to the current project.

Figure 31. Map. Current configuration of the intersection of Rockville Pike and Tuckerman Lane, North Bethesda, MD.

Participants

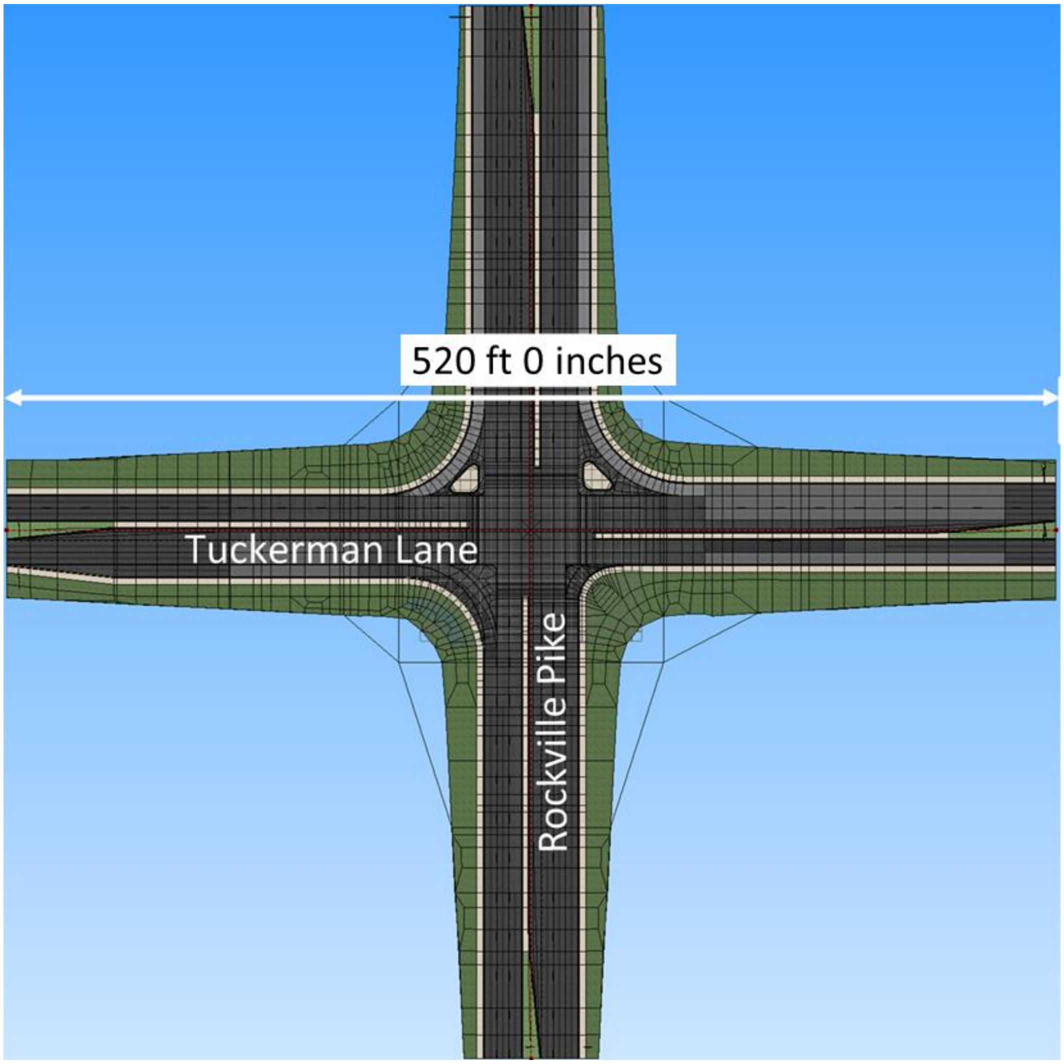
Participants were licensed drivers from the Washington, DC, metropolitan area. Of 107 recruited participants, 96 provided useable data. Of the remaining 11, 10 dropped out due to simulator sickness, and data from 1 participant were lost due to a simulator failure. All participants were tested to ensure they had a binocular visual acuity of 20/40 or better. The useable dataset contained an equal number of males and females, and each sex contained an equal number of participants less than 47 yr of age and 47 yr of age or greater. All participants had previously completed at least one simulated-driving experiment without experiencing significant simulator sickness.

Research Design

Two simulated versions of the same intersection were developed: a conventional design loosely based on the existing intersection of Rockville Pike and Tuckerman Lane and a modified version of that intersection that incorporated a CLT lane. The conventional design was intended to serve as a control for comparison to driver performance in the CLT design.

Geometric Design

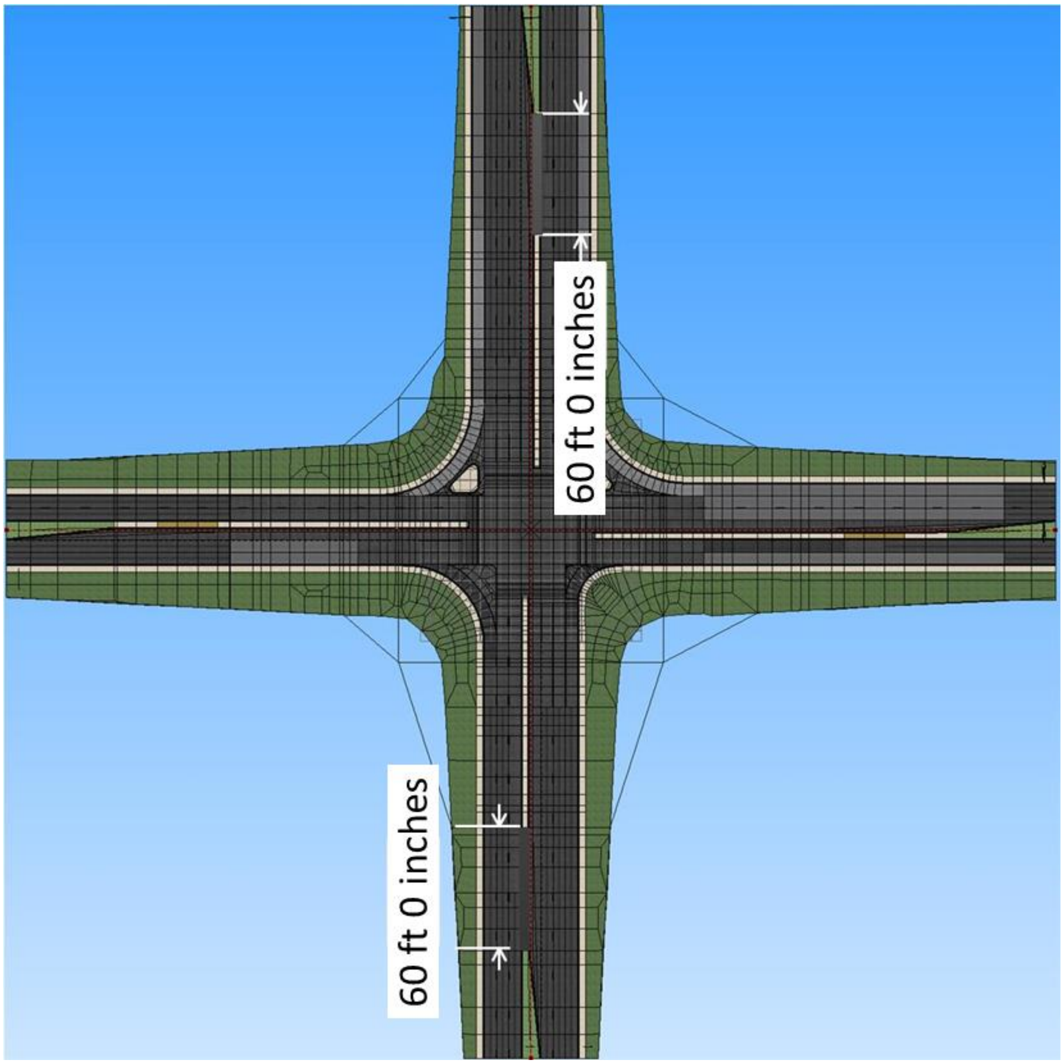
The geometry of the conventional intersection (control) is shown in figure 32. The curves and elevation changes in the existing intersection were removed from the simulated design to facilitate seamless transitions from one approach to the next. Because participants would drive through the same intersection multiple times, the simulated intersection was designed so that copies of the intersection design could be placed end-to-end or side-to-side to create the order of trials to which participants were exposed.



Source: FHWA.

Figure 32. Illustration. Geometric design of a conventional intersection.

