Enhancing Safety and Operations at Complex Interchanges with Improved Signing, Markings, and Integrated Geometry

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Research, Development, and Technology
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FOREWORD

The National Highway System has experienced rapid growth in demand that has far outpaced the increase in new capacity. Roadway designers are turning toward additional lanes, preferential lanes and ramps, and multilane exits in their interchange designs to address the continued mobility demands. While these mobility and capacity enhancements address the challenge of increased demand, they also complicate the design and operation of interchanges.

Drivers approaching these complex interchanges are required to perform several navigation tasks that are often short in both distance and time. The purpose of this study was to develop recommendations for signing, delineation, and geometric design that will reduce workloads at critical points approaching complex interchanges. In doing so, this project identified many attributes that contribute to complexity; evaluated multiple interchanges across the United States for their design, signing, and marking practices; conducted a series of driving simulator studies; and observed and analyzed video investigating real-world driving behaviors at complex interchanges.

Each key finding and recommendation is provided in the report, along with examples that explain the involved principles and suggested guidelines for implementation. This report should be useful to transportation professionals, State transportation departments, and researchers interested in developing complex interchange designs that consider driver behavior more effectively.

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16. Abstract
The purpose of this study was to develop recommendations for signing, delineation, and geometric design that will reduce workloads at critical points approaching interchanges that exhibit a high degree of complexity. In the development of these recommendations, the following activities were completed: identification of attributes influencing interchange complexity; evaluation of current geometric design, signing, and marking practices; a simulator study investigating driver behavior at different interchange layouts; and a field study investigating real-world driver behavior at complex interchanges.

This report details the process and outcomes of these activities to develop key findings with regard to traffic control devices, pavement markings, and geometric design being implemented across the country. Six categories of recommendations ("treatments") were identified and discussed. Each treatment is the result of understanding the interrelationships of various attributes within each research topic and the application of those relationships to practice outcomes. The report describes each treatment with examples of undesirable practices as well as anticipated and observed outcomes, provides existing design guidelines with a general perspective on implementations in multiple jurisdictions, outlines the primary principles of the concept, provides application examples, provides specific recommendations to address undesirable practices, and summarizes the breadth and depth of implementation options.

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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 ACRONYMS AND ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
APL	arrow-per-lane
C/D	collector–distributor
CMV	commercial motor vehicle
CSV	comma-separated values
DAQ	data acquisition
DP1	first decision point
DP2	second decision point
FHWA	Federal Highway Administration
GDOT	Georgia Department of Transportation
GPS	Global Positioning System
HO/T	high-occupancy vehicle and tolling
HOV	high-occupancy vehicle
HFs	human factors
I-	Interstate
ITE	Institute of Transportation Engineers
LSD	lane selection distance
MHFL	Mobile Human Factors Laboratory
MnDOT	Minnesota Department of Transportation
MUTCD	*Manual on Uniform Traffic Control Devices*
RRPM	raised reflective pavement marker
SHS	*Standard Highway Signs Catalog*
SR	state route
SSQ	Simulator Sickness Questionnaire
TCD	traffic control device
TH 62	State Trunk Highway 62
TMC	traffic-management center
UAV	unmanned aerial vehicle
ULC	unnecessary lane change
US	United States Route
WSDOT	Washington State Department of Transportation

EXECUTIVE SUMMARY

The modern highway system has experienced considerable changes since the interstate system and other limited access highways were first designed and constructed in the mid-1900s. Population movement outside of cities and the increased movement of passenger and freight traffic have led to increased congestion and necessitated new approaches for maintaining mobility.

Mobility and capacity enhancements, including additional lanes, preferential lanes and ramps, and multilane exits have subsequently complicated the design and operation of interchanges. Drivers approaching an interchange must undertake the navigation task while workloads from the guidance and control tasks are particularly high. In addition to the task of selecting a lane appropriate to the desired route, which typically requires lane changes, drivers experience workload demands related to conflicting traffic from lane changes associated with entering and exiting maneuvers. The combined workload of guidance and control tasks related to collision avoidance and navigation is easily exacerbated by a reduction in available time to make a maneuver (due to speed or short distances between critical points) and factors associated with roadway geometric design, roadway cross section, and traffic volumes and density.

The purpose of this study was to develop recommendations for signing, delineation, and geometric design that will reduce workloads at critical points approaching interchanges that exhibit a high degree of complexity. In the development of these recommendations, the following activities were completed:

- Identification of attributes influencing interchange complexity.
- Evaluation of current geometric design, signing, and marking practices.
- Simulator study investigating driver behavior at different interchange layouts.
- Field study investigating real-world driver behavior at complex interchanges.

The project team conducted a literature review to understand previous research on interchange complexity and identify elements that influence the complexity of an interchange. Previous research and feedback from stakeholders identified specific scenarios that make an interchange (and common challenges associated with them) complex as well as practices that have been implemented to try to address these challenges. As an outcome of the literature review, a list of nearly 200 characteristics that contribute to complexity was defined, and this list was distilled into 10 topics for further review.

Building on the literature review, the project team conducted a practices evaluation to determine, by means of site visits and a scan of photographs and videos available to the project team, the variations in the application of engineering design undertaken by various States. Differences related to geometric design, traffic control devices (TCDs), pavement markers, delineation, and raised reflective pavement markers were captured and discussed.

The project team conducted a simulator study to experimentally evaluate driver lane selection in complex interchange situations. Complex interchanges typical of the existing field applications were designed, and multiple alternative approaches to guide signing were developed for four interchange layouts. The effectiveness of driver decisionmaking was evaluated in terms of both whether drivers make accurate lane choices and the potential impacts to safety and efficiency.

The simulator study included a sample of 121 research participants (60 male and 61 female) in 3 geographic areas: Orlando, Florida; Myrtle Beach, South Carolina; and Gainesville, Virginia. Participants were found to be accurate regardless of the signing approach used. Similarly, participants seemed to understand the signing alternative—that is, in general, there was an average of less than one unnecessary lane change (ULC) per interchange. Together, the high accuracy presented by participants and few ULCs indicate that drivers tend to understand a series of guide signs leading up to complex interchanges as long as the interchanges are designed consistently and with good signing practices. This simulator study also found different signing approaches affected where participants tended to make their lane changes; this information can be useful when designing interchanges as it could have implications on safety and operational issues.

To complete the field study, the project team collected data from six complex interchanges across the United States. Three types of data were collected for this field study: photographs, videos from fixed-location cameras, and videos from unmanned aerial vehicles. Findings from the field study highlight common behavior as drivers approach complex interchanges. No major safety issues were observed through the field study. One common finding across all sites was that exiting traffic was found to most commonly use the exit-only lane rather than the option lane. In addition, few common behaviors identified through the field video show last-minute lane changes; drivers typically entered their target lane well upstream of the interchange.

The project team's efforts in the various activities led to six key findings:

- Consistent application of signing principles, both among locations and within various geometric design scenarios, leads to correct driver responses.
- The existence of explicit technical policy typically results in improved consistency in signing, pavement markings, and geometric design.
- A well-developed pavement marking and delineation policy generally results in appropriate application of pavement marking patterns.
- The consistent use of arrows on guide signs appears to correspond with a design that correlates with intention in the signing of freeway-grade facilities and is generally indicative of fewer design and fabrication errors in the field.
- Providing specific guide signing with corresponding appropriate delineation appears to reduce the likelihood of roadway departures and abrupt lane changes.
- A uniform application of warning signs for lane reductions, for both mainline lanes and entering lanes, is lacking in many jurisdictions.

Six categories of recommendations ("treatments"; see list that follows) were identified and discussed. Each treatment is the result of understanding the interrelationships of various attributes within each research topic and the application of those relationships to practice outcomes, including those evaluated in the field study and simulator study:

- Ramp terminal arrangements.
- Sign layout: sign legend arrangement and panel configuration.
- Sign placement: arrows, distances, and relationship to geometric design.
- Delineation for exiting lanes and special use lanes.
- Lane-reduction methods, signing, and delineation.
- TCD education and design review workshops.

In this report, the project team describes each treatment with examples of undesirable practices and anticipated and observed outcomes, provides existing design guidelines with a general perspective on implementations in multiple jurisdictions, outlines the primary principles of the concept, provides application examples, provides specific recommendations to address undesirable practices, and summarizes the breadth and depth of implementation options.

CHAPTER 1. INTRODUCTION

The urban freeway interchange can present a very demanding environment for drivers. Drivers approaching an interchange must undertake the navigation task while workloads from the guidance and control tasks are particularly high. In addition to selecting a lane appropriate to the desired route, which typically requires lane changes, drivers experience workload demands related to conflicting traffic from lane changes associated with entering and exiting maneuvers. The combined workload of guidance and control related to collision avoidance and navigation is easily exacerbated by limited available time to make a maneuver (due to speed or short distances between critical points) and factors associated with roadway geometric design, roadway cross section, and traffic volumes and density.

Freeway interchanges with exit-only lanes, multilane exits, and so-called option lanes may be readily understood to the degree that interactions between these features do not create a situation in which road users experience a workload that results in task saturation and primacy order rejection. Primacy order rejection is defined as placing a task of lower primacy but higher complexity (such as the navigation task) ahead of a task of higher primacy but lower complexity (such as the control task). For example, when the navigation task supplants the guidance task, abrupt and erratic maneuvers may occur. Often, task saturation and primacy order changes can result in late lane changes and erratic movements near the gore that may result in crashes.

The Federal Highway Administration's (FHWA's) Office of Safety Research and Development is undertaking a sequence of studies intended to address safety and operational issues related to complexity within interchange areas. The purpose of this study, which is part of this sequence of studies, was to develop recommendations for signing, delineation, and geometric design that will reduce workloads at critical points approaching interchanges that exhibit a high degree of complexity. These recommendations are based on human factors (HFs) analyses and practice evaluations conducted within a framework of logical application consistency.

USING THIS REPORT

This report is divided into nine chapters. This first chapter and chapter 2 provide background information and a contemporary literature and policies summary, respectively. Chapter 3 describes the development and categorization of attributes typical of complex interchanges. Chapter 4 describes the site evaluation and selection process, basis for the field study, and input for the practices evaluation. Chapter 5 presents the practices evaluation, including information on a new method of evaluating traffic control devices (TCDs) alongside this project's examination of contemporary practices throughout the United States and Canada.

Chapters 6 and 7 describe the simulator study and field study, respectively, detailing the study methodologies, data collection, and analyses. Chapter 8 presents the research results, which in combination with the practices evaluation in chapter 5, forms the foundation of the recommendations in chapter 9.

APPROACH AND OUTCOMES

Project activities are organized into seven tasks. The tasks' purpose is to achieve the outcomes listed in table 1. For each project objective, an X has been placed in the column corresponding to the task in which work was performed to meet the objective.

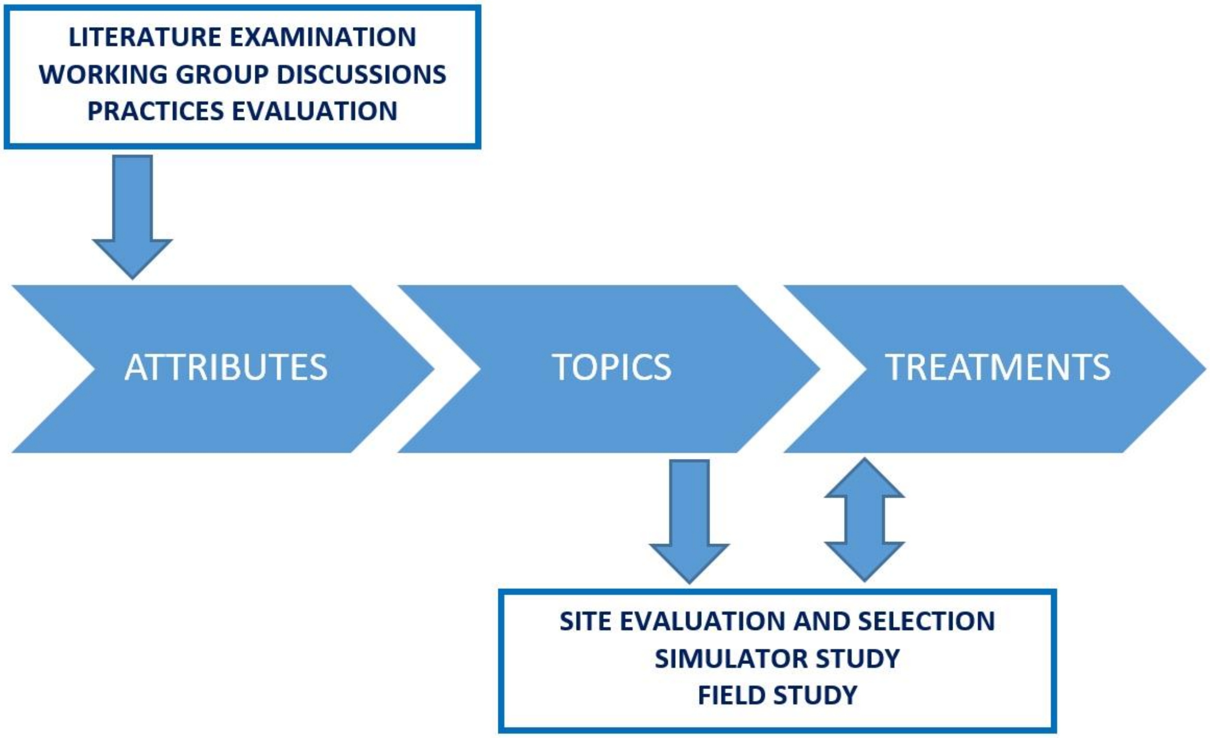
Table 1. Correlation of project objectives and project tasks.

FHWA Project Objective	1. Project Management	2. Literature and Standards Review	3. Working Agreements and Stakeholder Input	4. Simulator Studies	5. Field Study	6. Visualizations and Evaluation Tool	7. Prepare Final Project Report
Working group and policy evaluation	X	X	X	—	—	X	X
Data collection and analysis	X	X	—	X	X	X	X
Practice recommendations with HFs basis	X	X	X	X	X	X	X
Visualizations of common typical interchange approaches	X	—	X	—	X	X	X
Complex interchanges mitigation analysis tool	X	X	X	X	X	—	X

X indicates work was done to meet this objective.
—This task was not performed to meet the corresponding project objective.

As illustrated in figure 1, the project team developed a work plan for completing these objectives that included three investigation activities: a discussion framework development activity and two experimental activities. The three investigation activities occurred under tasks 2 and 3 and included the literature and standards review (part 2), the working group discussions (included in part 3), and the practices evaluation (included in part 3). The practices evaluation is an additional activity not explicitly identified as a task, but it is valuable because this evaluation helped the project team identify trends in practice and differences between agencies and within agencies, a key to understanding how existing documentation and policy influence interchange design and operations.

These three investigation activities were the predecessors to the discussion framework development activity, which included a thorough evaluation of complex interchange characteristics. This activity culminated in the identification and selection of more than 200 attributes related to interchange complexity. From these attributes, a list of research topics comprising related attributes with interactions was developed, and these research topics formed the basis for the simulator study, treatment development, and field study. The development of the attributes—the framework for the entire project's experimental activities and recommendations formulation—was undertaken as part of task 3 and is described in chapter 3.



Source: FHWA.

Figure 1. Graphic. Project process for developing and organizing information.

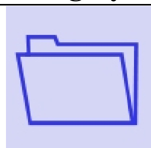
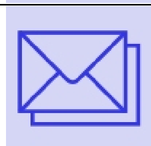
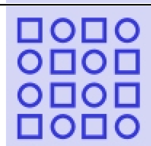
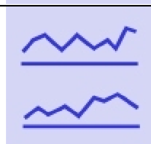
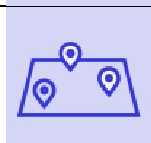
The ultimate result of this process is the preparation of recommended practices and a list of pertinent considerations. The recommendations are based on research results and the application of consistency principles outlined in the practices evaluation.

BASIS OF RECOMMENDATIONS

The recommendations made in chapter 9 address technical practice issues and functional policy issues. Each recommendation is made on the basis of one or more of the tasks in this report. A description of the basis for recommendations (included in table 2) also includes indexing symbols. The purpose of these symbols is to help the user of this report readily identify the supporting work for each recommendation.

The use of the consistency principle, explained in chapter 5, helps address the shortcomings of heuristic analyses by providing a means of evaluating TCD installations using a logic model. The consistency principle, when properly applied, can identify TCD uses for which a revision to the use will improve consistency and road-user expectancy. In many cases, it will also form the basis of the suggested revision to practice. In other cases, when further evaluation is necessary to determine what type of revision to practice would be suitable, such a need for evaluation is identified.

Table 2. Basis of recommendations with indexing symbols.

Indexing Symbol	Description
	**Literature and policy review (chapter 2):** Input from the literature review includes agency policy manuals and memorandums; standard plans and details; and published, peer-reviewed guidance from technical support organizations.
	**Practitioner input and insights (chapter 3):** Practitioner input was obtained from the working group and the technical evaluation panel. This input includes preferences based on heuristics, background on policy, and practice descriptions.
	**Practices evaluation with consistency principle (chapter 5):** The consistency principle provides for the assessment of TCD implementations by using a logic model that considers the interaction between geometric design and TCDs.
	**Simulator study (chapter 6):** The simulator study was used to evaluate various signing treatments approaching interchange divergences that exhibited complexity.
	**Field study (chapter 7):** The field study was used to evaluate real-world driver response to signing and pavement markings in complex interchange environments in several States.

Each recommendation made in chapter 9 is classified according to six treatments. These six treatments address corresponding topics used in the development of the simulator study and field study.

PREPARATION FOR THE FINAL REPORT

In previous tasks, the project team completed a literature review, prepared a comprehensive list of attributes contributing to complexity within motorway interchanges, and identified sites where potential field analysis could occur. For each of these primary work products, a report was submitted, and the completed reports are listed in table 3.

Table 3. Previous project deliverables.

Deliverable	Date
Literature and standards review summary report	November 2014
Site selection report	December 2014
Complex interchanges evaluation tool revisions (attribute identification)	April 2015
Mitigation strategies selection report	May 2015
Progress update presentation to technical evaluation panel	July 2015
Progress update presentation to technical evaluation panel	February 2016
Preliminary research results report	April 2016

Prior to preparing this final project report, the project team submitted a preliminary research results report to FHWA that discussed the research results from literature examination, practices evaluation, field studies and data analysis, and driving simulator study and analysis. It also presented the initial draft recommendations for practice concerning guide signing, regulatory signing, pavement markings and delineation, geometric design, and agency policy and practice associated with the selected topics identified in the attribute identification process.

As the project team developed the list of attributes contributing to complexity and examined the resulting topics over the course of the practices evaluations, a definition of complexity emerged, particularly related to driver needs within complex interchanges:

> Complexity occurs when the choice of more than one movement is available from a lane or group of lanes where the decision or departure points occur successively in close proximity.

This working definition addresses the key issue of interchange complexity: drivers must make decisions about lane choice and point of departure in quick succession. This definition of complexity is independent of the overall design of the interchange, the number of overall ramps, and other factors that may challenge drivers (e.g., narrow lanes, insufficient or improper use of TCDs, or inadequate roadway and traveled way delineation).

CHAPTER 2. SUMMARY OF CONTEMPORARY RESEARCH EFFORTS

This chapter provides a literature and policy review, including agency policy manuals and memorandums; standard plans and details; and published, peer-reviewed guidance from technical support organizations.

APPROACH

A variety of sources were researched and reviewed, including standards and guidance documents, published research, conference proceedings, and various other literature on signing or marking for complex interchanges. FHWA has sponsored recent research related to complex interchanges, including *Simulator Study of Signs for a Complex Interchange and Complex Interchange Spreadsheet Tool*, *Driver Expectations When Navigating Complex Interchanges*, and *Collecting and Analyzing Stakeholder Feedback for Signing at Complex Interchanges*.[1–3] The research had the following objectives:

- Determine design elements and traffic characteristics that contribute to complexity.
- Identify and understand driver expectations of freeway signing and marking.
- Determine characteristics that increase confusion (e.g., lane drops, lane splits, and left exits).
- Quantify interchange complexity.
- Understand practitioner experience and gather input on complex interchange design characteristics.

This report is intended to complement the previous three efforts, rather than duplicate the literature review and information-gathering efforts already performed. Therefore, the report focuses on identifying the critical elements of these previous efforts and other key pieces of literature in addition to summarizing existing guidance and state of practice for exit signing and markings at complex interchanges. Combined, these elements will influence how the remaining project tasks are conducted. The key findings are summarized in the subsequent sections of this chapter, which is organized as follows:

- Driver expectations of interchanges.
- Identifying complex situations.
- Existing design guidance.
- Interchange design practice.
- Summary.

DRIVER EXPECTATIONS OF INTERCHANGES

The following subsections focus on driver expectations and perceptual factors.

Driver Expectations

Drivers have expectations for many aspects of driving, including speed, traffic, the roadway's geometry, and the information supplied to them—including when, how, and where that information will be provided. Roadway conditions that contribute to driver expectations include roadway alignment, width, shoulders, surface texture, and signs and markings.(4) Violations of driver expectations can increase driver confusion, frustration, and workload, which may lead to navigational errors or potentially unsafe driving behavior (e.g., speed variability or erratic maneuvers). Driver expectancy, therefore, has a major impact on highway safety and operations.

Understanding the drivers' expectations provides information on the types of scenarios that may contribute to the overall complexity of an interchange and serves as a guide when designing treatment options for evaluation.

Russell (1998) describes the technique of "commentary driving," in which verbal comments are made while driving to indicate initial expectations of drivers and when those expectations are violated. When used appropriately, such techniques can be used to flag potential problem sites that may require additional evaluation.(4) Russell also identified the following factors that affect the information needs of drivers:(4)

- Consistency—the "sameness" of the road.
- Positive guidance—sufficient information to avoid hazardous situations.
- Uncertainty—confusing or insufficient information (e.g., road "disappears").
- Decision sight distance—the distance available to see and react to a situation.
- Missing, incomplete, inconsistent, or misleading/confusing information.
- Inappropriate message or location.
- Signs obstructed by weeds, brush, and so forth.

Richard and Lichty (2013) conducted a thorough literature review of previous work on driver navigation problems and driver expectations at interchanges and intersections.(2) Various measures are identified that can be used to record driver behavior and expectations, including driver errors (e.g., number of missed exits, unnecessary lane changes (ULCs), and erratic maneuvers), operational measures (e.g., lane change distance, response time, and vehicle speed), and subjective measures (e.g., sign expectations and certainty of choice selection). The researchers employed these performance measures to make the following inferences about driver expectations:(2)

- Drivers expect that they need to be in the lane closest to the exiting direction to be able to exit.(5)

- Drivers expect lane drops at exits.(6)

- Signs and lane markings appear to be effective ways to set driver expectations at interchanges.[7]

- Driver expectations affect how drivers acquire information.[8]

Although such performance measures can be used to deduce driver expectations, it is difficult to draw direct conclusions about expectations without specifically asking about them as they are often intertwined with performance factors (i.e., sight distance) and driver motivations, preferences, and familiarity, among other factors.[2]

In addition, little research explicitly identifies driver expectations for specific interchange elements. Nonetheless, overall themes of design principles or guidance can be applied to interchange design and, thus, will be useful in subsequent tasks of the current project. Richard and Lichty (2013) identified 10 principles based on a thorough review of existing research; these design principles and supporting research are shown in table 4.[2]

Table 4. Key design principles from existing research.

Principle	Supporting Research Gathered by Richard and Lichty (2013) (pp. 22–24)(2)
Provide adequate forward sight distance	• Continuous visual cues should be provided before a lane reduction. • Sight line restrictions should be avoided. • Sight distance is required because of the reliance on visual information and for complex decisionmaking. • Visibility should be proportional to feature criticality.
Provide transition cues	• Provide a taper at lane reductions that allows a smooth transition and informs the driver that the lane is ending. • Look for possible expectancy violations where changes in roadway characteristics (e.g., geometrics, design, or operation) or changes in operating practices (e.g., speed zones, no passing zones, or signal timings) occur. • Provide adequate transitions.
Minimize attention-dividing conditions	• Resolve conflicts when information sources compete. • Use spreading by moving less-important information upstream or downstream.

Provide navigation information to address all of the driver information needs	• Appropriate signing is needed to guide drivers.
	• Drivers expect in-trip cues and services to guide them.
	• Drivers expect the roadway information to tell their current location and provide information to help them to their destination.
	• If drivers need to change course during a trip, they expect to be provided with the necessary information to do so.
	• Navigation information should satisfy all driver information needs.
	• Information-related error sources should be eliminated. Deficient, ambiguous, confusing, missing, misplaced, blocked, obscured, small, illegible, or inconspicuous displays should be avoided.
	• Interchange information should not be so far upstream that it is forgotten by the time that the interchange is reached (may require repetition).
	• All available navigation aids and treatments should be used.
	• For lane drops with option lanes, the following should be clearly communicated:
	  ○ The right lane can only reach the exit.
	  ○ The option lane leads to either the exit destination or the mainline.
	  ○ Any other lane only reaches the mainline.
	  ○ The identifying information for each destination (e.g., street name).

Maintain compatibility between interchange and visual cues	• Create lane-reduction transitions on the better side of the freeway for the observed traffic and geometric conditions. • Coordinate visual and operational transitions; disguise the operational reduced lane upstream from the physical drop so that the lane appears to be physically dropped (even if the pavement for the lane exists beyond the transition).

Principle	Supporting Research Gathered by Richard and Lichty (2013) (pp. 22–24)[2]
Design to accommodate the drivers' expectations and abilities	• Expectancies occur with all driving task levels and driving phases. • Drivers experience problems and make errors when their expectations are violated. • Drivers believe that the roadway will not mislead or confuse them. • Be aware of features that drivers may find unusual or special. • Information that reinforces expectancies helps drivers respond faster; information that violates expectancies leads to longer task times and errors. • Be responsive to task demands and driver attributes; avoid overloading the driver with too much or too little processing demand. • Design for drivers and target populations. • Design to give the driver what he expects to see.
Warn drivers of situations that may violate their expectations	• Structure driver expectations through advanced warning. • At a lane reduction, notify drivers that the lane is not continuous.
Allow drivers to recover after making an error	• Provide adequate escape areas at lane drops. • Provide a forgiving roadside at critical features.
Design for simplicity	• For route continuity, provide a route on which changing lanes is not necessary to continue on the through route. It is better to have the greater number of lanes continue on the through route. • For lane balance, arrange the traffic lanes (using auxiliary and option lanes) to minimize the required number of lane shifts. • Provide adequate ramp spacing to allow for clear and simple guide signing and to prevent congestion from heavy traffic entering and exiting. • Avoid creating compound geometric features.
Design for consistency and predictability	• Drivers should not be surprised by the roadway elements or vehicle movements. • Drivers anticipate based on elements common to the road they are on (i.e., transition locations and unexpected features cause problems). • More predictable design and operation leads to fewer errors. • Be aware of features that are unique to a particular roadway.

In an effort to isolate driver expectations in specific complex interchange scenarios, Richard and Lichty (2013) developed video scenarios based on geometries and interchange elements identified in the literature review and complexity factors identified by Fitzpatrick et al. (2013).[1,2] These videos were used as part of a focus group to identify the sources of expectation-related problems that drivers encounter and potential solutions/countermeasures that drivers suggest. The project team identified the following key driver expectations for the navigation of complex interchanges:[2]

- Drivers expect that there will be functional relationships between lanes on the roadway and arrows/text on signs, and that the signs themselves will make these relationships clear.
- Drivers expect that the distance between a guide sign and a "last chance" decision point will be sufficient to allow for making any necessary lane changes in a safe and timely manner.
- Drivers expect that they will have more than one opportunity to obtain necessary destination and lane information before they need to make a final decision about lane choices.
- Drivers expect that the freeway system (i.e., lanes, arrows, signs with text, lane markings, and so forth) will provide them with the necessary information to construct a mental model, and that it will be sufficient to support timely and accurate decisions about lane choice.
- Drivers expect that the information available to them through the freeway system will be sufficient to support decisions about lane choices. At the least, drivers expect they will never have to move over more than one lane at the last moment.
- Drivers expect that the freeway system will provide sufficient information to support decisions about all route choices, not just frequent or popular choices.

Perceptual Factors

As stated previously, drivers form expectations about where and how information is provided to them. This indicates a need for consistency, and if there is consistency in signing within and between States, then signing will more reliably meet driver expectations. In addition, drivers will form expectations about the upcoming geometry of the roadway and the actions they should take based on the design and placement of signs and markings. The location and layout of a sign, as well as how information is grouped within a sign, will all influence how drivers interpret the sign.[1,2] These factors must, therefore, be considered during design and implementation to ensure that the signs will be effective and intuitive/usable to drivers. This is especially important for complex situations that may be inherently confusing to drivers. The following examples are perceptual factors that may affect how drivers interpret signs.

Lateral Sign Placement

One study compared a yellow left-exit panel at the bottom of the guide sign and a yellow left-exit-number plaque on the top of the guide sign to a plain/green exit-number plaque atop the guide sign. Although the green left-exit plaque was less noticeable to drivers than other left-exit notations, sign placement on the sign bridge was a stronger cue than the left-exit notation; most participants remained in the rightmost lane when viewing the left-exit panel, indicating that the left-exit panel may be confused with an exit-only panel.(2) Similarly, a simulator study showed minimal difference in a yellow left-exit plaque at the top left of the sign and a yellow left-exit panel at the bottom of the sign when both signs were placed above the left lane.(1) These findings indicate that the lateral position of the sign as well as the placement of information within a sign can influence driver lane selection and expectations about the geometry of the roadway.

This has implications for other signing concepts as well (i.e., sign spreading). Some research has shown that spreading a lot of information across multiple signs on a sign bridge can lead to incorrect lane changes or ULCs as drivers may position themselves underneath the sign that contains their intended destination.(2) Therefore, the lateral location of pull-through signs on a sign bridge is important.

Separation and Organization of Information

Separation cues and lateral placement of destinations on a sign can influence how drivers associate destinations with specific lanes. For example, Richard and Lichty (2013) examined different types of destination separators on guide signs for a two-lane exit that divides after the exit to determine whether the sign indicated an immediate split or a downstream split (i.e., they could use either lane to exit, and then, they would need to change lanes after the exit).(2) In each condition, the exit panel extended the full length of the guide sign so that both destinations were above the exit panel. The researchers then examined multiline separation (destinations stacked vertically on top of one another), vertical separator lines (destinations on the same horizontal row, separated by a vertical line), and hyphen separators (destinations on the same horizontal row, separated by a hyphen). Multiline and hyphen separators were found to be better than vertical separators at communicating that both lanes would allow drivers to reach both destinations; the vertical separator lines caused drivers to think they had to change lanes immediately to reach their destination.(2) Similarly, a simulator study examined three signing conditions for a Y-split: a split-sign configuration in which all three signs used vertical separator lines, a multiline separation configuration in which all three signs used a vertically stacked format, and a condition in which the two advance signs used the multiline separation, and the sign at the gore used the vertical separator lines. The results indicated that the lateral location of the destination on the sign influenced drivers' lane-changing decisions.(1)

It is important to note that some sign elements (e.g., vertical separator lines) may have different effects when used in different scenarios and in combination with different sign elements. For example, a study by Katz et al. (2014) evaluating different sign elements for combined lane use and destination signing indicated that the presence of vertical separator lines did not have a significant effect on driver comprehension of guide signs.(9)

Visual Presentation of Lane Information

The visual perspective on the alignment of lane information can also influence driver behavior and lane selection.[2] Some research has shown that conventional guide signs may produce fewer lane placement errors than certain types of diagrammatic signs, or that modified diagrammatic signs providing separate arrows for each lane (i.e., arrow-per-lane (APL) signs) are more effective in communicating lane assignment than the diagrammatic sign and other conventional signing options.[10–12] Furthermore, some research has examined driver interpretation of such signs, and lane movements may also vary depending on the particular situation. For example, modified diagrammatic signs may be better than diagrammatic signs in some interchange scenarios, but not in others, or that visual cues (e.g., the number of lanes) may influence the distinctiveness and effectiveness of a diagrammatic sign.[2,13]

As indicated in previous sections, driver expectations and perceptual factors that influence guide sign interpretation can affect driver behavior and comprehension of the roadway geometry. Such considerations should be taken into account in the design of signing and markings to make them more intuitive and useful to drivers; failing to do so can lead to unnecessary or incorrect lane changes, erratic maneuvers, and driver confusion. These factors should not only be considered in the design process, but should also be further explored as they could help identify minor changes in current designs that could be used to improve signing at complex interchanges.