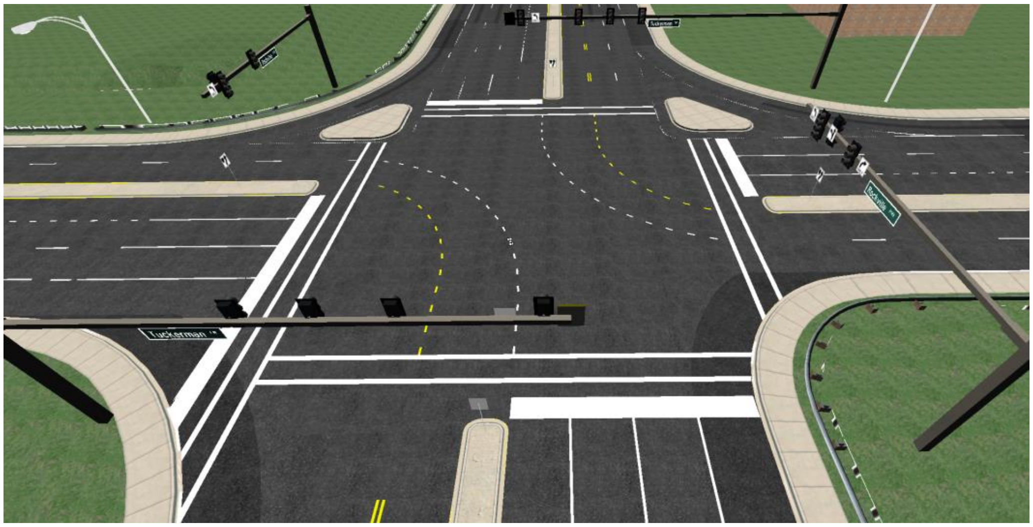
The geometry of the CLT intersection is shown in figure 33. The only change between the geometry of the conventional and CLT intersections is the addition of a gap in the median of the conventional intersection to accommodate entry into the CLT lane.



Source: FHWA.

Figure 33. Illustration. Geometric design of a CLT intersection.

Lane markings informed by results of the DRLT study described in chapter 4 were used to augment the flow of traffic through the CLT intersection. An overhead view of the CLT configuration illustrating lane markings is shown in figure 34.



Source: FHWA.

Figure 34. Illustration. Configuration of CLT intersection showing lane markings aligned with geometry.

Signs

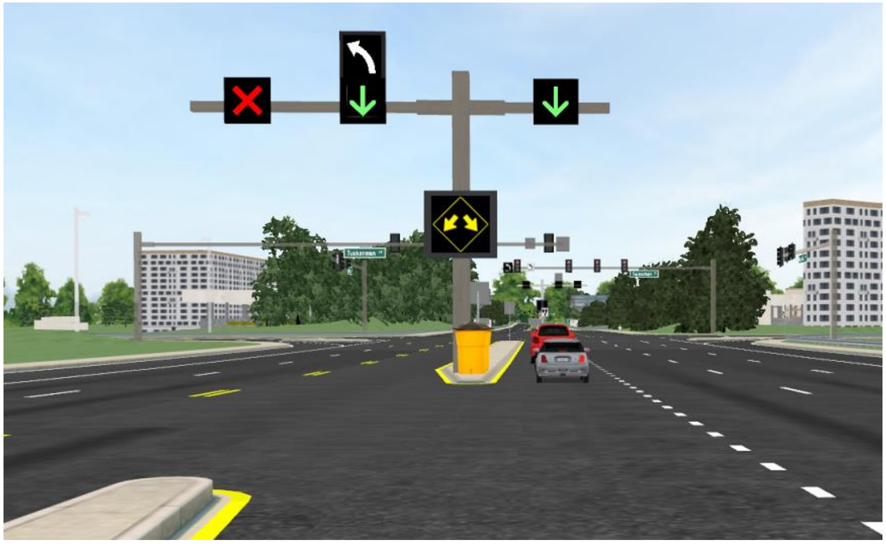
Where appropriate, signs (e.g., bus stop, trailblazer, street name, and speed limit) present near the actual intersection of Rockville Pike and Tuckerman Lane were used in the simulation. The following descriptions of signs focus on those that were necessary to the experiment and guided participants making through and left-turn movements at the intersection.

The first sign intended to control participant movements was located on the approach to the intersection. A guide sign placed in the median indicated the Strathmore Music Center was at the next left (figure 35). This sign was located on both Rockville Pike approaches. When participants were instructed to "follow the signs to the Strathmore Music Center," they were to make a left turn at the intersection.

Source: FHWA.

Figure 35. Illustration. Advance guide sign.

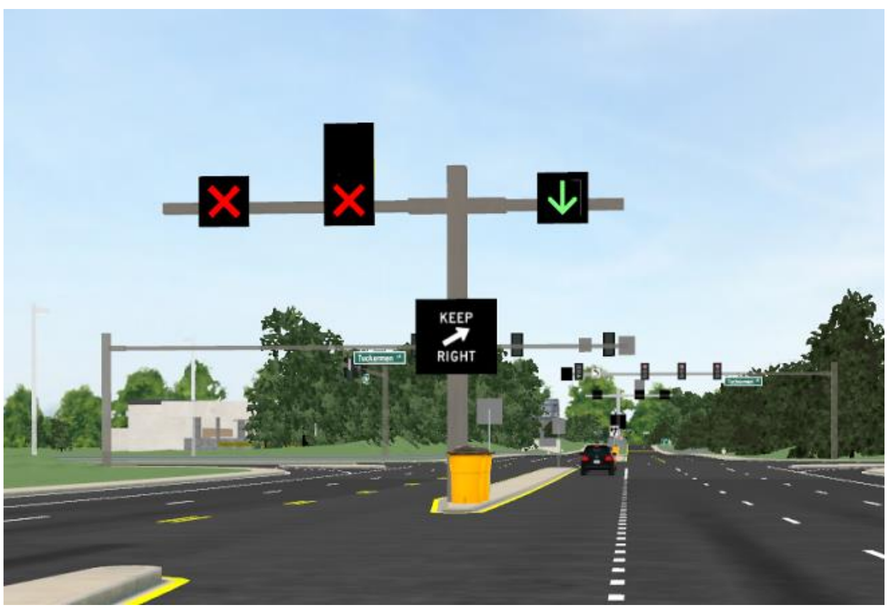
The sign configuration—located on the median just downstream of the median opening—shown in figure 36 was used during peak-period operations. All signs appeared in positive contrast. A red-X CMS over the lane adjacent to the CLT lane was required per the MUTCD. Green, downward-pointing arrows were displayed over the nonreversible left-turn and CLT lanes via CMSs. An MUTCD R3-5 sign (i.e., left-turn-only arrow) was displayed on a CMS over the CLT lane. The CMS on the vertical median post displayed an electronic MUTCD W12-1 sign (i.e., two symmetrical, yellow arrows, each pointing downward at a 45-degree angle).



Source: FHWA.

Figure 36. Illustration. Configuration of signs at the entrance to the CLT lane when open.

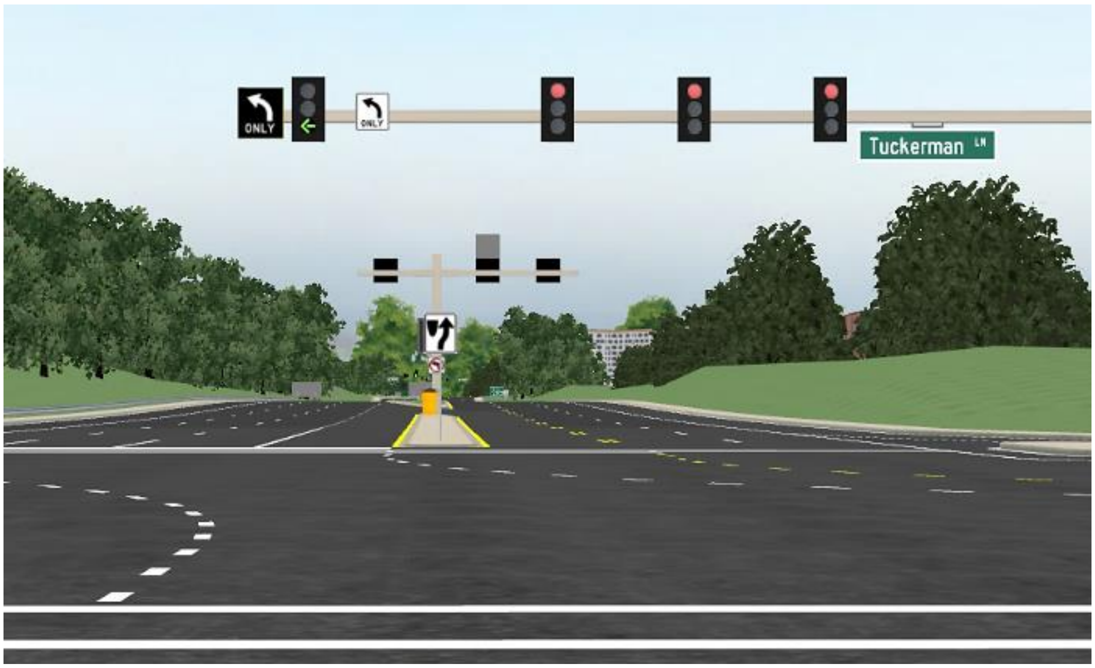
The sign configuration at the median opening when the CLT lane was not in operation is shown in figure 37. All signs appeared in positive contrast. A red-X CMS was displayed over the CLT lane. The CMS on the vertical median post displayed an electronic MUTCD R4-7b sign (i.e., an arrow pointing upward at a 45-degree angle to the right and the words "KEEP RIGHT"). A green, downward-pointing arrow CMS was displayed over the nonreversible left-turn lane.



Source: FHWA.

Figure 37. Illustration. Configuration of signs at the entrance to the CLT lane when closed.