IDENTIFYING COMPLEX SITUATIONS

Doctor, Merritt, and Moler (2009) describe a complex interchange as "a facility that typically contains many lanes, usually four or more in each direction, and carries high traffic volumes through a maze of tightly spaced ramps and connectors."[14] Complex interchanges do not typically have conventional layout patterns; instead, each interchange is unique, and thus, the current guidance and practices are not always sufficient for complex conditions.[14] Because each interchange is unique, the challenges for complex interchanges are often the result of the unique interaction between multiple components, rather than one particular scenario. These components may include roadway geometry variables, signing and markings, traffic volume, driver-expectancy violations, and driver workload. Therefore, it is difficult to explicitly define a complex interchange.

A variety of resources address the geometric and signing conditions that contribute to interchange complexity. For example, the *Guidelines for Ramp and Interchange Spacing* (Ray et al. 2011) discusses complex geometric situations and topics, such as ramp and interchange spacing, collector–distributor (C/D) roadways, ramp braids, and weave sections, and provides guidance in evaluating various safety and operational considerations of potential solutions.[15]

Lichty, Bacon, and Richard (2014) gathered feedback on complex interchanges through telephone interviews with stakeholders representing 17 State transportation departments and through a web activity with stakeholders from 32 regions. Stakeholders, including roadway engineers and other stakeholders who have responsibilities related to interchange planning, design, or maintenance, identified specific elements that cause problems for drivers and, thus, contribute to the complexity of an interchange, which are shown in table 5.[3]

Table 5. Characteristics of complex interchanges as reported by stakeholders.[3]

Characteristics of Complex Interchanges	Number of Mentions by Stakeholders
System interchanges	6
Multiple/successive option lanes, splits, or exits	5
Short weaving sections	4
C/D roadways	4
On ramps and off ramps for HOVs and managing/signing access	3
Providing a lot of information to drivers	1
Unfamiliar sign/marking elements	1
Lack of lane balance leading to forced merges	1
Unexpected maneuvers/violations of driver expectations	1
Horizontal/vertical alignment of interchange	1

HOVs = high-occupancy vehicles.

Stakeholder feedback revealed that multiple routes converging or diverging within a short distance are a common indication of a complex interchange.[3] The stakeholders were also asked to discuss examples of when they had to address a problem at a complex interchange and identify HFs challenges that they encounter at such interchanges. The following topics were mentioned most often:

- Close spacing of interchanges, routes, or access points.
- Signing lane movements.
- Guide sign destination information (e.g., control destinations).
- Driver task overload.

Other topics included left/right exit plaques, route continuity, diverging diamond interchanges, lane balance, and arrows on signs.

Closely spaced interchanges, routes, or access points are a common problem because drivers have to make more decisions in a shorter amount of time and engineers are more constrained in the amount of space they have to provide information.[3] Such circumstances lead to other challenges, such as short weaving sections, C/D roadways, exit lane splits, information overload, multiple routes that run concurrently, lack of space for advance signing, density of access points, and the number of decisions the driver is required to make at the interchange.

Fitzpatrick et al. (2013) developed a complexity rating tool to evaluate the complexity of an interchange. The researchers compiled an initial list of noteworthy variables for inclusion in the tool and then held an expert panel discussion to finalize the list of variables that contributed to interchange complexity. The resulting tool focused on three interchange-wide characteristics, a selection of cross-section characteristics at the terminus of the speed-change lane of each ramp, and ramp-specific characteristics that are dependent on whether the ramp is an entrance or exit ramp.[1] The tool contains threshold values for scoring each variable and weights to assign relative importance and measure of complexity for a given factor (i.e., factors with higher weights are considered to have a greater impact on the complexity of an interchange than factors with lower weights); the 32 factors and their weights are shown in table 6.[1]

Table 6. Factors and weights included in complexity rating tool.[1]

Factor	Weight
Is lane continuity violated?	5
Is there <0.5-mi weaving section between entrance and downstream left exit?	5
Are the approaching main lanes curved?	4
Entrance ramps per mile	4
Is a loop present on exit ramp?	4
Is a taper speed-change lane present on entrance ramp?	4
Is a taper speed-change lane present on exit ramp?	4
Is the number of general-purpose lanes greater than three?	4
Is there a claustrophobic feeling (e.g., buildings close to freeway)?	4
Is there a concrete barrier less than minimum width distance of 4 ft to the left of the travel way?	4
Is there an entrance ramp within a minimum distance of 1,000 ft downstream of this entrance?	4
Is there an exit ramp within a minimum distance of 800 ft downstream of this exit?	4
Left entrances per mile	4
Left exits per mile	4
Number of exit ramps with multiple destinations per mile	4
Proportion of ramps where lane balance is not satisfied	4
Is there an entrance ramp followed closely by an exit, and is the auxiliary lane missing based on dimensions shown in the 2011 version of the American Association of State Highway and Transportation Officials' (AASHTO's) *A Policy on Geometric Design of Highways and Streets?*[16]	3
Is the ramp straight while the main lanes are curved?	3
Is there a concrete barrier less than minimum width distance of 10 ft to the right of the travel way?	3
Number of concurrent routes	3
Number of missing movements	3
Exit-only lanes per mile	2
Are managed lanes present?	2
Exit ramps per mile	2
Is the left shoulder less than the minimum width of 4 ft?	2
Is the right shoulder less than the minimum width of 10 ft?	2
Is the number of exit lanes equal to or greater than the number of thru lanes?	2
Multilane exit ramps per mile	2
Number of levels	2
How much shorter than minimum distance is the shortest auxiliary lane (as a percentage of minimum distance)?	1
Is the number of entrance lanes equal to or greater than the number of thru lanes?	1
Optional/shared exit lanes per mile	1

Lane continuity violations and weaving sections (less than 0.5 mi in length) were given the largest weights as they were considered to be the biggest contributors to driver workload and perceived complexity.[1] Other factors with higher weights include number of entrance ramps per mile, ramp densities, number of general-purpose lanes, loop ramps or curved approaches to ramps, left-side ramps, and ramps with multiple destinations. Similarly, stakeholder feedback revealed that multiple routes converging or diverging within a short distance are a common indication of a complex interchange.[3]

Additional research and crash data support that factors such as interchange spacing and ramp characteristics play a significant role in interchange complexity. For example, research in California and Washington State shows that inserting an additional interchange between existing interchanges could increase freeway fatal injury crash frequencies by as much as 88 percent.[17] This is not surprising, as decreased spacing between interchanges will likely increase driver workload. Some other crash-related findings include the following:

- Horizontal curves at exit ramps are among the major contributors to crashes at interchanges.[18]
- Most accidents at weaving sections are rear-enders that either occur upstream of the weaving section as drivers respond to congestion from the weaving section or due to drivers seeking a gap to merge.[19]
- While crash counts at freeway exit ramp sections increase with the total mainline lane numbers, crash counts decrease with the number of exit ramp lanes.[20]
- Two-lane exit ramps without an option lane result in 10.8 percent higher crash counts than two-lane exit ramps with an option lane.[20]

EXISTING DESIGN GUIDANCE

Design guidance for interchange type selection, layout, and geometric design can be found in several key resources, including AASHTO's *A Policy on Geometric Design of Highways and Streets*, commonly referred to as the Green Book.[16] Many States base their State design manuals on information contained in the AASHTO Green Book. In the United Kingdom, the resource that contains similar types of information is the *Design Manual for Roads and Bridges*, a document that also forms the basis for Middle Eastern and some South Asian design manuals.[21]

The design of TCDs for interchanges is typically undertaken in a separate process using separate design documentation. The *Manual on Uniform Traffic Control Devices* (MUTCD) contains illustrations and text identifying the requirements and recommendations for signing at interchanges.[22] In general, MUTCD language does not consider entire systems as a whole, although the illustrations indicate a systematic approach to typical scenarios. MUTCD users must select discrete TCDs based on individual expertise with the process of designing for particular conditions.

In the process of exploring how design guidance is selected for interchange projects, the project team sought feedback from practitioners to discuss their experiences in locating, screening, using, and interpreting resources.

Interchange Geometry

A leading reference for geometric design guidance is the AASHTO Green Book.[16] Support for design decisions and methodology for selecting cross-section and geometric features are provided in other documents, including the following:

- AASHTO *Highway Safety Manual*.[23]
- AASHTO *Roadside Design Guide*.[24]
- Institute of Transportation Engineers (ITE) *Traffic Engineering Handbook*.[25]
- ITE *Freeway and Interchange Geometric Design Handbook*.[26]
- State and agency design manuals and internal policy documents.
- National Cooperative Highway Research Program reports.
- Strategic Highway Research Program project outcomes.
- Transportation Research Board *Highway Capacity Manual*.[27]

In addition, the FHWA's National Highway Institute offers various training classes to help increase awareness and application of many of these additional resources. With some transportation agencies facing staffing challenges, practitioners may lack the technical background necessary to effectively design freeway interchange components, particularly traffic signing. Designers who do not have a strong background in the application of traffic engineering principles and an understanding of HFs may be unaware of these resources. Even with knowledge of these resources, recommended practices may be misapplied in complex situations, leading to poor choices in the selection, layout, and fabrication of freeway guide signing.

For the geometric design of interchanges, the AASHTO Green Book addresses interchange configuration and ramp geometry in several sections, including information in section 10.1.[16] Section 10.9.3 of the Green Book provides information on four-leg interchange designs but does not specifically address how those interchange configurations might be modified to fit local conditions in ways that introduce complexity.

Section 10.9.5 of the Green Book addresses issues related to driver expectation, such as route continuity, lane balance, and the selection of auxiliary lane termination designs.

Section 10.9.6 of the Green Book addresses issues related to interchange complexity, including ramp terminal spacing and ramp terminal design. In particular, figure 10-73 and the associated text describe the problems associated with the "tapered design" for multilane entrance ramps. The Green Book cautions against using the tapered design, as it causes the "inside merge," or "forced merge," wherein two vehicles compete for the same space with no clear assignment of right-of-way and no escape option (e.g., a shoulder).

In addressing the use of multilane exit ramps, the Green Book discusses the lane changing required for the parallel design, while discussion concerning issues related to signing of option lanes and the forced merge tapered design is notably absent.

Traffic Signing and Pavement Markings

While not specifically addressing signing, the Green Book does include several photos that illustrate important design features, including signing.[16] In some instances, the photos in the Green Book may not be consistent with practices from the MUTCD.[22]

The MUTCD lists freeway signing treatments that potentially reduce driver workload and provide pertinent information on movements. The following items, which are from section 2E.07 of the MUTCD, are intended for application as operational needs warrant but are all considered applicable to complex interchange mitigation methods:[22]

- Provision of interchange sequence signs (design tool).
- Implementing sign spreading (design tool).
- Removal of general or specific service (policy tool).
- Provision of overhead signs.
- Provision of overhead signing with arrows (conventional or APL).
- Coupling roadway names with route marking, including freeway designations.

INTERCHANGE DESIGN PRACTICE

The project team conducted a cursory examination of the intersection design practices of roughly 10 States/provinces, representing locations across the United States and in Canada. The examination of the interchanges considered such design elements as layout and ramp geometry and the application of traffic signing, pavement markings, and other elements to the system. These elements include upstream lane additions and eliminations, longitudinal origin and method of addition or elimination of lanes, lane type or function, and lane reduction in close proximity to exiting traffic.

Beginning in the 1960s, interchange designs were typically characterized by ample accommodation of ramps, wider median strips, and potential accommodations for additional lanes in future years. However, often, current traffic volumes have exceeded the projections from that era, and ramps have capacity constraints. Reconstruction of these ramps and the addition of lanes can create geometric constraints, particularly for lane and shoulder width, sight distance, and lane arrangements upstream of decision points.

In the 1980s and 1990s, interchange reconstruction projects were often constrained by funding sources. Environmental considerations, including community opposition to freeway construction or expansion, often resulted in the construction of an improvement that was less than optimal and constrained for the construction of future capacity, typically because of bridge abutments, retaining walls, and noise barriers.

The project team considered an examination of these overarching trends an important aspect of understanding how design processes are influenced by prevailing trends in the cultural, economic, and policy realms. Those trends can cause transportation officials to select designs that may not satisfy all desired goals of the project.

In researching prevailing practice, the project team examined four aspects of interchange design and operations: interchange layout, interchange modification strategies, interchange signing practices, and interchange pavement marking practices.

Interchange Layout

Interchange layout, in reconstruction projects, is particularly constrained by adjacent land uses and development. Increasingly, designers are turning to more costly methods of providing sufficient space for ramp connections, including grade separations, large retaining walls, and fill sections.

As interchange reconstruction projects occur, optimal ramp spacing, configuration, and signing are often challenging to provide. Removal of existing ramps may be fraught with political difficulties and efforts to reduce cost, and impacts may result in decisions to not use design features that have the potential to reduce interchange complexity such as braided ramp sections and additional lanes. The proper selection of interchange type and differentiation between service interchanges (those serving arterial roadways with ramp junctions that are not free flowing) and system interchanges (those serving intersecting freeways and expressways and characterized by free-flow ramps) is also key in preserving system performance.

Interchange Modification Strategies

When confronted with poor traffic operations performance and safety deficiencies, agencies may seek to modify existing interchanges. In some instances, these modifications may make an interchange previously not considered complex into one that exhibits characteristics of a complex interchange. Some combinations of interchange characteristics may yield more undesirable results regarding safety performance or operations than if the two characteristics were separately implemented. Determining the safety performance of interrelated elements can often be difficult; as such, determinations are rarely addressed by design guidance for specific instances, although some scenarios are addressed. One example would be the application of information on ramp terminal spacing. The development of an interchange complexity checklist may be one tool that could assist the practitioner in avoiding combinations of features that exhibit poor safety performance while at the same time illustrating practices that demand consideration.

In the survey of practice, the project team identified 12 interchange modification strategies applied to existing infrastructure where the core configuration of the interchange remained unchanged:

- Construction of C/D roadways in cloverleaf interchanges.
- Construction of braided ramps with nearby service interchanges, with concomitant access limitations.
- Construction of restricted-access—typically high-occupancy vehicle (HOV)—bypass lanes where left entrances or left exits for general-purpose traffic are extant.

- Construction of outside restricted lane direct access ramps to inside-positioned restricted lanes.
- Modification of ramp terminals to permit auxiliary lanes to continue beyond a ramp terminal and then terminate.
- Installation of ramp meters on freeway-to-freeway interchanges.
- Conversion of existing single-lane ramps to two-lane ramps, often with option lane exits at the upstream terminal.
- Addition of service interchange ramps in close proximity to the system interchange, creating the problem of a service interchange exit followed by a downstream mandatory movement from the outermost lane.
- Modification to existing roadways to provide multiple access points for the same exit from the mainline lanes.
- Installation of tolling infrastructure for select lanes or all lanes.
- Closure of direct-access system interchange ramps from mainline lanes due to realignment of ramps to adjacent C/D lanes, changing access points to distances further upstream.
- Construction of long deceleration lanes for left exits.

Interchange Signing Practices

Evaluation of current traffic signing practices in the United States and Canada and countries with available published documentation was conducted to help identify areas where significant variations in practice were observed. The following six areas of significant concern were identified:

- Signing practices for multilane exits with downstream junctions.
- Signing practices for closely spaced interchanges.
- Signing practices for option lanes.
- Signing practices for exit ramps that originate from an exit-only lane where the lane continues to a downstream exit.
- Signing practices for HOV direct-access exits, particularly for interchange exit numbering and sign layout treatments.
- Inconsistent use of arrow types and orientation, particularly for exit-direction signing at the exit ramp departure area.

The following are six other practices of concern for interchange complexity that were also examined, but not in detail, for this report:

- Exit numbering for exits to the same route and direction differing by direction of travel.
- Exit numbering differing between restricted access lanes and general-purpose lanes.
- Superfluous use of pull-through signing at service interchanges.
- Inconsistent use of messages on primary guide signs.
- Inconsistent use of cardinal directions on guide signs.
- Modified exit gore signs with poor design characteristics.

Interchange Pavement Marking Practices

The review of agency practices indicated that agency proficiency with freeway operations appeared to be highly correlated with the use of pavement marking treatments that improve motorist comprehension of lane use and freeway geometric changes.

In particular, the use of "drop line" (wide dotted lane line) markings, dotted extension lines, and gore markings is critical to providing for reduced workload in the "guidance" portion of the driving task. FHWA HFs research posits that there are three tasks related to the operation of a vehicle. Roadway users navigate within the network, using guide signs and other information, and choose a path of travel based on pavement markings, regulatory and guide signs, and other roadway and roadside features. The physical operation of the vehicle, the "control" task, requires appropriate inputs associated with the guidance task.

Typically, a distinction is made between the dotted lane line markings and the dotted extensions. In Washington State, Minnesota, and several other States, the dotted lane line markings are used only adjacent to full-width non-continuing lanes. In some States, their use is restricted to exit-only lanes, so as to not create confusion between exit-only lanes and lanes subject to a downstream lane reduction. The Minnesota Department of Transportation (MnDOT) and Washington State Department of Transportation (WSDOT) call for a 3-ft line with a 12-ft space, permissible per the guidance statements in MUTCD sections 3A.06 and 3B.04. Other States, such as North Carolina, do not distinguish between the dotted lane line and dotted extensions in pattern or width, and some States have eliminated the narrower, closely spaced pattern of the dotted extension (typically a 2-ft line with a 6-ft space) in favor of using 3-ft lines with 9-ft spaces for all dotted markings. Ongoing TCD pooled fund study efforts may help provide the research results that justify additional design guidance and changes to the MUTCD.

Reviews of pavement marking practices indicated that some agencies are extremely proficient in providing uniform markings to indicate the present and downstream status of individual lanes; the delineation associated with exit and entrance ramps; and the marking of gore areas, particularly those in areas with horizontal alignment changes. However, the project team also noted several inconsistent pavement-marking applications, particularly as they are associated with complex interchange features:

- Failure to differentiate between dotted extension markings and dotted lane line markings in width, pattern, and application.

- Failure to use drop line markings in advance of mandatory movements, despite the standard statement in section 3B.04 of the MUTCD.

- Improper application of MUTCD figure 3B-10 for two-lane exit ramps leading to a single destination (application B) and two-lane exit ramps leading to separate destinations (application C).

- Limited or absent lane-reduction arrows; figure 2 displays an effective use of these arrows on a C/D roadway in central Seattle.

- Use of yellow markings to separate lanes of traffic moving in the same direction, on the left side of the traveled way.

- Lack of angled markings in wide areas (e.g., right shoulders) where it is not immediately evident that the space is not reserved as a travel lane; an example is illustrated in figure 3.

- Poor maintenance of lanes in weaving areas.

- Inconsistent applications of dotted extension and dotted lane lines.

Figure 2. Photo. Satellite imagery of northbound Interstate 5 (I-5) C/D roadway north of I-90 with multiple successive lane-reduction arrows.[(28)]

Source: FHWA.

Figure 3. Photo. Washington State Route (SR) 520 westbound near 92nd Avenue northeast.

Barriers to Best Practice

In several States, the project team noted that practices differed between locations, between installations in different time periods, and between regions or districts within a State. While some variations are to be expected, variations in projects in the same administrative region and along the same freeway corridor point to issues with consistent practice within an agency.

Based on a cursory review of agency practices and using notes prepared on previous projects, particularly projects involving the preparation of contract plans, the project team identified the following as potentially contributory to inconsistent application of design principles in interchange design:

- Lack of a systematic approach to guide sign design.
- Lack of centralized review process for signing plans.
- Lack of oversight of agency special project teams (e.g., urban corridors teams and design-build consortium oversight teams).
- Lack of appropriate consultant oversight.
- Lack of knowledge of specialized local conditions.
- Use of sign designers who are not specialized traffic engineers.

- Unfamiliarity of MUTCD requirements and recommendations.
- Unfamiliarity of research on geometric design, signing, and marking practices.
- Not identifying and correcting inconsistencies within a corridor or region.
- Lack of documentation for handling special cases not covered by MUTCD.
- Lack of centralized source for traffic signing approval and management.
- Adoption of new standards, guidance, or options (e.g., different fonts), leading to confusion in sign design.
- Lack of continuity in traffic engineering staff.
- Lack of design road safety audits by outside experts.
- Lack of MUTCD guidance for common lane configurations.

SUMMARY

The findings of this literature and standards review will help guide the efforts of the current project as important complex interchange characteristics are identified, types of challenges that need to be addressed within these interchanges are analyzed, and strategies to address the constraints associated with complex interchanges are identified, while also seeking to improve uniformity and decrease driver confusion.

Previous research and feedback from stakeholders has identified specific scenarios that make interchanges and common challenges associated with them (e.g., close spacing of interchanges results in lack of space for advance signing, density of access points, and short weaving sections) complex, as well as some practices that have been implemented to try and address these challenges.

Previous complex interchange research efforts have also identified driver expectations and subsequent design principles and have begun to work toward identifying solutions for problems that drivers encounter. This information can be used to identify gaps in research or areas that would benefit from additional research and applied to existing complex interchanges. Understanding driver expectations will not only provide insight into what types of scenarios may contribute to the overall complexity of an interchange, but will also help identify modifications that may unintentionally increase the complexity of an interchange.

Driver expectations and design principles will also be used as a guide when designing and implementing signing and marking strategies for evaluation to ensure that signs are intuitive and usable to drivers. In addition, this information will be useful when creating the resulting guidance, visualizations, and decision criteria that practitioners can use. Although guidance that can be adapted to a variety of scenarios will ultimately be developed, it should be consistently based on key design principles and driver expectations. Multiple suggestions and decisionmaking tools that practitioners can use to reduce driver confusion in an attempt to reduce the challenges presented in a complex scenario should be included.

As potential strategies are identified, one should also look into possible modifications that can be made to make them more cost effective, while still providing the same benefits. For example, the current arrow standards for the APL-guide signs require larger signs and structures that may not be financially feasible in some situations. In this case, a reduced arrow size could be evaluated to determine if the signs would still be effective if implemented at a smaller size. Previous stakeholder feedback has already identified some constraints that practitioners face, and stakeholder interviews and working group discussions will help identify additional modifications that could be made to ensure that the signing and marking strategies will be useful to practitioners.

CHAPTER 3. ATTRIBUTES CONTRIBUTING TO COMPLEXITY

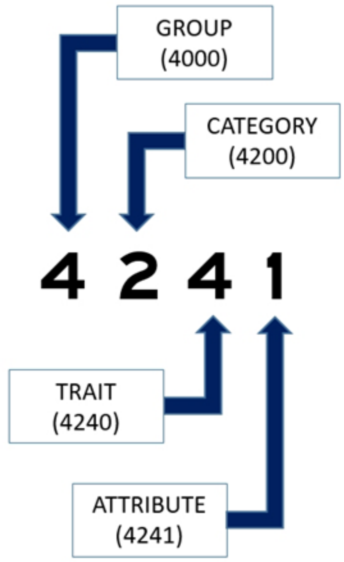
The project team developed a comprehensive list of attributes that contribute to interchange complexity. These 210 attributes were generally related to geometric design, interchange configuration, and some driver-expectancy and driver-comfort factors. From this list, the project team identified 10 topic areas into which the attributes could be grouped, providing a framework for the refinement of potential study sites.

DEVELOPMENT OF ATTRIBUTE LIST

The project team examined interchanges throughout the United States and Canada and identified more than 200 attributes that contribute to complexity. This examination considered prior project research, the literature, experience in design and operations, and in particular, a comprehensive examination of interchange design and operations practices with a particular emphasis on inconsistent applications.

The process for developing the treatments started with small, discrete pieces (attributes contributing to complexity) and moved into assembling those pieces into topics that could be addressed with research efforts. Based on the results of those research efforts, six individual treatments with specific applications were developed.

As an example, the hierarchal organization of attribute 4241 (exit preceding downstream exit only from same lane) is illustrated in figure 4. Each discrete attribute is assigned a four-digit code to aid in organizing the attributes and creating a useful tool for future research activities. The attribute list is divided into seven top-level groups. Within each group, subgroups, described with the nomenclature of "categories," are included to provide for a hierarchy and organization within the groups. In this example, the group is geometric design and the category is ramp terminal arrangements. The categories are defined by the second digit of the attribute code. The third digit is used to identify the trait, which can stand alone or be described as a trait set when it is the hierarchal grouping for multiple attributes. In this example, exit ramp terminal arrangements is the trait. The final digit identifies the specific attribute, which is 4241, exit preceding downstream exit only from same lane.



Source: FHWA.

Figure 4. Graphic. Hierarchal organization of attribute 4241.

The project team noted that there are three types of attributes: characteristic attributes, contributing attributes, and mitigating attributes. Characteristic attributes are simply characteristics of an interchange, such as the presence of an option lane, and may not necessarily be indicative of a complex interchange, whether alone or even in combination with other attributes. The other two types of attributes, however, are indicative of complexity. Contributing attributes (e.g., inconsistency in control cities (2140) or closely spaced exit ramp terminals (4213)) do contribute to complexity to some degree. The interactions between these attributes may cause complexity to a degree that is greater than the sum of the individual contributions to complexity. Mitigating attributes, on the other hand, are characteristics of an interchange that generally relieve complexity, and include attributes such as use of dotted extension (5212), when applied consistently and in conjunction with related elements that support the characteristic. The improper application of a characteristic, however, can create a contributing attribute; therefore, mitigating attributes must be understood in the context of correct and consistent applications. The issue of consistency in applications is further explored in chapter 5.

Group 1000—Impacts and Outcomes

The traits in group 1000 help categorize the impacts and outcomes of TCDs as measures of traffic operations and system performance. These traits are not descriptive of the system's built environment, but rather, its operation. The traffic operations attributes (category 1100, see table 7) describe various aspects of traffic operations, particularly those related to flow theory and performance.

Table 7. Category 1100 traits.

Category 1100	Traffic Operations
1110	Demand
1120	Volume
1130	Density
1140	Speed
1150	Fraction of nighttime operations
1160	Variability
1170	Reliability

Category 1200 (see table 8) continues traffic operations characteristics with an emphasis on those related to congestion. Additional characteristics related to user performance and information processing have been developed in other work, and future research in this area should examine the effects of various information sources on user reactions that affect traffic flow.

Table 8. Category 1200 traits.

Category 1200	Increased Congestion
1210	Reduced headways
1220	Incidents
1230	Slow-downs/information processing

Category 1300 (see table 9) deals with the general causes and outcomes of crashes. Additional future research on complex interchange characteristics that contribute to crashes will further develop the elements of this category.

Table 9. Category 1300 traits.

Category 1300	Crashes
1310	Crash type and severity
1320	ULCs
1330	Erratic maneuvers
1340	Forced lane changes

In addition to the distraction of information processing, users also experience distraction from other factors related to complexity and attendant congestion. These factors, generally categorized as “inconvenience” in category 1400 (see table 10), are socio-psychological in nature and may be difficult to measure.

Table 10. Category 1400 traits.

Category 1400	Inconvenience
1410	Missed exits
1420	Stress
1430	“Road rage”
1440	Letters to FHWA or State transportation departments

The group 1000 attributes are both contributing and characteristic and generally relate to contributing and mitigating user characteristics from group 2000.

Group 2000—User Characteristics

Group 2000 generally addresses user characteristics and includes attributes that influence user perception and reaction while not explicitly addressing those attributes that are indicative of the user’s reaction to complexity.

Category 2100 (see table 11) traits deal with violated expectations, where user experience and intuition are not served by the implementations of geometric design, TCDs, or operations and maintenance. These traits are typically contributing and are caused by categories, traits, and attributes of groups 3000, 4000, 5000, and 6000 and causative of the traits and attributes of categories 1300 and 1400.

Table 11. Category 2100 traits.

Category 2100	Violated Expectations
2110	Unusual interchange configurations
2120	“Non-standard” TCDs
2130	Inappropriate TCDs
2140	Inconsistency in control cities
2150	Poor maintenance

The user profile traits of category 2200 (see table 12) address user characteristics that have been demonstrated to be associated with driver performance and may exacerbate the driver’s response to complexity. Of particular interest here is trait 2240, driver age, as FHWA’s ongoing efforts to address the needs of the aging driver population have identified needs that older drivers have, particularly related to challenging and unfamiliar driving environments.[29]

Table 12. Category 2200 traits.

Category 2200	User Profile
2210	Fraction of unfamiliar motorists
2220	Spoken language
2230	Driver experience
2240	Driver age
2250	Fatigue/emotions/prescriptions
2260	Substance abuse

A brief overview of commercial motor vehicle (CMV) operations indicated specific traits that may present challenges for CMV operators (see table 13). While additional traits related to user characteristics could be assigned to category 2300, such work should involve the Federal Motor Carrier Safety Administration and is outside the scope of this report.

Table 13. Category 2300 traits.

Category 2300	CMV Operators
2310	Too much familiarity
2320	Challenging geometric design

Environmental characteristics have a definite impact on users. Category 2400 (see table 14) addresses environmental characteristics and includes some traits related to category 1100 attributes and traffic flow as causative of HFs responses rather than indicative of congestion.

Table 14. Category 2400 traits.

Category 2400	Environmental Characteristics
2410	Ambient light
2420	Obscured marking
2430	Obscured signing
2440	Traffic density
2450	Traffic speed
2460	Claustrophobic feeling

Group 3000—System Design

The group 3000 categories, traits, and attributes address system design. System design is the overall layout of the road network, including route marking, and the overall design of interchanges, including interchange configuration. System design does not address geometric design choices (e.g., ramp terminal spacing and ramp terminal design). The group 3000 attributes generally contribute to the complexity of the navigation task.

Category 3100 (see table 15) addresses interchange configuration, a component and expression of category 3200 traits and attributes (see table 16), which address system configuration. Interchange configuration traits and attributes include the types and presence of movements, and the application of these attributes influence how road users form a mental image of the interchange and its layout. While geometric design is addressed in group 4000, the overall alignment of the interchange is often a function of its configuration, and alignment-related attributes are addressed in trait 3150.

Table 15. Category 3100 traits and attributes.