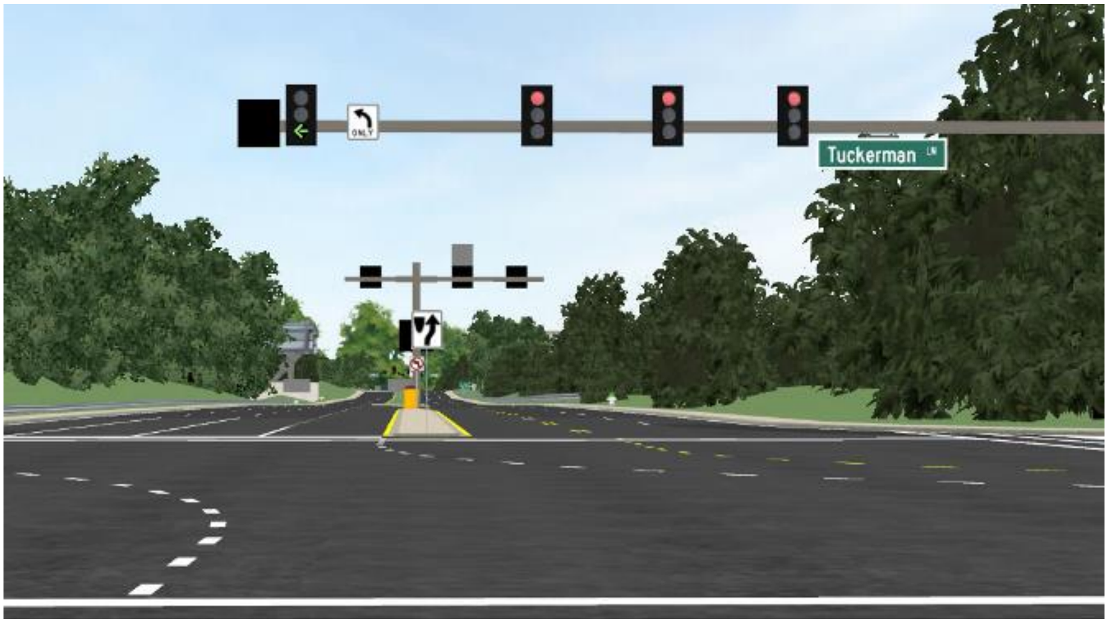
Figure 38 shows the TCD configuration for the main intersection where the contraflow design was employed. A CMS was aligned with the center of the CLT lane and displayed a positive-contrast R3-5 sign. The left-turn signal head was aligned with the center of the median adjacent to the turning lanes and served as the signal for both the left-turn and CLT lanes. A static negative-contrast R3-5 sign was aligned with the left side of the left-turn lane. White dotted lines were used to guide drivers into the correct receiving lane. Note that, because drivers originating from the left-turn lane were guided into the right receiving lane, this required either a no-right-turn-on-red restriction or a right-turn merge lane for opposing right-turn traffic.



Source: FHWA.

Figure 38. Illustration. Configuration of signs and TCDs at the main intersection when the CLT lane was open.

Figure 39 shows the TCD configuration for periods when the CLT lane was not in use. The only difference from the configuration shown in figure 38 was the change of the positive-contrast R3-5 sign to a blank CMS.



Source: FHWA.

Figure 39. Illustration. Configuration of signs and TCDs at the main intersection when the CLT lane was closed.

Both conventional and CLT interchanges were modeled on a square tile of simulated roadway that measured 0.53 mi on each side. Within the driving scenario, tiles were placed such that the order of conditions would be unaffected if the participant made a navigational error.

Highway Driving Simulator

The same FHWA Highway Driving Simulator used in the DRLT experiment was used to test the CLT intersection design. A six-degrees-of-freedom motion base that included heave, roll, pitch, and yaw motion cues supplemented those provided by the visual system.

Procedure

SSQ

After providing informed consent, participants were asked general health questions to assess their current susceptibility to simulator sickness. This was followed by completion of an initial SSQ. These responses were used as a baseline with which to compare subsequent SSQ administrations.

Driving Scenario

First, participants completed a practice drive on a freeway-like roadway that lasted approximately 10 min. This drive was intended to familiarize participants with the controls and displays of the simulator vehicle. When participants indicated they were comfortable with handling the simulator vehicle, they exited the vehicle and completed a second SSQ. Participants then completed the main experimental drive, which consisted of 18 drives through the CLT and conventional intersections.

Participants first made two left-turn and two through movements at the conventional intersection. They then made 14 trips through the contraflow design, which comprised 12 left turns from Rockville Pike to Tuckerman Lane and 2 through movements. When the experimenter intended for the participant to make a through movement, the participant received the direction, "Starting from the left lane, continue straight through the next intersection." When a left-turn movement was intended, the participant received the direction, "Starting from the left lane, follow the signs to the Strathmore Music Center." During through-movement trials, the participant was always the first vehicle to arrive at the red signal indication, which allowed participants to view traffic turning left from the opposing reversible lane. Table 4 and table 5 enumerate the number of trials per participant.

Table 4. Summary of conventional-intersection trials.

Condition	Instruction	Time of Day	CLT-Lane Status	CLT-Lane Queue	Left-Lane Queue	Vehicle Ahead*	Replications
A	Left	N/A	N/A	N/A	None	No	2
B	Through	N/A	N/A	N/A	None	No	2

*In through lane prior to reaching intersection.
N/A = not applicable.

Table 5. Summary of CLT-intersection trials.

Condition	Instruction	Time of Day	CLT-Lane Status	CLT-Lane Queue	Left-Lane Queue	Vehicle Ahead*	Replications
C	Left	Off-peak	Closed	None	Short	No	2
D	Left	Peak	Transition	Short	Long	Yes**	2
E	Left	Peak	Closed	None	Long	No	2
F	Left	Peak	Open	None	Long	No	2
G	Left	Peak	Open	None	Short	No	2
H	Left	Peak	Open	Long	Long	No	2
I	Through	Peak	Open	Long	Long	No	2

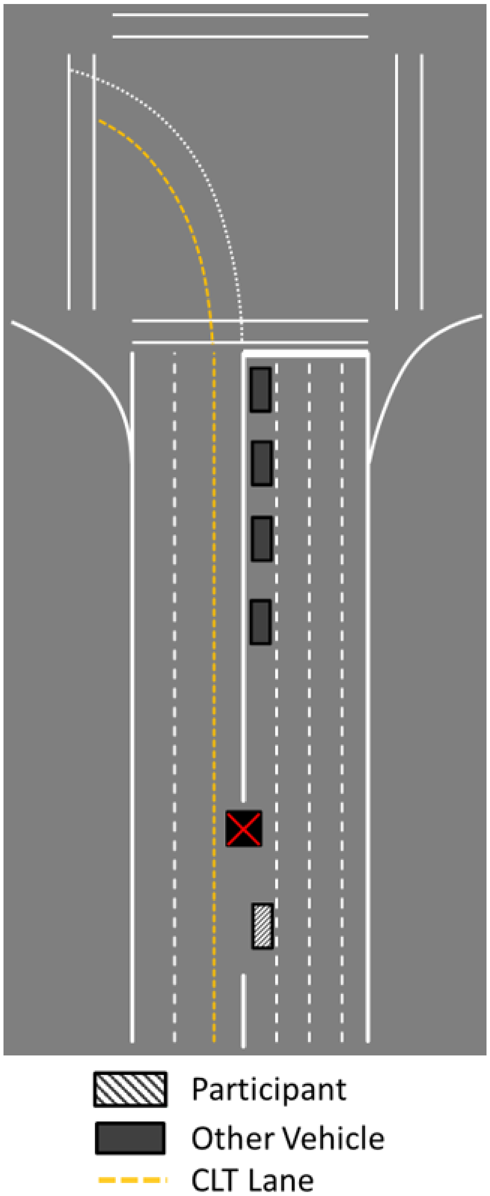
*In through lane prior to reaching intersection.
**Entered CLT lane while reversible lane was transitioning to closed.

Participants drove the four conventional-intersection movements (conditions A and B) first. These movements were followed by one of the through movements (condition I) in the CLT intersection, which was followed by one of the off-peak-period CLT movements (condition C). Movements for conditions D through H followed and were ordered based on one of four group sequences, which were as follows:

- Group 1: D, E, F, G, H.
- Group 2: H, D, E, F, G.
- Group 3: F, G, H, D, E.
- Group 4: E, F, G, H, D.