Category 3100	Interchange Configuration
3110	System interchanges
3120	Service interchanges
3130	General configuration
3131	System interchange with sub-optimal geometry
3132	Service interchange with system characteristics
3140	Movements
3141	Insufficient capacity for critical movements
3142	Non-provided movements
3143	Multiple accesses provided
3144	Braided ramps without inter-interchange access
3150	Geometric design/alignments
3151	Loop ramps present
3152	Roadway curvature in advance of decision point
3153	Curvature obscures exit ramp terminal
3154	Exiting movement/ramp has no curvature

Table 16. Category 3200 traits and attributes.

Category 3200	System Configuration
3210	Route marking
3211	Concurrent marked routes
3212	Route swaps (left/right to right/left along motorway)
3213	Urban core routing of marked routes
3214	Cardinal direction rotations (east-west route running north-south)
3215	“Ring” roads and signing of direction
3220	System design
3221	Multiple system interchanges in succession
3222	Multiple multi-destination ramps in succession
3223	Changeable accesses to important destinations/event centers
3224	Number of levels
3230	Service interchange surface-roadway access
3231	Different access points for C/D and mainline
3232	Trailblazing from parallel routes
3233	Opposite-direction turns for entrances
3234	Signing for left turns and right turns

Trait 3230 addresses surface street interactions, which can aid or hinder the navigation task on surface streets and contribute to crashes that involve vulnerable users. Additional research on crashes related to surface-network complexity concerns interchange access points, where drivers expect higher speeds and a reduction in delay, which will help develop relationships between network navigation task workload and driver attentiveness to vulnerable users.

Subsequent to the collection and analysis of transportation planning data, the process of designing system interchanges considers the selection of an interchange type based on the basic configurations in the AASHTO Green Book.(16) The selection of the interchange type is often predicated on the typical configurations within the corridor, the spacing of ramp terminals, the need for specific operational strategies on surface streets, and agency experience with constructing and operating particular interchange types. As the design develops, practitioners make choices concerning geometric design, including the location and spacing of ramp terminals; the provision of movements within an interchange network; the geometric design characteristics of the ramps and intersections; and the means of providing for guide signing, route marking, and wayfinding within interchanges.

Existing interchanges may contain less-than-optimal geometric design characteristics and may be inadequate to support demand. In some cases, interchanges were designed and built to provide for some future higher-order interchange or access, and the characteristics of such an interchange may lead to motorist expectations that are at odds with the interchange’s function in the network. In other cases, even the choice of arrow type on an overhead sign may be misleading for the design speed of movements or even the location and arrangement of turn lanes.

The six-ramp partial cloverleaf, for example, can be configured in two ways. In figure 5, the interchange shown permits right turns from the surface roadway and a single exit from the mainline. An alternate configuration places the loop ramps as departures from the mainline or a continuous or terminating C/D roadway. This configuration can result in limited visibility of pedestrian crossings on the loop ramps at the surface street. It also necessitates the provision of either an exit with a downstream split or two exits from the mainline for the intersecting roadway. Attribute 3132 could be a contributing factor in intersection crashes in service interchanges where the roadway geometric design appears to support a higher-order interchange.

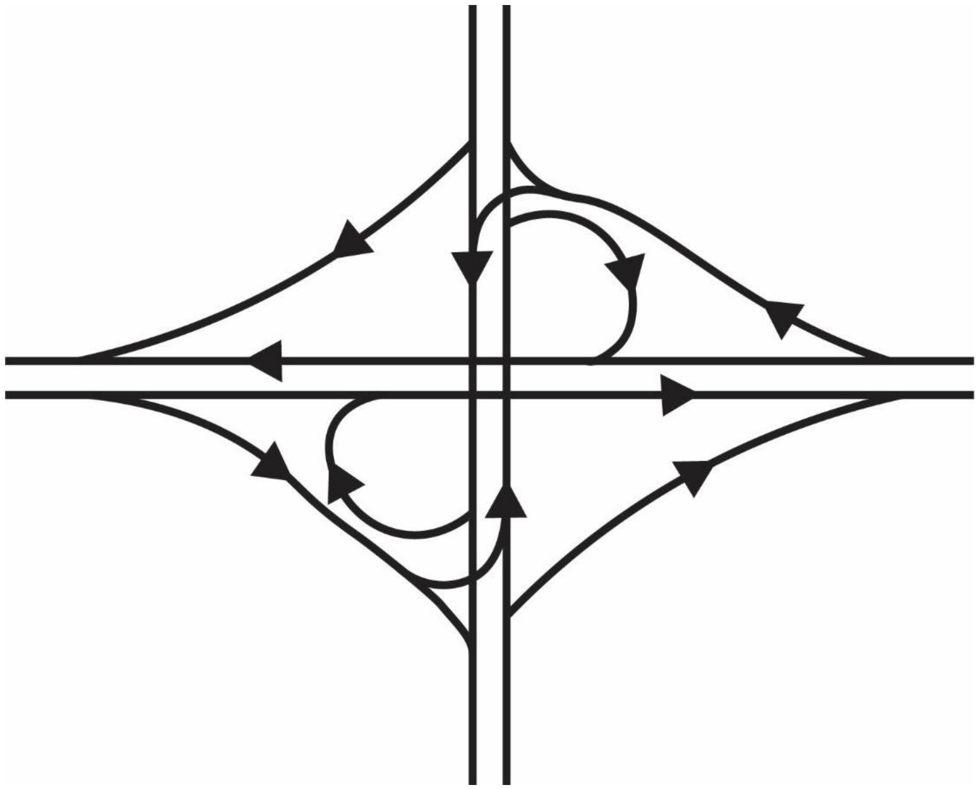


Figure 5. Graphic. AASHTO Green Book excerpt of partial cloverleaf design A, depiction E from figure 10-1.

Attribute 3142 occurs in both urban and rural settings. Practices for signing indicate there is no reentry to the motorway. In some cases, the non-provided movements occur in system interchanges between major routes. The lack of a connecting movement may lead to road-user misrouting, erratic lane changes, and general system inefficiencies. The provision of adequate advance signing is essential. Attribute 3222 is evident in the downtown core areas of several large cities, including on eastbound I-94 in Saint Paul, MN.

Group 4000—Roadway Geometric Design

Group 4000 addresses the geometric design of the roadways within complex interchanges. Category 4100 includes attributes for lane configurations on the approaches to exits and within the ramp terminal areas, including lane balance characteristics. The group 4000 categories, traits, and attributes contribute to the complexity of the guidance task, including lane selection and time-based demands on drivers. While these are influenced by interchange layout, they are factors generally related to geometric design choices.

Category 4100 is divided into four traits (see table 17 for traits 4110 and 4120; see table 18 for traits 4130 and 4140). Trait 4110 relates to the length and presence of auxiliary lanes, as defined by AASHTO, between interchange segments and in advance of exit ramps and subsequent to entrance ramps. Trait 4120 addresses the roadway design characteristics and cross section upstream of and at exit ramp terminals. Trait 4130 addresses entering lanes and the geometric design characteristics of cross-section and acceleration lanes. Finally, trait 4140 relates to the concept of lane balance, which is evaluated for all ramp terminals. Many of the attributes are merely characteristic, but some can be both mitigating and contributing. For example, attribute 4136 may appear to be mitigating, as long acceleration lanes might help to reduce weaving and other unsafe driving behavior, but improper or insufficient signing (addressed from group 5000) of such situations can impact traffic safety and operations because drivers may become confused. Warning sign installations should be considered in these cases.

Table 17. Trait 4110 and 4120 attributes.

Category 4100	Lane Configuration
4110	Auxiliary lanes
4111	Auxiliary lane present
4112	Short auxiliary lanes
4113	Auxiliary lanes not provided between closely spaced ramp terminals
4120	Exiting lanes
4121	Exit-only lanes
4123	"Escape" lanes (MnDOT practice)
4124	Option lanes
4125	Multiple exiting lanes
4127	Exit ramp with tapered design (no deceleration lane)

Table 18. Trait 4130 and 4140 attributes.

Category 4100	Lane Configuration
4130	Entering lanes
4131	Multiple entering lanes
4134	Entrance ramp with tapered design (no acceleration lane)
4135	Short acceleration lanes
4136	Long acceleration lanes
4140	Lane balance
4141	Lane count in cross section
4142	Entrance lanes n > downstream thru lanes n (inside-lane merge)
4143	Exit lanes n > upstream thru lanes n (see attribute 4124)
4144	Lane continuity not present

Trait 4140, lane balance, includes one type of lane balance addressed specifically by AASHTO's Green Book.[16] The design of entrance ramps for freeway facilities is typically of two types, either the parallel design or the tapered design. Either design is acceptable for single-lane entrances, but the use of the tapered design for multilane entrances can create complications. In situations when the tapered design is used for multilane entrances at major convergences, there is a high potential for safety and operational drawbacks, particularly with large vehicles. Road-user operation, in this environment, can be especially demanding because both the operation and piloting tasks are taxed as users anticipate and execute the merging maneuver. The following list identifies the impacts of the tapered design characteristics for multilane entrance ramps:

- **No clear assignment of right-of-way exists for entering vehicles.** Although vehicle paths and the through lane could be remedied with pavement marking, it would remain unclear how the yielding vehicle is to avoid a conflict.

- **No recovery area is available for vehicles that are unable to complete or are prevented from completing the merge.** The lack of a shoulder for either merging vehicle eliminates an escape path.

- **Increasing taper distances compound uncertainty.** As the volumes and design speed increase, the longer taper creates a longer area with enough width for two lanes, further reducing the intuitive visual impact of converging pavement markings.

- **Larger heavy vehicle volumes can increase difficulty of merging maneuvers.** Trucks need more room to negotiate the merge and space to occupy the destination lane. This can precipitate lane changes and speed reductions in the destination lane, impacting the capacity of the affected lane and increasing safety risks.

- **Capacity collapses under high volumes.** The merge maneuver required by the tapered design requires more judgment, a difficult speed-matching activity, and more time, all of which are factors leading to a potential reduction in capacity. The parallel design is generally preferred because it enables drivers to perform a simple lane-change maneuver from the adjacent and parallel lane.

Furthermore, FHWA has published the *Highway Design Handbook for Older Drivers*, often referred to as the Design Handbook, which cites research that indicates tapered merges, even for single-lane entrance ramps, are difficult to navigate.(29) Add to that all the insufficiencies of the inside-lane merge situation, and the case could easily be made against such installations in high-volume system interchanges. Principles of design for older drivers are applicable to most geometric design issues and certainly a worthwhile study in any design undertaking. The *Highway Design Handbook for Older Drivers* states the following:

> Another issue addressed by NCHRP 3-35 was acceleration lane geometry. Koepke (1993) reported that 34 of the 45 States responding to a survey conducted as a part of NCHRP 3-35 on SCL's use a parallel design for entrance ramps. Thirty of the agencies interviewed use a taper design for exit ramps and a parallel design for entrance ramps. The parallel design requires a reverse-curve maneuver when merging or diverging, but provides the driver with the ability to obtain a full view of following traffic using the side and rearview mirrors (Koepke, 1993). Although the taper design reduces the amount of driver steering control and fits the direct path preferred by most drivers on EXIT ramps, the taper design used on entrance ramps requires multitask performance, as the driver shifts between accelerating, searching for an acceptable gap, and steering along the lane. Reilly et al. (1989) pointed out that the taper design for entrance lanes poses an inherent difficulty for the driver and is associated with more frequent forced merges than the parallel design. Forced merges were defined as any merge that resulted in the braking of

> lagging vehicles in Lane 1, or relatively quick lane changes by lagging vehicles from Lane 1 to a lane to the left. The parallel design would thus appear to offer strong advantages in the accommodation of older driver diminished capabilities. (p. 137)[29]

The Green Book addresses the issue of the parallel design in chapter 10: "Generally, parallel designs are preferred. While tapered designs are acceptable, some agencies are concerned about the inside merge on the tapered entrance ramps" (p. 821).[16] The project team has identified approximately 12 sites in Illinois, including 1 constructed as recently as 2006. One site, the convergence of eastbound I-80 and I-94 in Lansing, IL, features a multilane entrance of the tapered design where the minimum recommended merge length of 2,500 ft was not met (see figure 6). Both freeways feature a truck percentage of approximately 50 percent.[30]

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Figure 6. Photo. Multilane entrance ramp with tapered design, I-80 at I-94 eastbound, Lansing, IL.[31]

Category 4200 includes traits and attributes that address ramp terminal arrangements, including the spacing and relative arrangement of ramp terminals (see table 19). Ramp terminal arrangements are independent of lane configuration. The key trait in this category is trait 4260: decision point interactions (see table 21), which is a candidate for future research examining the effect of ramp terminal arrangement choices, relating in particular to multiple categories in groups 3000 and 4000.

Table 19. Trait 4210 attributes.

Traits 4210	Ramp Terminal Spacings
4211	Closely spaced ramp terminals (short weaving area)
4212	Closely spaced entrance ramp terminals
4213	Closely spaced exit ramp terminals
4214	Density of option lane exits

Traits 4220 and 4230 are omitted from the current version of the attributes list to permit future expansion of the attribute tables to address other interactions related to geometric design considerations considered in ramp terminal design, particularly related to managed lanes and tolled facilities.

Trait 4240 (see table 20) addresses the ramp terminal arrangements from the perspective of ramp sequence and road-user perception of exit order and proximity. Specific information that explains some attributes associated with trait 4240 is provided in the subsections that follow.

Table 20. Trait 4240 attributes.

Trait 4240	Exit Ramp Terminal Arrangements
4241	Exit preceding downstream exit only from same lane
4242	Exit with downstream split of distributor roadway
4243	Exit with downstream right exit from distributor roadway
4244	Exit with downstream left exit from distributor roadway
4245	Directional ramps out of order relative to direction of travel
4246	Directional ramps swapped at ramp terminal relative to direction
4247	Option lane preceding downstream exit-only movement
4248	Exit-only movement preceding downstream “escape lane”
4249	Option lane preceding downstream “escape lane”

Attribute 4244—Exit with Downstream Left Exit from Distributor Roadway

Left exits present challenges from mainline freeway lanes and can lead to confusion on distributor roadways. In the case shown in figure 7, the left exit from the distributor roadway for I-4 southbound carries left-turning traffic to United States Route (US) 192 eastbound. However, the primary movement in the interchange is the ramp to US 192 westbound, which is accommodated with two lanes.

Figure 7. Photo. I-4 distributor roadway upstream of US 192 interchange in Kissimmee, FL, showing left exit from the distributor roadway.[32]

In this particular case, upstream signing is provided, advising road users who intend to head eastbound on US 192 “TO KEEP LEFT.” This type of signing is not uniformly provided in similar circumstances, however, and additional emphasis on the presence of a left-hand movement, such as a “LEFT EXIT” supplemental plaque, is typically warranted when high volumes are present.

An example of explicit, simplified signing, sometimes referred to as "positive guidance," is illustrated in figure 8, where multiple signs are provided, including a ground-mounted exit-direction sign and overhead exit-direction sign with angled down arrows.

Source: FHWA.

Figure 8. Photo. Ramp from I-35E southbound to I-94 and US 52, Saint Paul, MN.

Attribute 4245—Directional Ramps Out of Order Relative to Direction of Travel

One example of attribute 4245 is the interchange of US 175 and I-20 southeast of Dallas, TX (see figure 9). The southeast-bound movements from US 175 to I-20 are out of order relative to conventional thinking about left and right turns.

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Figure 9. Photo. US 175 interchange with I-20 in Dallas, TX, with upstream exit carrying left-turning traffic to northeast-bound I-20.[(33)]

Typically, to turn right, a road user would keep to the right and, therefore, be making the first right-hand movement. In some applications of this interchange configuration, turning right requires remaining out of the right-hand lane and using the second right-hand exit. On this approach, the right lane serves the left-turning movement first and then terminates as a mandatory movement lane to the lower-volume movement to westbound I-20. This case compounds the problem as it also involves topic 3, the upstream exit from a lane terminating as a downstream exit-only lane.