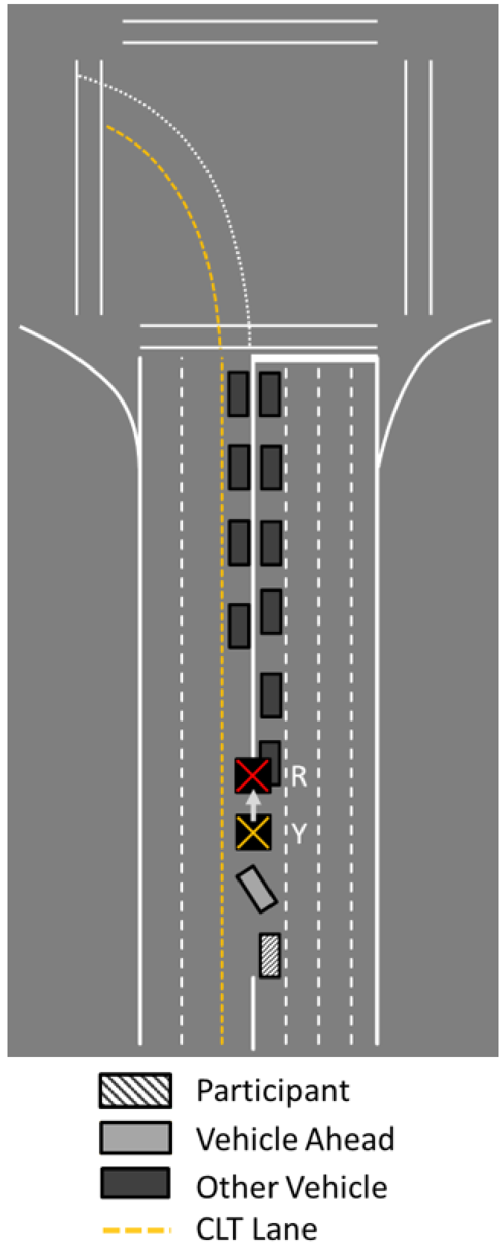
An equal number of participants were assigned to each group sequence to achieve a partial counterbalancing of conditions. After completing one group sequence, participants drove the second of the through movements in the CLT intersection (condition I) and then the second off-peak-period CLT movement (condition C).

Participants then repeated the movements of conditions D–H in the same order as they were first assigned. Figure 40 through figure 46 illustrate each of the CLT-intersection trial conditions.



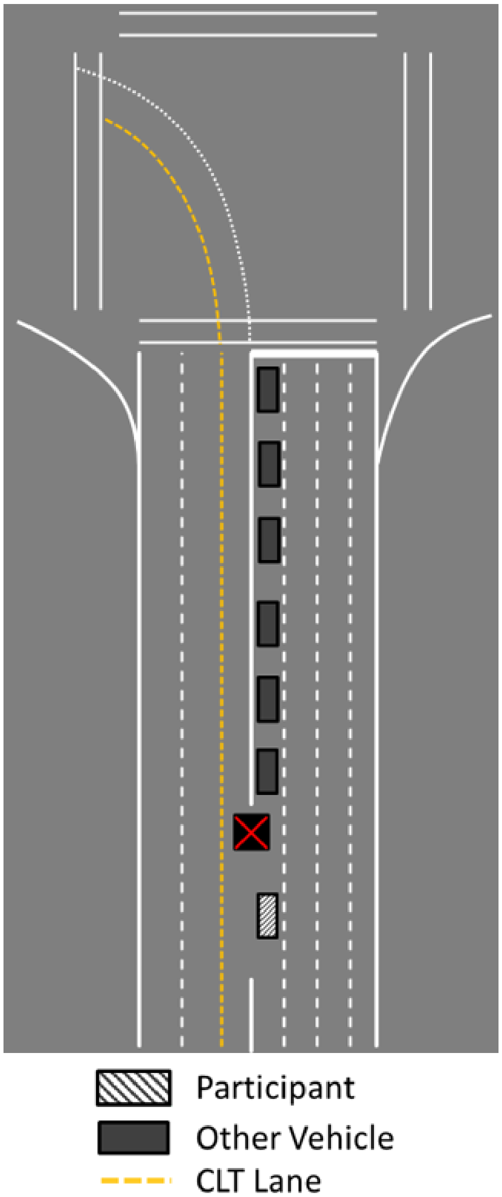
Source: FHWA.

Figure 40. Illustration. CLT intersection, condition C.



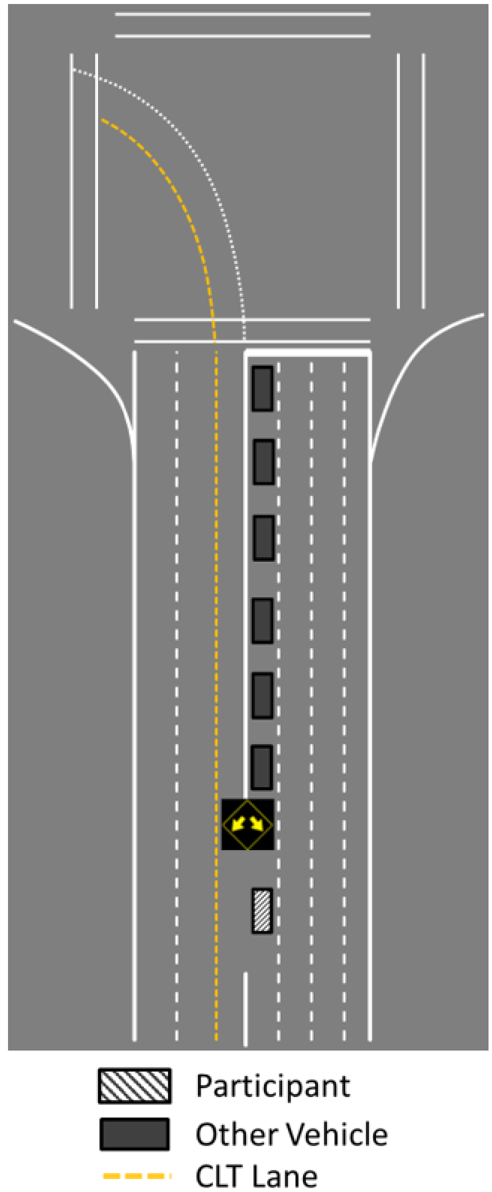
Source: FHWA.
R = red; Y = yellow.

Figure 41. Illustration. CLT intersection, condition D.



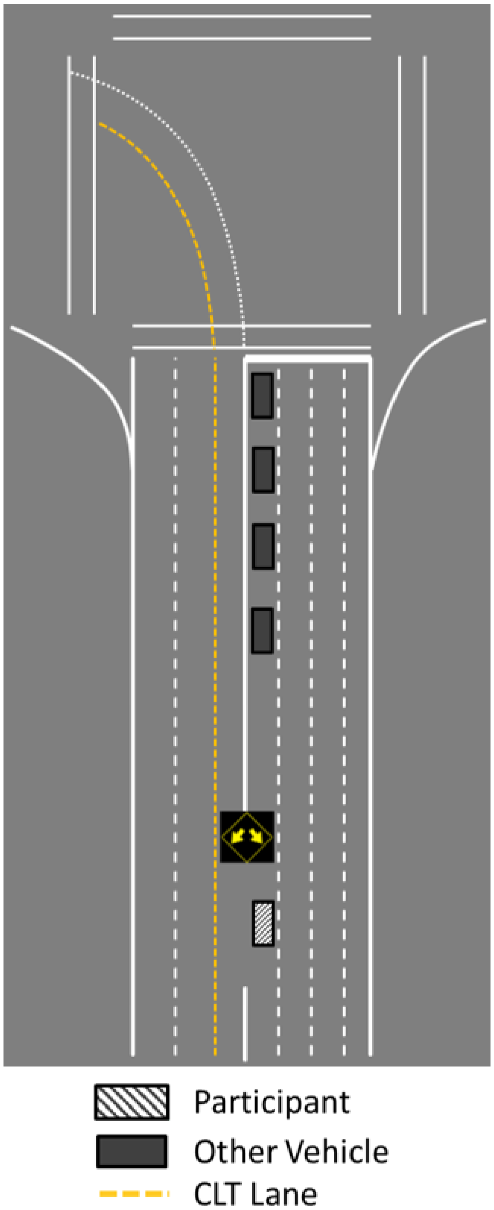
Source: FHWA.

Figure 42. Illustration. CLT intersection, condition E.



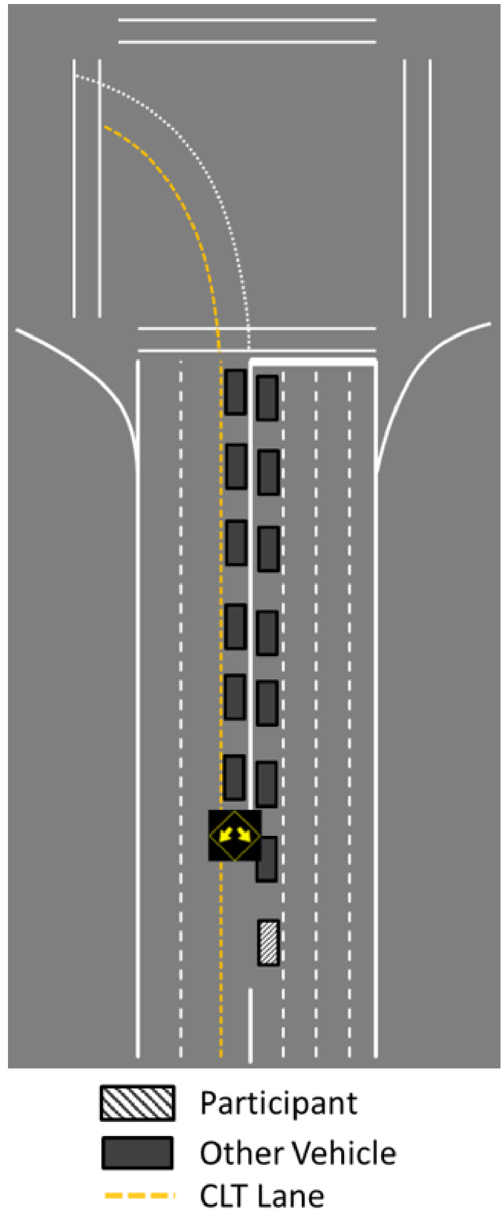
Source: FHWA.

Figure 43. Illustration. CLT intersection, condition F.



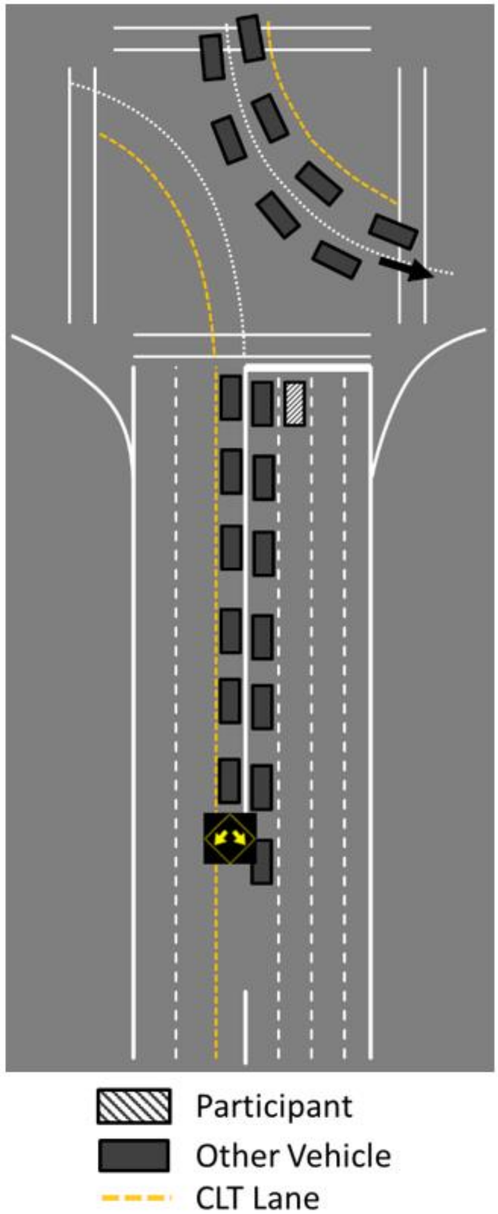
Source: FHWA.

Figure 44. Illustration. CLT intersection, condition G.



Source: FHWA.

Figure 45. Illustration. CLT intersection, condition H.



Source: FHWA.

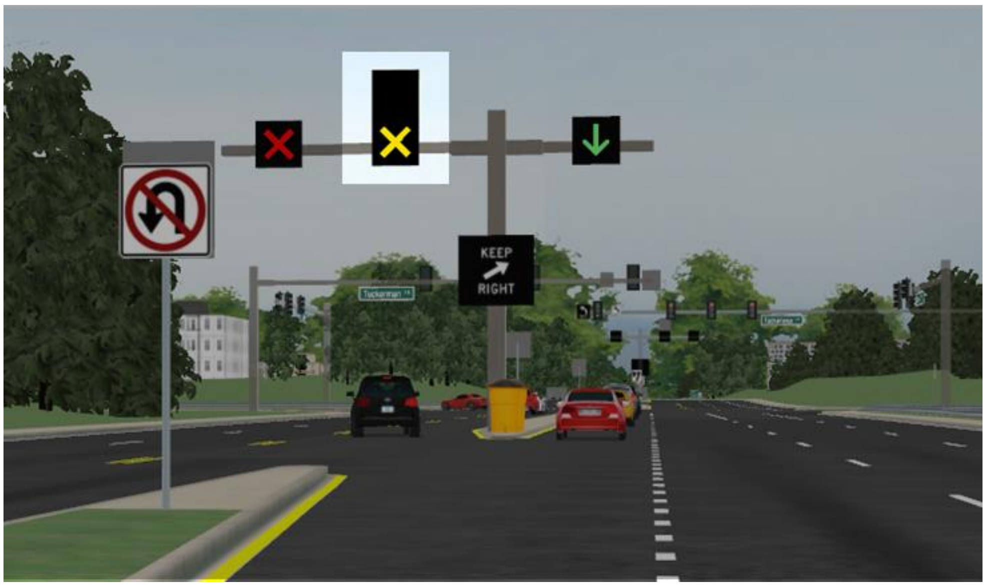
Figure 46. Illustration. CLT intersection, condition I.

After completing the last trial, participants exited the simulator and completed another SSQ.

Post-Task Questionnaire

After the driving simulation was completed, a brief questionnaire was administered to obtain feedback on several components of the experimental scenarios. Participants entered their responses directly into an electronic form. A research assistant provided clarification on survey questions if requested. The survey, which refers to the CLT lane as the "extreme left-turn lane," contained the following questions:

1. Did you find any of the signs or symbols to be confusing? If so, please describe them and explain why they were confusing.
2. What is the meaning of the sign highlighted below? (See figure 47.)
3. What made you want to use the extreme left-turn lane?
4. What made you hesitant about using the extreme left-turn lane?



Source: FHWA.

Figure 47. Illustration. View of the CLT intersection with a yellow-X CMS preceding the closing of the CLT lane as it appeared in the post-task questionnaire.

Hypotheses

It was of interest whether or not participants would use the CLT lane when it was open or closed. The following probabilities were assessed:

- Using the CLT lane when it was advantageous to do so (condition F).
- Using the CLT lane when either left-turn lane would be appropriate (condition H).
- Using the CLT lane when it was closed (conditions C and E).
- Using the CLT lane when it was closed after observing vehicles use the CLT lane when it was open (trials 6 and 13 for all groups).
- Following another vehicle into the CLT lane when it was closed or transitioning to being closed (condition D).
- Using the correct receiving lane for CLT-intersection through movements (condition I).

Other measures of interest included the following:

- Noticeable delay entering the CLT lane when it was open.
- Stopping, swerving, etc., at the entrance to the CLT lane when it was closed.
- Startup delay at the stop bar for CLT-intersection through movements compared to conventional-intersection through movements.
- Failure to clear the CLT lane before the signal phase should have ended (in the simulated scenario, signals remained green indefinitely following a red phase; the time needed to clear the CLT lane was compared to that of the nonreversible left-turn lanes in the CLT intersections).

It was hypothesized that the CLT lane was properly signed and the probability of driver errors would be 0 or close to 0. This simulation was the result of considerable development efforts and was therefore expected to verify a successful development process.

RESULTS

SSQ

The final rate of simulator-sickness incidence resulting in participant dropout was approximately 9 percent. Among participants who completed the study, reported simulator-sickness symptoms were slight; on a weighted scale from 0 to 33.66 points, the mean weighted total SSQ score across study segments was 0.47 points, with a standard deviation of 2.05 points.

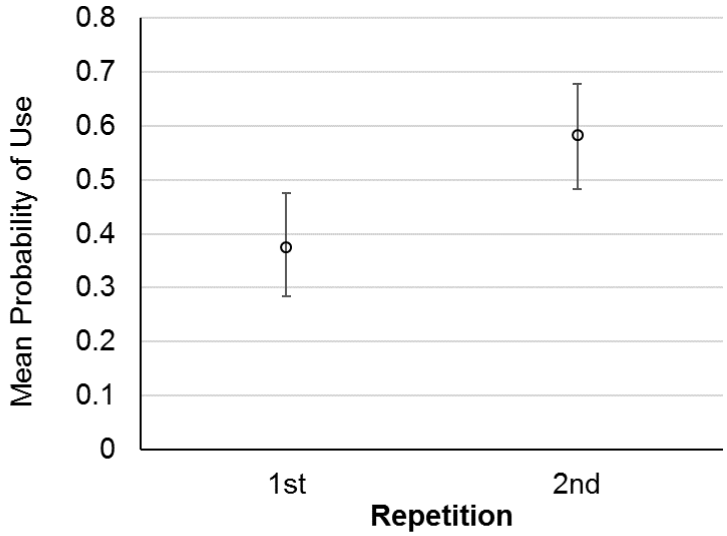
Lane Choice

A GEE model was used to construct the probabilities of binary responses and their respective 95-percent confidence intervals. A binomial distribution with repeated measures and a logit link function were specified. Each factor in the model was analyzed at a 95-percent confidence level using the Wald χ^2 test. Bonferroni correction for multiple comparisons was applied to models testing the effect of a condition group (groups 1–4), which determined the sequence of scenarios encountered. Additional demographic factors included in the analyses were age group and sex.

Shorter Queue in CLT Lane

The average probability of using the empty, open CLT lane when a long queue was present in the conventional left-turn lane (condition F) was 0.48. Age group was not found to have a significant effect on CLT-lane use in this situation, and the model revealed no statistically significant relationship between group condition and CLT-lane use. However, lane use did vary across sex, with males significantly more likely to use the CLT lane than females, Wald $\chi^2(1) = 4.81$, $p = 0.028$. On average, males used the CLT lane in 57 percent of trials compared to females at 38 percent.