In contrast to trait 4240, trait 4250 addresses the configuration of the interchange in localized areas related to how ramps are positioned relative to the roadway (see table 21). While ramp sequence is the focus of trait 4240, ramp configuration and access are the focus of trait 4250.

Attribute 4253 ("swap-sided" exits), while occurring rarely, is particularly problematic. When directional exits are available from both sides of the freeway, road users typically expect that the left-side exit will provide a left-hand movement and the right-side exit a right-hand movement. However, if the exits are swapped, not only does the left exit exist but it is also not intuitively directional.

Such circumstances exist when the right-hand movement is the primary direction of travel and carries a marked route associated with the upstream segment. In these cases, additional signing and explicit use of geographic destinations are often provided, in addition to posting of the marked route and direction in conjunction with the exit gore sign.

Table 21. Trait 4250 to 4270 attributes.

Category 4200	Ramp Terminal Arrangements
4250	Exit ramp interchange configurations
4251	Multilane exit ramps in succession
4252	Left-side exits
4253	"Swap-sided" exits
4254	Entrance preceded by opposite-side exit
4255	Left-side entrances
4256	C/D roadways
4257	Major splits
4260	Decision point interactions
4270	Expectancy violations
4271	Asymmetric lane balance at ramp terminal

Category 4300 traits and attributes relate to the cross-sectional elements of geometric design (see table 22). Numerous research studies have indicated that these elements alone do not contribute to complexity but can exacerbate the effects of complexity and contribute to crashes where other attributes exist. In particular, the lack of shoulders (attribute 4311), when associated with attribute 4142 (the tapered multilane merge), eliminates a potential escape path for vehicles that cannot merge as a result of lack of a gap or driver hesitancy. In addition, attribute 4142 was found in this research to be typically associated with traits 2120, 2130, 4340, and 4350.

Table 22. Category 4300 traits and attributes.

Category 4300	Geometric Design/Cross Section
4310	Shoulder width sub-optimal
4311	General-purpose lane (right)
4312	General-purpose lane (left)
4313	Auxiliary lane (right)
4314	Auxiliary lane (left)
4320	Narrow lanes
4330	Concrete barrier less than minimum width distance
4340	Wider lanes without appropriate delineation
4350	Unmarked/non-signed merging areas
4360	Sight distance sub-optimal/sight distance limitations

Group 5000—TCD

TCDs provide information that aids both the navigation and guidance tasks and, when implemented consistently and when needed, can reduce the complexity of the navigation task considerably.

Category 5100 traits and attributes, which deal with traffic signing, address the mitigating and contributing attributes with the recognition that some of those attributes, when presented in a physical device, could reduce complexity or increase it.

Traits 5110 and 5120 address information load in both proclivity (e.g., the amount of information and its distribution) and message characteristics (e.g., the composition, configuration, and type of messaging) (see table 23). One example of this is attribute 5122, use of route names with route shields. In Chicago, IL, and in the New York metropolitan area, for example, these names are used in common parlance and are an aid to the navigation task. In other areas, the superfluous information on guide signs may simply mean additional information is being presented for processing, which increases driver workload.

Table 23. Traits 5110 and 5120 attributes.

Category 5100	Traffic Signing
5110	Information load/proclivity
5111	Density of signs
5112	Spacing of critical signs
5113	Signs on one structure
5114	Excessive supplemental and ancillary signing
5115	Use of business logo and specific service signs in urban areas
5120	Information load/message characteristics
5121	Messages per sign
5122	Use of route names with route shields
5213	Messages per structure

Trait 5130 attributes address the design and implementation of guide signing for option lanes (see table 24). The MUTCD currently provides four methods for signing option lanes, and States are using additional methods, some uniformly and others not appearing to adhere to existing practices or sign design principles.

For the purposes of this research, three styles of option lane signing were considered. The method used most often is the discrete arrow method, where a single down arrow is provided over each lane in advance of the interchange, typically with signing over only the exiting lanes. The newly introduced APL method is described here as the blended arrow method, because it uses a combination of arrows on the sign panel, some with both one arrowhead and others with two. Finally, the venerable diagrammatic method is considered. This report does not address the problems associated with multiple down arrows pointing into a single lane.

Table 24. Trait 5130 attributes.

Trait 5130	Guide Signs for Option Lanes
5131	Distances on advance signing
5132	Discrete arrow
5133	Blended (APL)
5134	Diagrammatic
5135	Omission of option lane from signing

Trait 5140 attributes describe guidance for freeway signing in the gore area (table 25).

Table 25. Traits 5140 through 5180 attributes.

Category 5100	Traffic Signing
5140	Explicit specific ("positive") guidance in gore area
5150	Colored indexing panels
5160	Advisory speed on sign panel
5170	Sign design policies (beyond MUTCD)
5171	Overhead signing provided
5172	Panel separation by movement
5173	Use of borders and dividing lines
5174	Advance guide signs display distance to exit
5175	Right lane must exit (lane use control arrow) signs in use
5180	Exit numbering
5181	Old/former exit numbers in use
5182	Lack of exit numbers
5183	Exit numbers out of sequence in one direction
5184	Exit numbers non-matching in opposite directions

The attributes of trait 5190 (see table 26) are considered pivotal to the design of good overhead freeway signing. The use of guide sign-specific arrows from the MUTCD ensures arrow legibility from a distance. Arrow type, size, angle of rotation, and position on the sign all combine to convey specific information from distances beyond the legibility distance for associated word messages and other symbols.

Table 26. Trait 5190 attributes.

Trait 5190	Arrow Design and Selection
5191	Down arrows used in advance of exits
5192	Type A and type B arrows used at service interchange exits
5193	Down arrows used at major splits
5194	Type A and type B arrows angled 30 degrees upward off vertical at typical exits
5195	Differentiation for “blended arrow” signs between advance and exit directions
5196	Arrow placement on panel over center of lane (overhead signs only)
5197	Arrow placement on panel in legend group, preserve green space

Roadway delineation, in the form of pavement markings and roadside delineation, is critical to the guidance task and must support the navigation task. Category 5200 traits and attributes address pavement marking by marking orientation in three traits: longitudinal, transverse, and symbols (see table 27). In addition, the use of supplemental and substitute markings, including raised reflective pavement markers (RRPMs), is imperative for lane delineation during inclement weather, and roadside delineation is used in States where snowfall is experienced to aid in the guidance task and to assist with maintenance operations.

Table 27. Category 5200 traits and attributes.

Category 5200	Pavement Markings
5210	Longitudinal markings
5211	Use of “dotted line”
5212	Use of “dotted extension”
5213	Solid lines in advance of exits
5214	Improper markings of double exit-only and adjacent exit-only lanes
5220	Transverse markings
5221	Marking of wide shoulder areas
5222	Marking of long, “shallow” gore areas
5230	Symbol markings
5231	Only and arrow markings (for mandatory movement lanes)
5232	Multi-headed arrow markings (for option lanes)
5233	Lane-reduction arrows
5234	Route markers on pavement
5240	Pavement markers (reflective and substitute)
5241	Raised pavement marking patterns for drop lanes
5245	Illuminated markers for managed lanes
5250	Colored pavements
5260	Roadside delineation
5261	Reflective markers (vertical delineation)
5262	Rumble stripes (secondary function)
5623	Vertical delineation in gore area
5264	Progressive roadside delineation approaching ramp terminals

Group 6000—Management and Operations

System management and operations philosophy, practice, and execution continue to have an increasing impact on traffic operations. The implementation of these strategies, though often a mitigating factor in traffic congestion, can contribute to interchange complexity. Nearly all of these attributes result in an increased driver workload in advance of decision points and generally require driver knowledge of the management strategy to guarantee comprehension and proper use.

Category 6100 traits and attributes relate to restricted and managed facilities, including restricted-use lanes, managed lanes, tolled lanes (addressed specifically in category 6500), and various iterations of the implementations that can include reversible facilities and other management strategies designed to optimize the use of the network (see table 28).

Table 28. Category 6100 traits and attributes.

Category 6100	Restricted/Managed Facilities
6110	Restricted lanes
6120	Restricted exits
6121	Arrangement of sign panels
6122	Use of exit numbering
6130	Restricted entrances
6131	Restricted bypass lanes (for ramp meters)
6132	Restricted ramps
6133	Restricted bypass ramps
6140	Reversible facilities
6141	Open to all traffic
6142	Restricted and partially restricted
6150	Restricted bypass lanes
6160	Restricted bypass roads
6170	Variable HOV restrictions

Category 6200 includes system management strategies that microscopically manage demand, as opposed to the categories 6100 and 6500 attributes, which are macroscopic-level demand-management tools (see table 29). While certainly more tools are available, the project team identified one trait that can increase the complexity of the navigation task, particularly when longer queues are involved.

Table 29. Category 6200 trait.

Category 6200	System Management
6210	Freeway to freeway ramp metering

The information systems traits and attributes in category 6300, like most system management strategies, can mitigate complexity by aiding in the navigation task but can also increase complexity where information processing workloads are highest (see table 30). Understanding driver reaction to user information and the sequencing and presentation of user information is the key to reducing the adverse effects of user-information systems on driver workload in complex environments.

Table 30. Category 6300 traits and attributes.

Category 6300	Information Systems
6310	Highway advisory radio
6320	Variable message sign equipment
6321	Mounting of signs
6322	Spacing of signs
6323	Message policies and consistency

Category 6400 traits and attributes relate to active traffic-management systems (see table 31).

Table 31. Category 6400 traits and attributes.

Category 6400	Active Traffic-Management System
6410	Variable speed limits (speed harmonization)
6420	Congestion warning systems (queue warning)
6430	Environmental condition warning systems
6440	Variable lane use
6441	Incident-managed
6442	Volume-managed (junction control)
6450	Part-time shoulder use (shoulder running)
6460	Variable-destination fixed signing (European Union: dynamic rerouting)
6470	Free/flexible rerouting systems using variable message sign

In practice today, no system management strategy seems to be evolving faster than roadway pricing, either for congestion management or simply for finance and operations (see table 32). Congestion pricing by means of road segment pricing is conducted by a variety of schemes and, even within one region, various schemes are applied to the roadway network or even along the length of the corridor. Road-user decisionmaking, particularly related to navigation and lane selection, can become a task-saturated process when road users must make decisions on price tolerance, compliance with regulations, and destination availability from the managed facility in a framework that changes throughout a region.

Table 32. Category 6500 traits and attributes.

Category 6500	Pricing (Tolling)
6510	Facilities
6511	Lanes
6512	Connectors
6513	Entire segments
6514	Entire facilities
6515	Bridges
6520	Rate set
6521	Fixed
6522	Time-of-day
6523	Variable (historic)
6524	Variable (responsive)
6530	Multiples of the following attributes:
6531	Classifications
6532	Payment methods
6533	Tolling points
6534	Priced segments

Category 6600 traits and attributes relate to incident response and resilience, including the operation and work of traffic-management centers (TMCs) and incident management strategy (see table 33). In an interchange with other attributes related to complexity, incident response operations can exacerbate complexity by increasing driver workload, reducing capacity, and affecting the spacing between access points.

Table 33. Category 6600 traits and attributes.

Category 6600	Incident Response
6610	Shoulder use and immediate-tow regulations
6620	Incident response policies and procedures
6630	Police/fire policies on motorway closures
6640	System resilience
6641	TMC readiness and capabilities
6642	Diversion strategies for incident response (use of restricted lanes)

As system management strategies and techniques further evolve, it will likely be necessary to divide group 6000 into additional groups. Future publications concerning freeway operations, congestion pricing, and incident response will guide this work. To accommodate this, the project team left group 7000 and group 8000 unused.

Group 9000—Institutional Factors

The categories in group 9000 relate to institutional factors, typically exclusive of technical policy addressing the implementation of TCDs (see table 34). Agency policies, processes, and preferences for planning, design, design documentation, standards development, and cost control all affect the design and operation of interchanges in urban areas. Overall agency philosophy, particularly as it relates to the importance of traffic engineering support and HFs integration, is cultivated over a length of time, and long-term philosophies can also affect the agency's delivery of projects, operations, and maintenance. Finally, fewer agencies today plan for long-term facility expansion, but those that do tend to integrate future geometry into existing projects, ensuring that future constructed improvements satisfy geometric design requirements.

Table 34. Group 9000 categories.

Group 9000	Institutional Factors
9100	Planning and interchange design study policies
9200	Design documentation and standards
9300	Value engineering
9400	Agency philosophy
9500	Planning for future facility expansion

SELECTION OF TOPICS

Attributes from all groups were examined so that related attributes and those with potential and known interactions could be organized and addressed with a single research activity. The following criteria were used to help identify topic areas and select attributes related to those topic areas:

- Crash modification factor for improvements rates higher than other attributes.
- Demonstrated to affect capacity and or safety performance.
- Attribute common in many older or poorly performing interchanges.
- Subject to correction with TCD changes and minor geometric adjustments (for existing interchanges).
- Identified as critical or problematic by the stakeholder working group.
- Identified as recurring design flaw/shortcoming by the stakeholder working group and the project team.
- Determined to be an area of inconsistent practice in field applications.

Table 35 lists the 10 topics used to develop the research plan in addition to identifying the type of testing proposed to address each topic. These testing types generally fell under the work of the simulator study (chapter 6) and the field study (chapter 7), which were designed to develop a better understanding of these attributes and their interactions.

Table 35. List of topics advanced for testing.

Topic Number	Trait/Attribute Number(s)	Topic Description	Type of Testing Proposed
1	1120, 1130	Traffic volume and density impacts	Field video
2	4222, 4223, 4224, 4232	Confusion related to ramp terminal placement and sequence	HFs lab Field video
3	4221	Upstream non-mandatory exiting movement from an outside lane terminating as a downstream mandatory exiting movement	HF lab Field video
4	2110, 2120, 2130, 2140, 3152, 3154	Impacts of violation of expectations	HF lab
5	3131, 3132, 3142, 3221, 3222	System design characteristics	HF lab Field video
6	4130, 4140, 4210	Impacts of ramp arrangements	HF lab Field video
7	4110, 4120, 5130	Signing and marking for auxiliary and option lanes	HF lab Field video
8	5110, 5120	Information loading, panel layout and design, and specific messaging for guide signs	HF lab
9	5210, 5220, 5230	Pavement markings	HF lab Field video
10	6120	Impacts of restricted lane exiting maneuvers	HF lab Field video

CHAPTER 4. SITE EVALUATION AND SELECTION

Following on the initial screening of previous related work, the literature review, and an initial examination of attributes related to interchange complexity, the project team selected four States to serve as partners in this project. The intention of the State transportation department participation was to permit for streamlined access to sites for data collection purposes and the easy acquisition of background information on safety performance and traffic operations related to each site selected from those under the jurisdiction of the participating agencies. This process included the selection of partnership States, the preliminary site list, and the final site list. The site selection process was detailed in the *Site Selection Report*[1], submitted in December 2014, and that information is included here.

SELECTION OF PARTICIPATING STATES

The process of selecting participating States was conducted in coordination with FHWA and the technical evaluation panel. The project team identified seven characteristics of a suitable partnership agency:

- Freeway system in a large urban area or mega-region.
- Established, published sign design criteria.
- Mixture of central office and regional oversight of planning, design, and operations.
- At least one interchange with an unusual configuration.
- Interchanges exhibiting attributes from the preliminary attributes list.
- Agency commitment to working with FHWA.
- Availability of agency staff and resources to support project.

Subsequent to a review of the States meeting these characteristics, the project team identified four suitable agencies. These agencies and the characteristics of the complex interchanges within their jurisdictions are listed in table 36.

[1]The Site Selection Report was an internal report submitted as a deliverable as a part of this project. This internal deliverable was submitted to FHWA in December 2014.

Table 36. Participating agency list and characteristics.

Participating Agency	Characteristics
Florida Department of Transportation	• Established practices for freeway signing with uniformity throughout the State. • I-4 through Kissimmee features multiple braided ramps along a segment inclusive of five interchanges in an area with a high percentage of unfamiliar drivers.
Georgia Department of Transportation (GDOT)	• Atlanta area is home to several interchanges with original, retrofitted, and new designs. • GDOT is implementing APL signing.
MnDOT	• Established practices for freeway signing with uniformity throughout the State and central office oversight of freeway signing. • I-35W/TH 62 interchange features two subsequent option lane splits with multiple approaching lanes for each split.
WSDOT	• Freeway signing duties split between central office and region staff. • Extensive use of option lanes throughout the State. • Retrofits of existing interchanges to ease congestion.

TH 62 = State Trunk Highway 62.

PARTNERSHIP AGREEMENTS AND MEMORANDA

Each State was invited to sign a partnership agreement. The intent of the agreements was to clearly define relationships and responsibilities for the involved parties, identify areas where State transportation department contributions could occur, manage the relationships and contacts with agency staff, and provide a managed scope for efforts in support of the research project.

All four agencies provided prompt communication. The sheer size of agency operations, however, precluded timely information on sign replacement projects throughout each jurisdiction, and individual project delays that were beyond the control of the project team prevented some data collection activities from taking place during the course of the project.

Host State Documentation

Some State agencies have produced comprehensive materials in support of freeway design tasks (e.g., interchange configuration, ramp terminal design, freeway corridor design, and the design of freeway signing and pavement markings).

MnDOT produces a document that addresses specific sign-design criteria, using FHWA publications as a basis for design assistance. The MnDOT *Traffic Guide Sign Design Manual* provides design criteria not specifically addressed in the MUTCD or the *Standard Highway Signs Catalog* (SHS).[34,35] For example, the manual provides specific information on fractions sizes and the design and use of guide sign arrows. Publications from other agencies address other aspects of guide sign design, including the arrangement of the legend, a method for determining how many legend elements appear on a sign (for sizing of signs where standard legend sizes are not used), and specific design and use criteria for signs related to tolling systems.

SITE SELECTION PROCESS

In tasks 4 and 5, the project team conducted testing and evaluation of various traffic engineering treatments in an effort to demonstrate which treatments are likely to address specific HFs, operational, and safety performance needs in the complex interchange environment. Field work at these interchanges was the basis for evaluations of real-world driver behavior. While the team anticipated data collection concomitant with regular signing replacement and upgrading work, internal agency communications and the proximity of other construction contracts prevented this from being a practical work product during this project.

Selection Criteria

The original candidate site list numbered 70 interchanges from throughout the United States and Canada. The initial 35 junctions were compiled during the development of the complex interchanges spreadsheet tool. The remaining 35 interchanges were selected by the project team. Factors influencing the selection included the following:

- Similarity to nearby interchanges or interchanges of similar type in other regions.
- Geographic dispersion within administrative regions.
- Geographic dispersion throughout the United States.
- Location in States that are probable candidates for working agreements.
- Presence of numerous attributes related to complexity.
- Presence of multiple attributes related to complexity on a single approach.
- Presence of differing treatments for similar geometric designs within a single interchange or administrative region.
- Age of signing within the interchange.
- Type, extent, and age of modifications and improvements.
- Compliance with contemporary design criteria.
- Traffic congestion experience.

The project team did not analyze crash history in the selection process. However, in some cases, selected interchanges were inclusive of geometric design features that appear to have been subject to various safety treatments in an effort to mitigate crashes. The team’s field visits to these sites included an examination of roadside design elements and the presence of devices used to reduce the severity of roadway departure crashes, including redirective elements and energy dissipating elements. In some cases, obvious or known retrofits of upgraded impact attenuation equipment indicated that task saturation or insufficient information may be occurring upstream of that location.

In the original process, the project team considered interchanges located in Canada. Signing and pavement markings in Canada differ, in some cases, from applications in the United States. One interchange in British Columbia was newly constructed and features an application of blended APL signing that is similar to the practice outlined in the 2009 MUTCD. The team chose not to conduct field analysis at these sites, owing to the complexity of international travel and the provision of suitable sites within the United States.

Candidate Interchange Sites

Table 37 lists the interchanges that were selected as candidate sites for further evaluation, including the gathering of data, photographs, and other information.

Table 37. Final list of candidate sites for evaluation with field study activities.

Number	State	Location	Municipality (Region)
11	Florida	**I-4:** SR 417 to SR 536 (five interchanges with braided ramps)	Kissimmee
24	Georgia	**I-75:** I-285 (northwest)	Atlanta
25	Georgia	**I-75 at I-85:** North of Downtown Atlanta	Atlanta
26	Georgia	**I-85:** I-285 (southwest)	College Park (Atlanta)
27	Georgia	**I-85:** Georgia Route 400 (toll)	Atlanta
28	Georgia	**I-85:** I-285 (northeast)	Atlanta
31	Minnesota	**I-35W:** TH 62	Minneapolis
32	Minnesota	**I-35W:** Minnesota Highways 36 and 280	Minneapolis
35	Minnesota	**I-94:** I-694 westbound entrance ramp	Maple Grove
41	Washington	**I-5:** I-405 and Washington SR 518	Tukwila
42	Washington	**I-5:** I-90 and Downtown exits	Seattle
43	Washington	**I-5:** US 101 to SR 510 (three study interchanges)	Olympia

Not all of the candidate interchange sites were included in evaluation and study activities. Additional sites were selected for the final list so that some redundancy in site availability would be possible in case of unplanned impacts to sites. For this project, sites 25, 26, 27, 28, 32, 33, 41, and 42 were not evaluated using field data collection. For these sites, evaluation was limited to the collection of photographs and observations based on drive-through activities. Complete descriptions of the field study sites are provided in chapter 7.

In addition, the initial candidate list included three sites from California. Because California was not selected to be a participating State, these locations were not included for evaluation with field study activities. The sites did provide important context, however, for how agencies deal with multiple exiting lanes, direct-access ramps from restricted lanes, and C/D roadway systems. Each of these sites, listed in table 38, exhibits attributes related to complexity.

Table 38. Candidate sites for evaluation without field study activities.

Number	State	Location	Municipality (Region)
X1	California	**I-880:** California Route 237	Milpitas (Bay Area)
X2	California	**I-110:** I-105	Los Angeles
X3	California	**I-5:** California Route 22/57	Santa Ana (Los Angeles)

For each interchange, a separate sheet has been provided. These interchange description sheets include satellite imagery of the interchange and a brief description of specific characteristics that set that particular interchange apart from others. This information is included in appendix A.

The sites selected for evaluation are inclusive of interchanges and freeway corridor segments. Within each site, several locations may be identified to help adequately describe the specific areas of individual study tasks. For example, site 31 has been divided into three locations, location 31-1, location 31-2, and location 31-3, each inclusive of one approach to the interchange.

STUDY EFFORTS

The site selection process and the work of the practices evaluation and field study resulted in a final list of sites examined in detail in this project. Table 39 lists the final field study sites, detailing where project personnel undertook in-person evaluations or collected data, including those locations where only photographs were collected.

Table 39. List of field study sites with field study effort descriptions.

Number	State	Location	Data	Municipality
11	Florida	**I-4:** US 192 to SR 535	UAV	Kissimmee
26	Georgia	**I-85:** I-285 (northeast junction)	Photographs	Atlanta
27	Georgia	**I-20:** I-285 (west junction)	Video	Atlanta
28	Georgia	**I-85:** I-285 (northeast)	Photographs	Atlanta
31	Minnesota	**I-35W:** TH 62	Video	Minneapolis
32	Minnesota	**I-35W:** Minnesota Highways 36 and 280	Photographs	Minneapolis
35	Minnesota	**I-94/694:** I-494 (west junction)	UAV	Maple Grove
41	Washington	**I-5:** I-405 and Washington SR 518	Photographs	Tukwila
43	Washington	**I-5:** US 101 to SR 510	UAV	Lacey, Olympia

TH 62 = State Trunk Highway 62; UAV = unmanned aerial vehicle.

CHAPTER 5. PRACTICES EVALUATION

The project team conducted a practices evaluation prior to the final site selection process and at the beginning of the field study and simulator study. The purpose of the practices evaluation was to determine, by means of site visits and a scan of photographs and videos available to the project team, the variations in the application of engineering design undertaken by various States.

Subsequent to examining signing and pavement marking practices in various States, the project team assessed uniformity between different applications to help identify persistent inconsistencies in design and fabrication and to develop recommendations. The summary of practices here is the foundation for the recommendations in chapter 9, including recommended future research and policy evaluation activities.

Because the practices evaluation was not conducted as a research activity with data collection for statistical analysis, traditional methods of evaluating the applicability and effectiveness of practices were not suitable. Instead, the project team developed a new methodology for evaluating traffic engineering practices on the basis of a logic model. This model is referred to here as the consistency principle.

DEFINING INCONSISTENCY

The outcomes from TCD installations are typically evaluated in the field using various proxy measures of effectiveness, including crash experience, conflicts, volume, and speed. In laboratory tests of TCDs, legibility, comprehension, and subject reaction to devices in a driving simulator are typically used as measures of effectiveness.

One significant drawback to these studies is that they are limited to the devices being used in the laboratory studies or the devices in place in the field. A review of the literature indicates that some devices considered effective by agencies are not included in laboratory tests, and the results of those tests occasionally indicate the use of a device that may, in fact, be less effective than devices already in use in the field. In addition, devices in laboratory tests and field tests are occasionally not compliant with the MUTCD or exhibit properties that are inconsistent with accepted traffic engineering practice.

The project team developed an independent logic model for evaluating TCD installations. This logic model is intended to facilitate comparisons between settings and implementations.

A setting is defined as a geometric design or layout with discrete characteristics in terms of number of lanes or the arrangement of lanes. The layouts in the simulator study are examples of settings. An implementation is defined as the use of a TCD or a system of devices with specific characteristics. The use of a particular warning sign in a particular location is an example of an implementation. An alternative implementation would be the use of a different warning sign in the same location or perhaps the use of the same warning sign but in a different location. In practice, implementations are applied to settings.

The consistency principle holds that implementations are reserved for specific settings and the use of an implementation across multiple, discrete, differing settings reduces the application of logic in identifying the setting based on the implementation. If left-hand curve warning signs are used only for left-hand curves, the left-hand curve sign (an implementation) will always indicate the presence of an upcoming left-hand curve (a setting). If a left-hand curve warning sign were used to indicate a right-hand curve, the road-user expectancy is violated.

To identify the various inconsistencies between settings and implementations, the project team created an applications matrix (see table 40). Using the inconsistency matrix, logic-based generic examples were created that can be applied to field cases.

Table 40. Applications matrix for inconsistency identification.

Prefix	Name	Description
C	Consistent application	Different settings Different implementations
D1	Diametric inconsistency	Different settings Swapped implementations
D2	Broadening application	Different settings Identical implementations
S	Erratic application	Identical settings Different implementations
U	Unrelated application	Identical or different settings Unrelated implementations

Using the generic logic models, five consistency matrices can be created. One matrix illustrates true consistency while the others illustrate two types of inconsistency. The two that illustrate inconsistency among different settings are classified as implementation-dependent, using the prefix "D." The two that illustrate inconsistency among identical settings are classified as setting-dependent, using the prefix "S."

This logic model can be used to compare applications across locations with identical settings, across locations with dissimilar settings, and in segments leading up to an interchange where cross-sectional characteristics change along the length of the roadway.

Implementing Consistency

It is important to note that, whether or not a practice represented a departure from established standards such as those found in the MUTCD, the project team considered all practices that exhibited any inconsistency to be candidates for evaluation. Inconsistent application of implementations to one or more settings is the foundation of nearly all violations of what is commonly referred to as driver expectancy. Quite simply, a driver expects to see implementation A associated with setting A and not setting B, where the application of implementation B is expected. Failure to observe the consistency matrix in freeway design is especially critical because driver expectancy is often relied on in the absence of other cues, in situations where heavy traffic blocks the view of pavement markings or where large vehicles prevent signing from being visible.

Both broadening application and erratic application lead to inconsistent road-user expectations. Some practitioners argue that prescribing specific use cases for TCDs and indicating clear designs in the MUTCD is some type of a "secret code" that only practitioners will know and that few will practice. This viewpoint fails to consider that consistently applied TCD treatments, with narrow use cases and uniform applications, will lead to road users adapting to the treatments, recognizing the relationships, and reacting appropriately when presented with information in the form of TCD treatments.

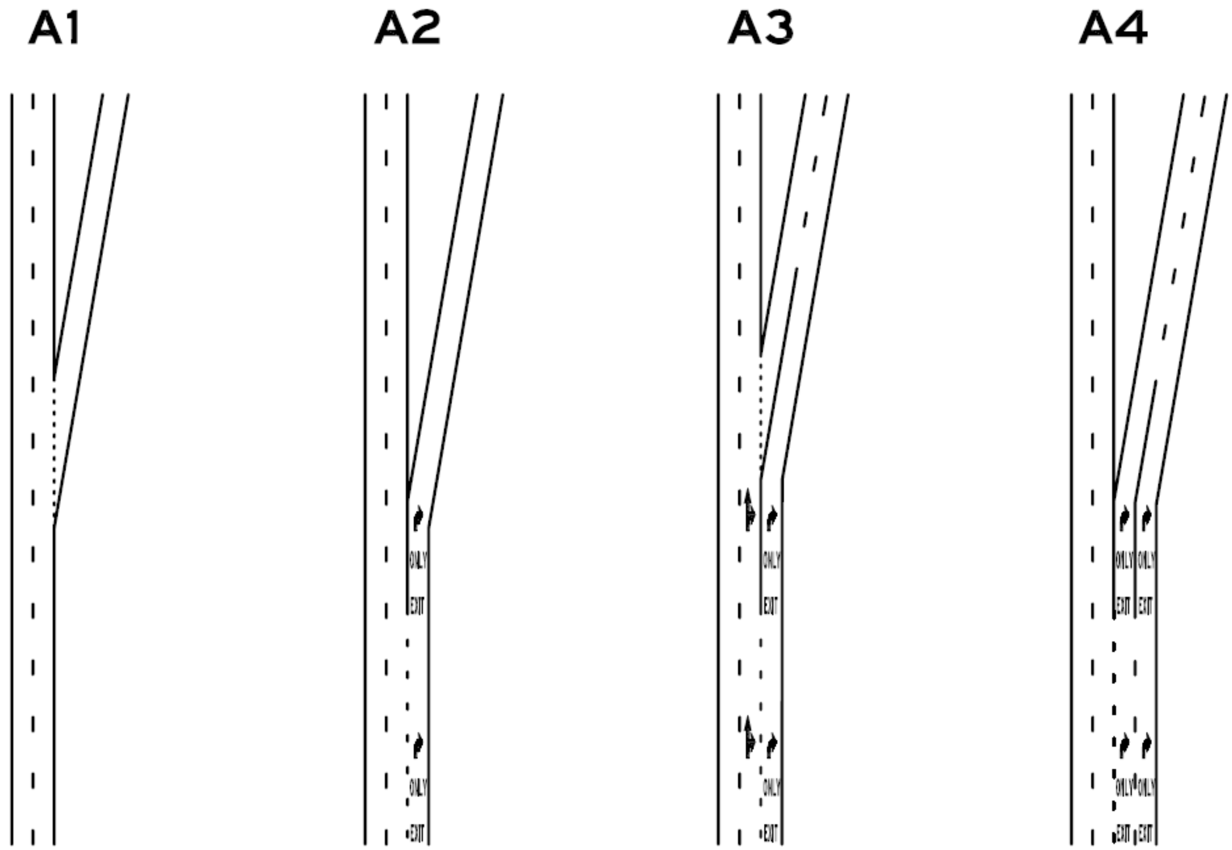
INCONSITENCY EXAMPLES

An example of inconsistency that can be studied from the perspective of both field implementations and traffic engineering policy is the use of various arrows on overhead guide signs in interchanges with option lanes.