Participants were significantly more likely to use the CLT lane the second time they encountered condition F, with a probability of 0.58 versus 0.38, Wald $\chi^2(1) = 8.22$, $p = 0.004$. The effect of the repetition is illustrated in figure 48. No significant interactions between repetition and age group, sex, or condition group were identified.



Source: FHWA.
Note: Error bar represent the 95-percent confidence limits of the mean.

Figure 48. Plot. Mean probability of CLT-lane use as influenced by first or second exposure to condition F.

When the CLT lane was empty and a short queue was present in the nonreversible left-turn lane (condition G), the average probability of using the CLT lane was 0.31. The effects of age group and group condition on CLT-lane use were not significant. Similar to condition F, sex was identified as a significant effect as males used the CLT lane in this situation in 58 percent of trials where females used it in 23 percent, Wald $\chi^2(1) = 4.87$, $p = 0.027$. In condition G, participants were also significantly more likely to use the CLT lane during the second exposure, with a probability of 0.38 versus 0.24, Wald $\chi^2(1) = 4.08$, $p = 0.043$. The analysis revealed no evidence of significant interactions between repetition and age group, sex, or condition group.

Conditions F and G consisted of an empty CLT lane with some vehicles occupying the nonreversible left-turn lane. Therefore, both scenarios may be considered advantageous in favor of the CLT lane. Combined, the average probability of using the CLT lane when the queue in the CLT lane was shorter than in the nonreversible left-turn lane (conditions F and G) was 0.39. Sex was significantly correlated with CLT-lane use, such that males used the CLT lane in 48 percent of trials and females in 31 percent, Wald $\chi^2(1) = 5.82$, $p = 0.016$. Repetition also had a significant effect, with a probability of using the CLT lane of 0.31 in the first exposure and 0.48 in the second, Wald $\chi^2(1) = 11.74$, $p < 0.001$. Condition and age groups did not have a significant effect, and no interactions between repetition and age group, sex, or condition group were found.

Long Queue in Both Turn Lanes

When the CLT lane was open and the queues of vehicles in both the nonreversible and CLT lanes were long (condition H), the average probability of using the CLT lane was 0.31. Use of the CLT lane was not found to vary by age group. However, CLT lane use, again, varied by sex, with males using the CLT lane significantly more often (39 percent of trials) than females (23 percent of trials), Wald $\chi^2(1) = 4.95$, $p = 0.026$. Group condition and repetition were not found to be significant factors in CLT lane use for condition H. No significant interactions between repetition and age group, sex, or condition group were found.

CLT Lane Closed

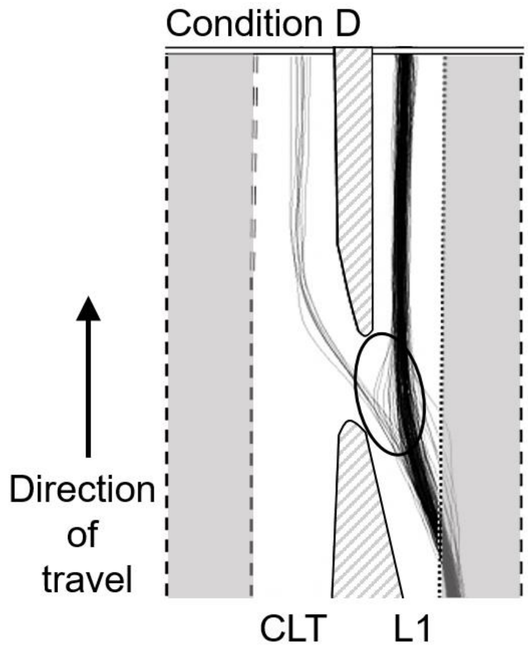
No participants were observed entering the CLT lane when it was closed (conditions C and E). This observation, however, does not include condition D, in which seven participants entered during the red indication while following a vehicle that entered during the yellow indication (see the following section). In condition E, two participants were observed making a left turn from the leftmost through lane.

CLT Lane Transitioning to Closed

Condition D exposed participants to a vehicle entering the CLT lane as it transitioned from open to closed status. During these trials, two participants turned left from the leftmost through lane. Results showed that, out of 192 trials, participants followed the vehicle into the CLT lane a total of 9 times, about a 0.05 probability. The probability of entering the CLT lane in this scenario was not significantly affected by age group, sex, or repetition. Group-condition interactions could not be assessed statistically, and no significant interactions existed between repetition and age group or sex.

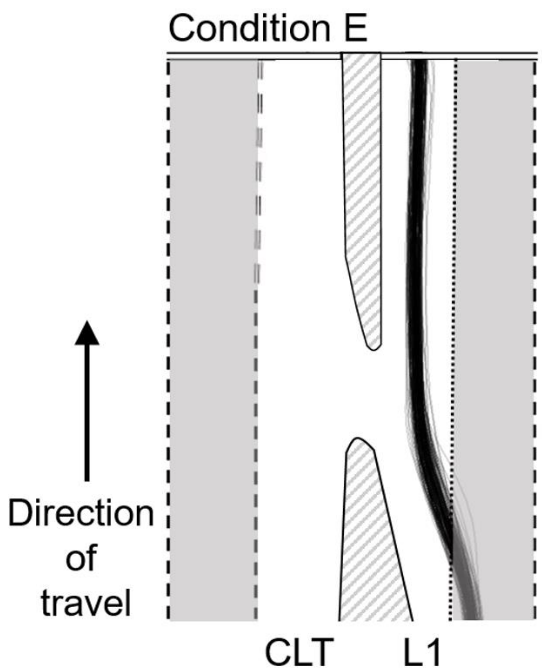
It was notable that the seven participants who entered the CLT lane behind the lead vehicle (two of which entered the closing CLT lane twice) belonged to groups 3 and 4, which exposed participants to three sequential open CLT lanes immediately before the transition scenario. Thus, it is possible that the experimental scenario biased participants' choices to enter the closing CLT lane. The number of participants who entered the CLT lane in this condition was too small to statistically test the hypothesis that this behavior was related to the order of conditions.

Slightly more swerving was observed near the opening of the CLT lane in condition D when the CLT lane was transitioning to closed status compared to condition E when the CLT lane was closed. Figure 49 illustrates the drive paths of all participants in these two conditions.



Source: FHWA.

A. Participant drive paths near the CLT-lane entrance in condition D (CLT lane transitioning to closed); the region of notable swerving near the CLT-lane entrance is circled.



Source: FHWA.

B. Participant drive paths near the CLT-lane entrance in condition E (CLT lane closed).

Figure 49. Illustrations. Participant drive paths for conditions D and E.

Lane Changes

Through Movements

Condition I required participants to come to a stop in the leftmost through lane and wait as two queues of CLT and nonreversible left-turn traffic on the near and far sides of the intersection cleared (figure 46). Prior to arriving at the stop bar, participants were instructed to continue straight through to the next intersection. If participants drove through the intersection as intended by the design, they would travel through the lane that was previously used by opposing CLT-lane traffic after receiving the green indication.

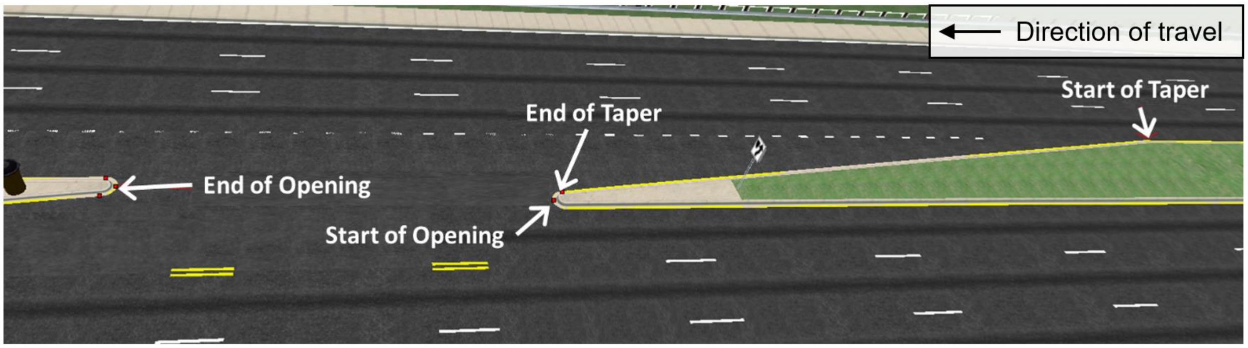
Participants were considered to be following instructions if their executed maneuver (left-turn or through movement) matched the intended maneuver as provided in figure 35, regardless of the lane from which the maneuver was made. Twelve trials in which participants did not follow instructions were removed from the dataset prior to conducting the analysis of through-movement conditions B and I. The analysis contained a total of 180 trials.

In nine of the retained cases (5 percent of trials), drivers did not remain in their starting lane through the intersection. The probability of changing lanes did not vary by age group, sex, or repetition. No significant interactions were found between repetition and age group or sex, and interactions with group condition could not be analyzed due to the small sample of trials in each interaction.

Performance in the CLT intersection (condition I) was compared to that of its conventional counterpart (condition B) to identify variations in lane-change behavior related to intersection design. Among CLT- and conventional-intersection scenarios, 27 out of 384 trials were removed prior to the analysis due to participants' failure to follow instructions (turning left instead of continuing straight). During conventional-intersection through movements, participants remained in the leftmost travel lane through the intersection in all but 1 of 177 trials. The difference between the probability of remaining in the same lane through the CLT intersection (0.95) and conventional intersection (0.99) was statistically significant, Wald $\chi^2(1) = 4.78$, $p = 0.029$. However, given the small number of cases in which drivers did not remain in their starting lane, this test reflects marginal validity and primarily serves to describe the behavior of participants in this particular study.

Time Performance

The reference points illustrated in figure 50 were used to determine delays in entering and traveling within the CLT lane. Note that the time measures discussed in this section are influenced by the amount of traffic present in either left-turn lane on a given condition. This makes direct comparisons between conventional and CLT lanes problematic due to conventional trials being modeled only for off-peak-period conditions.



Source: FHWA.

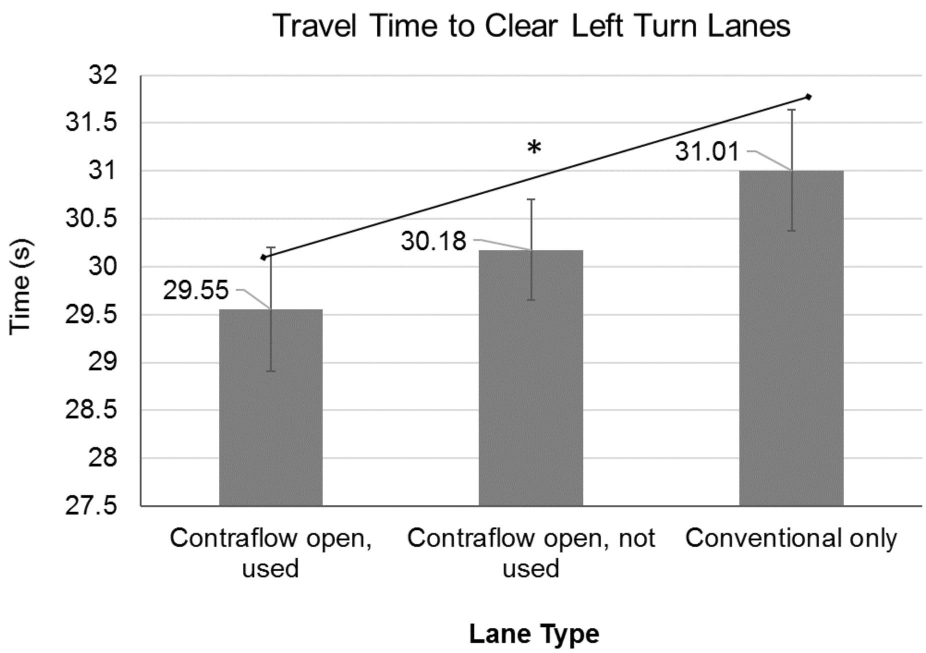
Figure 50. Illustration. Overhead view of the CLT-lane opening with relevant reference points.

Startup Delay

The time between a green signal phase and the continuation of driving in through-movement scenarios after participants observed opposing traffic completing a CLT maneuver was of interest. Results showed that participants were slower to press the accelerator pedal following a green signal in the CLT-intersection through-movement condition (condition I) than in the conventional-intersection through-movement scenario (condition B), Wald $\chi^2(1) = 32.57$, $p < 0.0001$. There was an average acceleration delay of 1.35 s over both exposures to the CLT-intersection condition, in contrast to the average acceleration delay of 0.74 s over both conventional-intersection through movements. The pattern was similar for brake release, with drivers in the CLT-intersection trials releasing the brake later, 0.80 s after the signal turned green, compared to 0.38 s in the conventional-intersection trials, Wald $\chi^2(1) = 33.90$, $p < 0.0001$. There was no significant difference between the first and second exposures. Age group and sex did not have a significant effect on startup delay.

Travel Time Through Intersection

Travel time from the near stop bar to the beginning of the receiving lane at the far side of the intersection was used to measure the time needed to clear the turn lanes. When the CLT lane was open and available, average travel time for drivers in the CLT lane (29.55 s) was slightly faster than that of drivers who chose to use the nonreversible left-turn lane (30.18 s). This difference was not statistically significant and may be explained by the slightly sharper turning radius of the CLT lane, resulting in a slightly shorter travel distance than that of the nonreversible lane. However, when CLT-lane travel time was compared to left-turn-lane travel time in the conventional-intersection left-turn scenario (condition A), travel time for CLT-lane users was significantly shorter than that of conventional-intersection left-turn-lane users (31.01 s), Wald $\chi^2(1) = 24.91$, $p < 0.0001$. This effect was observed despite the presence of a long queue in one of the CLT-intersection scenarios (condition H). A graphical comparison of travel time for the three lane types is provided in figure 51.



Source: FHWA.
*Significant comparison between the conditions connected by the diagonal line.
Note: Error bar represent the 95-percent confidence limits of the mean.

Figure 51. Graph. Comparison of travel time needed to clear the left-turn lane in CLT and conventional intersections.

Post-Task Questionnaire

Responses to the post-task questionnaire were categorized into discrete groups based on content. Each of the following sections includes a table with a summary of response types and frequency for the four survey questions. When responses fell into multiple categories, they were placed into the category that appeared most strongly emphasized.

Question 1: Did You Find Any of the Signs or Symbols to be Confusing?

Overall, approximately 31 percent of participants indicated they found at least one sign or symbol confusing (table 6). Although the question specified signs or symbols, some participants appeared to consider various aspects of the experimental scenario when answering, including navigational instructions, signal timing, and distance from the assigned fictional destination—these responses were grouped into an “Other” category. Within the “Other” category, one participant mentioned confusion at seeing cars on the opposite side of the intersection occupying the same lane as their own.

Table 6. Response categories for question 1 of the post-task questionnaire.

Response Category	Number of Participant Responses
Yes	30
No	66
Keep Right (R4-7b)	6
Yellow X	3
Double Arrows (W12-1)	2
Other	7
Unspecified	12

Of the signs and symbols found confusing, the sign instructing participants to keep right of the median at the closed CLT-lane opening was most commonly mentioned (20 percent of responses). This sign is shown in figure 37 as it appeared in the driving simulation. The positive-contrast W12-1 sign above the median (figure 36) was unclear to 6 percent of respondents. A large portion of responses (40 percent) did not clearly specify the signs or symbols that participants found confusing. The third part of question 1, which requested an explanation for the confusion, was not categorized.

Question 2: What Is the Meaning of the Highlighted Sign Below?

The second survey question asked participants to explain the meaning of the yellow-X CMS shown in figure 47. It was of interest whether participants understood this sign as signaling the transition of the CLT lane to a closed status. Results showed that nearly 18 percent of respondents correctly described the signal as indicating that the CLT lane was transitioning from open to closed (table 7). An additional 25 percent understood that the lane was closed or that they should not enter it at that time. Finally, nearly 42 percent perceived the message to indicate some form of caution regarding the CLT lane.

Table 7. Response categories for question 2 of the post-task questionnaire.

Response Category	Number of Participant Responses
Caution	40
Lane closed/do not enter	24
Lane closing	17
Other	12
Unclear	3
Confident	88
Unsure/confused	8

Responses to question 2 that were categorized as "Other" included when participants stated that the yellow-X CMS instructed drivers to stay in their lane or that the CLT lane was unavailable at that time. Although these meanings appear to be indirectly related to the intended message of the sign, responses were not specific enough to assure that the intended meaning of the yellow-X CMS was adequately understood. Two additional participants provided clearly incorrect responses, stating that the yellow-X CMS signified the CLT lane is or would soon be available for use, with one participant stating that the “sign is about to change to green.”

To assess whether participants were guessing or unsure regarding the meaning of the yellow-X CMS, the level of perceived confidence in the response was evaluated separately. Confidence was assessed based on the presence or absence of phrases indicating that the participant was guessing or uncertain, such as “I think” or “not sure.” Most respondents (92 percent) did not indicate confusion or uncertainty in their answers, independent of their accuracy.

Question 3: What Made You Want to Use the Extreme Left-Turn Lane?

Question 3 was designed to assess the motivations and goals behind participants’ choices to use or avoid the CLT lane. In response to question 3, just under 22 percent of participants expressed no motivation to use the CLT lane (table 8). The amount of traffic in the CLT and nonreversible left-turn lanes was cited as the most common factor influencing a desire to use the CLT lane (55 percent of responses). The amount of responses that referenced traffic can be interpreted to mean that participants were more willing to use the CLT lane when the length of the queue in either lane favored use of the CLT lane. Other motivations in the remaining 23 percent of responses often included curiosity or a desire to try something novel, though one participant noted that they may not be so adventurous in a real-world driving scenario.

Table 8. Response categories for question 3 of the post-task questionnaire.

Response Category	Response	Number of Participant Responses
Motivation	Number of cars	53
Motivation	Other	22
Motivation	N/A	21
Goals	Speed/time	8
Goals	Lane position	4
Goals	Other	8
Goals	N/A	76

N/A = not applicable.

Several responses included a distinct goal component in deciding to use the CLT lane, prompting the definition of a second response category. Of the goals specified, a desire to clear the intersection faster (40 percent of specified responses) or to align with the far-left lane on the opposite side of the intersection (20 percent of specified responses) were most frequent. Several participants explained they were aware that they would be instructed to begin the next maneuver from the left lane once through the intersection and prepared for this by using the turn lane that would place them in the most convenient receiving lane.

Question 4: What Made You Hesitant About Using the Extreme Left-Turn Lane?

Similar to question 3, question 4 was designed to assess the motivations and goals behind participants’ choices to use or avoid the CLT lane. Factors that made participants hesitant to use the CLT lane included unfamiliarity with or confusion caused by the design of the CLT intersection (42 percent; table 9). Notably, several participants described greater confusion during the first exposure to the design than during subsequent exposures. Nearly 12 percent of responses indicated concerns of safety due to unfamiliarity, geometric design, or fear of facing opposing traffic (condition I). About 9 percent felt that using the CLT lane did not provide a meaningful advantage over the nonreversible left-turn lane, leading them to prefer the nonreversible left-turn lane out of convenience and familiarity. Several responses noted difficulty or increased effort in swerving through the median to enter the CLT lane. Others expressed that the turning radius of the CLT lane felt unusually sharp, and they were concerned that their vehicle would collide with adjacent traffic in the nonreversible left-turn lane while completing the turn.

Table 9. Response categories for question 4 of the post-task questionnaire.

Response Category	Number of Participant Responses
Design confusing/unfamiliar	40
Unsafe	11
Number of cars/no advantage	9
Operations unclear	7
Other	18
N/A	11

N/A = not applicable.

DISCUSSION

Signs and Symbols

Behavioral and self-reported data from the post-task questionnaire suggest that the signs used in the scenario served their intended purpose and were moderately well comprehended by participants. Drivers appeared to understand the signs and symbols that indicated when the CLT lane was open or closed, as evidenced by the complete lack of participants who attempted to enter the lane during off-peak-period trials, even after exposure to an open CLT lane. Although survey responses indicated some confusion regarding the meaning of the yellow-X CMS, a small proportion of participants were observed attempting to enter the CLT lane during its transition to a closed status.

The R4-7b CMS located above the center median when the CLT lane was closed was reported to be confusing for a notable number of participants. Several participants stated that the instructions to remain in the left lane and make a left turn at the intersection conflicted with their understanding of the sign that instructed them to “keep right.” These responses suggest that participant confusion may have been influenced by the instructions provided during the experiment. No participants were observed attempting to enter the closed CLT lane in the CLT experiment. Therefore, the R4-7b CMS, in combination with the overhead red-X and green-arrow CMSs, appear to be sufficient for preventing improper lane use.

Lane Use

When the amount of traffic favored use of the CLT lane (conditions F and G), participants used it in 39 percent of trials. However, frequency of use rose to about half of trials when the queue in the nonreversible left-turn lane was long (condition F), suggesting that the amount of traffic in the nonreversible left-turn lane had a significant effect on CLT lane use. Preference for the CLT lane was significantly related to sex in both scenarios in which the CLT lane queue was shorter than that of the nonreversible left-turn lane, with males more likely to use the CLT lane than females. This may be associated with personality factors such as risk taking, as reflected by the curiosity noted by several participants in the post-task questionnaire as a motivator for using the CLT lane. However, acceptance for perceived risk is generally assumed to be higher in a simulated environment than in a real-world driving scenario.

When either left-turn lane was appropriate, as in condition H (when both left-turn queues were long), drivers favored remaining in the nonreversible left-turn lane. In addition to driver preference, this behavior may have been influenced by the geometry of the CLT lane opening, leading drivers to believe that there was not enough space behind existing traffic to safely or completely enter the CLT lane.

Average preference for the CLT lane was low during initial encounters but rose to a maximum of over 50 percent with subsequent exposure (condition F). The increase in lane-use probability suggests that, although drivers unfamiliar with CLT intersections may be wary of using the CLT lane, repeated encounters may lead them to become comfortable rather quickly. Subjective reports of initial unfamiliarity support this prediction.

Compared to the conventional intersection, increases in braking or swerving were not observed in trials where the CLT lane was closed. Some swerving around the CLT opening was observed when the CLT lane was transitioning to a closed status, which suggests some uncertainty on the part of a few participants. Overall, driver behavior indicated that the presence of a closed CLT lane is unlikely to cause disruptions to traffic flow.

Small but statistically significant delays in mean brake release and acceleration (startup delay) were observed during through movements in the CLT-lane scenarios with opposing traffic (condition I). These delays may reflect driver confusion or discomfort that may ultimately limit potential benefits to traffic flow and left-turn capacity. However, it is possible that repeated exposure to CLT-lane operations in a real-world driving scenario may reduce these delays over time.

In scenarios where participants were instructed to continue straight after observing opposing traffic occupying their lane across the intersection, the overall rate of lane changes between the near and far sides of the intersection was low (5 percent). Observed lane changes and self-reports reflect uncertainty about the safety or appropriateness of remaining in the leftmost through lane through the CLT intersection. Such lane changes may pose safety concerns. However, similar to the DRLT experiment, the rate of observed lane changes may have been influenced by the lack of through-movement traffic in the adjacent right lane and traffic ahead to follow through the intersection.

Recommendations

Overall, participants used the CLT lane appropriately. During the second exposure, use of the CLT lane exceeded 50 percent. Participant responses to the questionnaire suggest that the perceived personal benefits of the CLT lane design may not be appealing enough to motivate use by drivers who are confused by or unfamiliar with its operation. However, if half the drivers approaching an open CLT lane are willing to use it, then the operational benefits to all drivers are likely to be notable based on simulations demonstrating large performance gains under full, correct usage.[(11)] The rate of maneuver errors was low, and the highest rate of error occurred on through-movement trials. It is unclear whether these errors resulted from the relatively low frequency of through-movement trials or were influenced by the presence of traffic in the CLT-intersection through-movement scenario. Very few participants made left turns from through lanes.

The similarity in travel time for CLT- and nonreversible-left-turn-lane users suggests that drivers do not experience significant challenges when navigating the CLT lane compared to the nonreversible left-turn lane. Therefore, the main benefit of the CLT lane may lie in its potential to increase throughput in each signal cycle. A scenario that includes accurate left-turn signal timing and multiple vehicles attempting to clear the intersection in a signal cycle may be useful for better assessing the potential improvement of traffic throughput. Further evaluation of startup delays during through movements at CLT intersections would also be pertinent to the estimation of potential throughput.

Future work may include minor modifications to the design and components of the CLT intersection to improve comprehension and ease of use. Feedback provided in the post-task questionnaire suggests that making the turn radius larger and lane width of the CLT lane slightly wider may improve driver comfort and perceived safety.

CHAPTER 4. GENERAL DISCUSSION

The results of the DRLT and CLT driving simulator studies showed that drivers used the reversible lanes safely and with high enough frequency to potentially improve throughput during periods of high traffic volume. Overall, performance in both studies suggests that most participants were able to navigate the DRLT and CLT lanes successfully. The amount of traffic in reversible and nonreversible lanes influenced drivers' decisions to use the CLT lane such that the likelihood of using the CLT lane was greater when the queue of traffic was shorter compared to the nonreversible left-turn lane.

In both studies, the effects of encountering opposing traffic in the receiving lane at the far side of the intersection were observed in various measures, including subjective feedback, lane-change maneuvers in the intersection, and startup delays at the stop bar. Given that the simulated scenarios seldom included traffic ahead or to the right of the participant, it is likely that lane changes would occur less frequently in real-world driving scenarios. However, minor but consistent acceleration delays following a green-signal indication could reduce throughput benefits. Although drivers in both interchange designs appeared to adapt quickly to reversible-lane operations during subsequent trials, informational signs located upstream of the intersection and possibly at the stop bar may help prepare drivers who are unfamiliar with DRLT and CLT interchanges and reduce confusion and intimidation.

Signs and symbols used in both studies appeared to be well comprehended. Despite some participants reporting confusion when asked to describe the meaning of a sign, the majority of observed behaviors conformed to the intended purpose of the sign. Cases in which participants entered closed or closing CLT lanes were infrequent, and it remains to be seen whether drivers will be motivated to enter a closing lane in the absence of a lead vehicle. Considering the risks associated with entering a closed CLT or DRLT lane that is open to opposing traffic, it is important to select signs and markings that convey this meaning as clearly as possible.

Several options for encouraging proper use of DRLT and CLT lanes are recommended, including modifications to signs, markings, road features, and possibly signal heads. The addition of advance guide signs of the reversible-lane interchange may be helpful to prepare drivers for the potential sight of opposing traffic in their receiving lane, inform them how to identify the operational status of the reversible lane, and provide guidance on how to use the reversible lane. Advanced knowledge may aid in reducing discomfort and hesitation at the intersection itself and reduce improper maneuvers. As reported by some participants, DRLT and CLT lanes may be made more accessible by occluding the sight of stop bars at the far side of the intersection. Stop-bar occlusion could be accomplished by altering the stop bars (e.g., raising, embedding, or milling the footprint of the stop bar and painting only one side) so that they are only visible to opposing traffic. Additional measures, such as low-profile raised curbs or flexible delineator posts installed along reversible-lane markings, to deter improper maneuvers such as lane changes within the intersection should also be considered.

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