Option Lane Signing

The signing of option lanes on freeways and expressways is a contentious issue in traffic engineering practice today, having been the topic of numerous proceedings in the meetings of both the National Committee on Uniform Traffic Control Devices and the AASHTO Subcommittee on Traffic Engineering. The option lane is illustrated in depiction A3 in figure 10.

Figure 10 shows that there are indeed four distinct cases of freeway exit types. For each of these cases, the guide signing must be treated differently; common signing methods follow.



Source: FHWA.

Figure 10. Graphic. Configurations of exiting lanes.

Figure 11 shows example signing for an exit with an option lane. Although this practice is included in the MUTCD, the MUTCD does not include the use of what will be referred to in this report as the discrete arrow method of signing for option lanes (see figure 12), which includes the yellow ONLY panel to distinguish between the option lane and the exit-only lane. Nonetheless, in current practice, approximately 35 States use the discrete arrow method of signing option lanes. Several States have also begun using the so-called APL signing, which this report will refer to as the blended arrow signing. Both the discrete arrow and blended arrow methods can use one arrow per lane, so the term “APL” can be considered a technical misnomer. An example of the two signing methods is illustrated in figure 12.

Source: FHWA.

Figure 11. Photo. Example of exit-direction signs based on MUTCD figure 2E-12.

Source: FHWA.

A. Discrete arrow guide sign (conventional practice).

Source: FHWA.

B. Blended arrow guide signs (APL).(22)

Figure 12. Graphics. Two examples of guide signs for option lane signing.

A U.S.-wide review of practices undertaken as part of a previous research effort identified four examples of practices and policy that serve as evidence of inconsistency in the application of option lane signing:(30)

- Three different methods for signing options lanes are permitted by the MUTCD.
- Although not included in the MUTCD, some agencies use a discrete arrow concept as shown in figure 12.
- Some agencies continue using multiple down arrows for each lane, despite specific prohibition in MUTCD.
- The use of angled down arrows, one per lane, in the discrete arrow method was a practical means of indicating roadway curvature and, yet, is no longer permitted.
- Down arrow use historically indicated major or pull-through movements, while angled type A and type B arrows indicated exiting movements.

Design of blended arrow guide signs can be challenging for legend arrangements and other key factors. Achieving effective guide sign design may require training to convey the principles of guide sign design and the appropriate use of sign design software.

The exit-direction sign shown in figure 13 matches the design in MUTCD figure 2E-11.(22) It shows two exit-only lanes at the gore, although one of the lanes is an option lane. One potential reason given for the use of the signs in figure 13 in option-lane applications is that, if the sign is placed far enough down the gore, both lanes are indeed exit-only. However, the road user’s attention is focused on the upstream geometrics that they encounter and the sign should adequately display those conditions so that the user’s decision, made in advance of the gore, is informed by an appropriate indication of the geometrics.

Source: FHWA.

Figure 13. Photo. Example of exit-direction signs.

OBSERVED PRACTICES

The project team visited several major metropolitan areas not included in the partner States to identify additional situations that are not directly addressed in the MUTCD.

Geometric Design and Traffic Control Devices

The following subsections describe several geometric designs and signing options for exit and entrance ramps.

Closely Spaced Exit Ramp Terminals

In some instances where closely spaced exit ramp terminals exist, the strategy of co-locating advance primary guide signs with the distances to each exit was used. Where the exit-direction sign for the first exit was placed overhead, an advance primary guide sign for the second exit was also included, often with a distance to the exit given in feet rather than fractions of a mile.

Several States, including Minnesota, provided full roadside delineation between some closely spaced exits, typically in the form of panel-style, post-mounted, white delineators. In cases where shoulders were in place, transverse, angled markings were placed across the shoulder to discourage its use and clearly identify the point where the second exit taper begins.

States addressing closely spaced exit ramp terminals generally appeared to address navigation issues and guidance issues by using a combination of additional guide signs, explicit distance information, and increased pavement markings and delineation.

Entrance Ramp into an Upstream-Extant Exit-Only Lane

The TCDs used to address this scenario varied most widely among all of the scenarios studied. In some States, the auxiliary lane was treated with overhead "EXIT ONLY" advance primary guide signs and exit-direction signs in combination with dotted lane line and arrow pavement markings; regulatory signing; and occasionally, preemptive signing on the entrance ramp into the auxiliary lane. This scenario can also be addressed with a "THRU TRAFFIC MERGE LEFT" warning sign, which when placed on the entrance ramp, provides an unambiguous message.

Cloverleaf Interchanges

Most cloverleaf interchanges include short auxiliary lanes between the ramp terminals of the entering loop ramp and the subsequent exiting loop ramp. In some States, these auxiliary lanes are marked with standard broken lane lines, and overhead signing does not indicate an exit-only movement.

In other States, dotted lane line pavement markings are used to separate the mainline lanes from the short auxiliary lane. Few States use "EXIT ONLY" overhead signing for these movements. Generally, the stated reason is that the auxiliary lanes are very short, and because the sign is visible prior to the beginning of the lane, it may be mistaken as applying to the right-hand lane upstream of the loop ramp entrance and development of the auxiliary lane.

The project team is aware of some international sites that were signed with a type of diagrammatic sign showing the entering ramp, a short segment of concurrent roadway, and the exit ramp.

Signing for Exit-Only Lanes Near an Exit Ramp

Many locations inappropriately use "EXIT ONLY" panels on signing at or past the theoretical gore of an interchange. Per chapter 2E of the 2009 MUTCD, "EXIT ONLY" panels on overhead APL guide signs shall not be located at or near the theoretical gore. This inconsistency violates user expectancy where in one case (e.g., sign is not located at or near the theoretical gore) the exiting lane continues, and where in another case (e.g., sign is located at or near the theoretical gore), the lane is dropped and exits the highway.

Signing of Short Continuing Auxiliary Lanes After Exit Ramps

MnDOT has used short continuing auxiliary lanes, or "escape lanes" in geometric design for more than 20 yr. These lanes are typically a short-distance continuation of an auxiliary lane that allows traffic in the auxiliary lane to continue straight, if necessary, even though that practice is discouraged by signing. In most cases in Minnesota, the lane reduction for the escape lane is not signed, as it is typically signed as an exit-only lane at the point of departure. In New Mexico, recent freeway reconstructions have incorporated escape lanes into the design of interchanges with an auxiliary lane.

In figure 14, signing for a lane reduction near the exit is shown. Note that the option lane is signed as an exit-only lane because the lanes have been fully formed.

Source: FHWA.

Figure 14. Photo. Escape lane signing that does not adhere to the consistency principle because the continuing lane is signed as an exit-only lane.

Including Exit Numbers on Interchange Sequence Signs

Some agencies include exit numbers on interchange sequence signs. This practice appears to be more prevalent in dense urban centers where multiple exits occur in succession and the supplemental guide signing for the exits cannot uniformly be placed in sequence prior to just one exit ramp. In all observed cases, the exit numbers were placed to the left of the street name or route marker (the destination of the exit), and adequate space was provided between the exit number and the destination or route marker.

Arrangement of Legend on Exit Gore Signs

There are several methods for arranging legends on exit gore signs. In figure 15, the left-hand image displays an observed exit gore sign. Note that the legend "EXIT" is centered on the sign panel, and the exit-direction arrow is positioned in the lower right-hand corner of the sign, not aligned with any legend on the sign. An alternative used by some agencies is to group related elements together. To reduce the width of the sign, which is desirable in most gore areas, the right-hand image is used as the design practice in several States, including Minnesota. This modified design mitigates the issue of legend grouping each element of the sign on a separate line.

Source: FHWA.

A. Exit gore sign with standard arrangement.

Source: FHWA.

B. Exit gore sign with legend grouping applied.

Figure 15. Photos. Exit gore signs.

Applications of exit gore sign delineation were also found to vary with differing legend sizes, arrow sizes and types, and arrow angles.

Omitting Intermediate Advance Guide Signs With Lane Drops

One practice observed in multiple States was the omitting of intermediate advance guide signs in advance of lane drops—that is, where a mandatory exiting movement occurs. While the installation of three signs (at 1 mi, at ½ mi, and at the departure point) is desirable, some States omit the ½-mi sign, even when a continuing lane is being dropped. In addition, several States do not use distances on "EXIT ONLY" signing, a practice that appears to be related to maximum sign size for cantilever trusses. It should be noted the MUTCD reserves use of distances on lane drop signing to distances of ½ mi or greater.

Omitting Distances on Advance Guide Signs

Omission of the distances on advance guide signs is becoming more common on freeways; the project team believes that the cause is a desire to reduce the area of the sign in an effort to control costs.

The problem is especially apparent in the large blended arrow signs being installed in many urban areas in the United States. Figure 16 illustrates signing with no displayed distances to the exit (or exits, in the case of multiple exits from the mainline, which are also signed with this same approach in other places). The lack of displayed distances is shown by the two red rectangles toward the bottom of the sign. In addition, the red square encompassing the right side of the sign depicts how this sign design does not separate out the right two lanes onto a separate panel. Dividing information on separate panels was found to produce greater upstream final lane selection confidence according to the simulator study (see chapter 6).

Source: FHWA.

Figure 16. Photo. New installation of blended arrow guide sign in North Carolina.

Inconsistent Arrow Design

Use of short-shaft arrows in place of the type B arrow is becoming prevalent (see figure 17). Recall that types B, C, and D are not permissible on freeway and expressway guide signs. Interviews have revealed that sign fabrication contractors are not using the MUTCD-standard arrows or the SHS designs but, rather, are using software-provided arrows manipulated to approximate what appears on shop drawings.

Source: FHWA.

A. Arrow underneath route shield

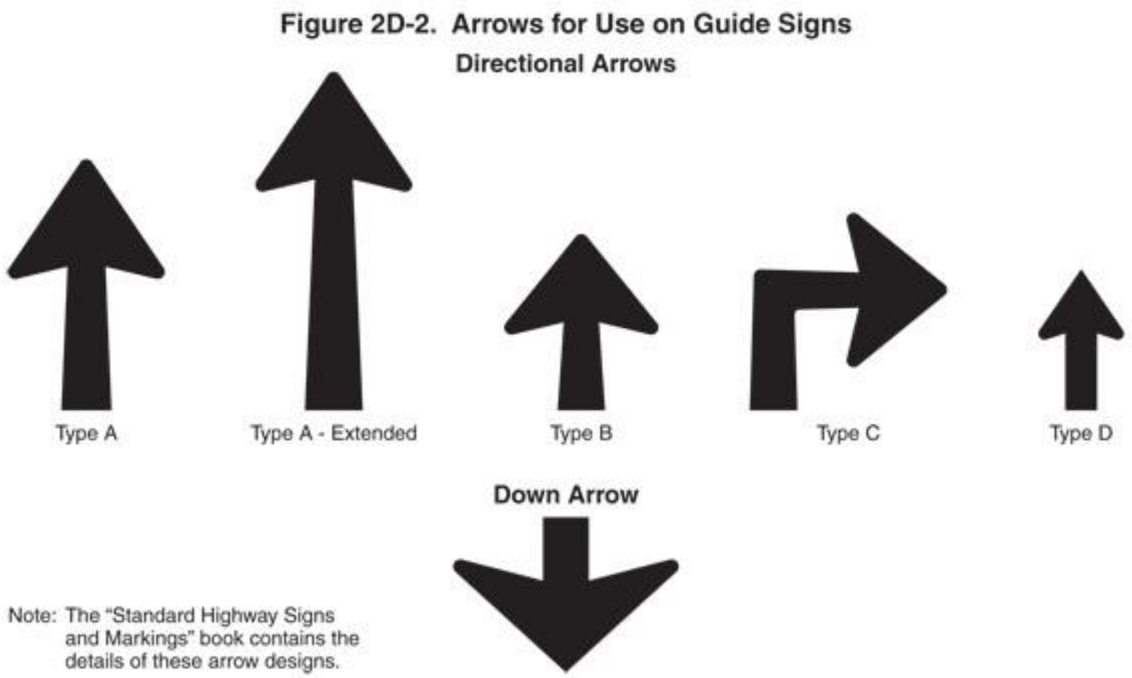
Source: FHWA.

B. Arrow next to route shield

Figure 17. Graphics. Two examples of inconsistent arrow design.

Use of Guide Sign Arrows

The MUTCD prescribes arrows per use on guide signs, in MUTCD figure 2D-2 displayed in figure 18. A comprehensive policy on the use of guide sign arrows is not currently available at the national level, although some States have more guidance for practitioners.



Source: FHWA.

Figure 18. Graphic. Arrows for use on guide signs (MUTCD 2009, figure 2D-2).[22]

Omitting Interchange Sequence Signs

In urban areas, the use of interchange sequence signs assists motorists in spatially locating their desired destination along the length of an upcoming segment of freeway. This is especially important in situations where the exit for a major interchange occurs prior to the exit for a service interchange where the overcrossing of the intersecting roadway is upstream of the major interchange.

Lane-Reduction Signing

The design of acceleration lanes typically takes into account the entrance ramp geometric design, the expected approach speed of vehicles on the entrance ramp, the expected speed of vehicles on the mainline, and the mainline and ramp volumes. Auxiliary lanes shorter than optimal can affect traffic operations when vehicles encounter an unexpected reduction in the physical number of lanes.

The primary issue causing complexity with acceleration lanes is the inconsistency in how they are signed and marked. Even within agencies, inconsistency of signing and marking practices leaves road users with insufficient information to form an expectation. Furthermore, the differences between treating short and long acceleration lanes, particularly with respect to signing, indicates a lack of understanding among practitioners of how explicit, case-specific pavement markings and the placement of warning signs and vertical delineation can assist road users in identifying the beginning of lane-reduction tapers for acceleration lanes.

In addition, the misapplication of signs in these areas can lead to road-user confusion and drastically increase the difficulty of comprehending the roadway geometric design. These misapplications include the following:

- Using lane-reduction signs along full-length auxiliary lanes, instead of the R3-33 "RIGHT LANE MUST EXIT" sign.
- Using the "THRU TRAFFIC MERGE LEFT" warning sign in place of lane-reduction signs in places where a physical reduction in the number of lanes occurs.
- Using a mixture of W9-1, W9-2, and W4-2 warning signs, at varying distances, in advance of lane reductions for long acceleration lanes.
- Using two identical warning signs in sequence without adding a supplemental distance plaque to the upstream sign.

Other ongoing research is looking into these issues in more detail.

Pavement Markings and Delineation

The design of pavement markings for situations not specifically described in the MUTCD requires a practitioner to consider how drivers perceive the markings, and the importance of maintaining consistency of width, color, and pattern between applications. This is critical not only for pavement markings consisting of longitudinal and transverse lines, but also markings created with point markers (e.g., RRPMs and non-traversable areas created by means of delineator posts). The project team observed pavement marking implementations inconsistent with the consistency principle, including the following:

- Inappropriate application between patterns for dotted extension lines and dotted lane lines.
- Use of white pavement markings and delineators on the left side of one-way facilities.
- Use of yellow pavement markings between travel lanes moving in the same direction.
- Incorrect use of angled transverse markings when chevron markings are required.

Typical Applications of Pavement Marking Patterns

Pavement marking patterns play an important role in providing road users with information on the status of a lane, whether continuing or not, whether there is a transition taper or not, and the type of restriction in the lane or restrictions for movement into and out of the lane. Of equal importance is the maintenance of markings, especially in areas where snow and precipitation are common, something undertaken to a higher degree of success in Europe for example.

In general, roadway facilities have six distinct classes of pavement marking pattern applications, outlined in table 41.

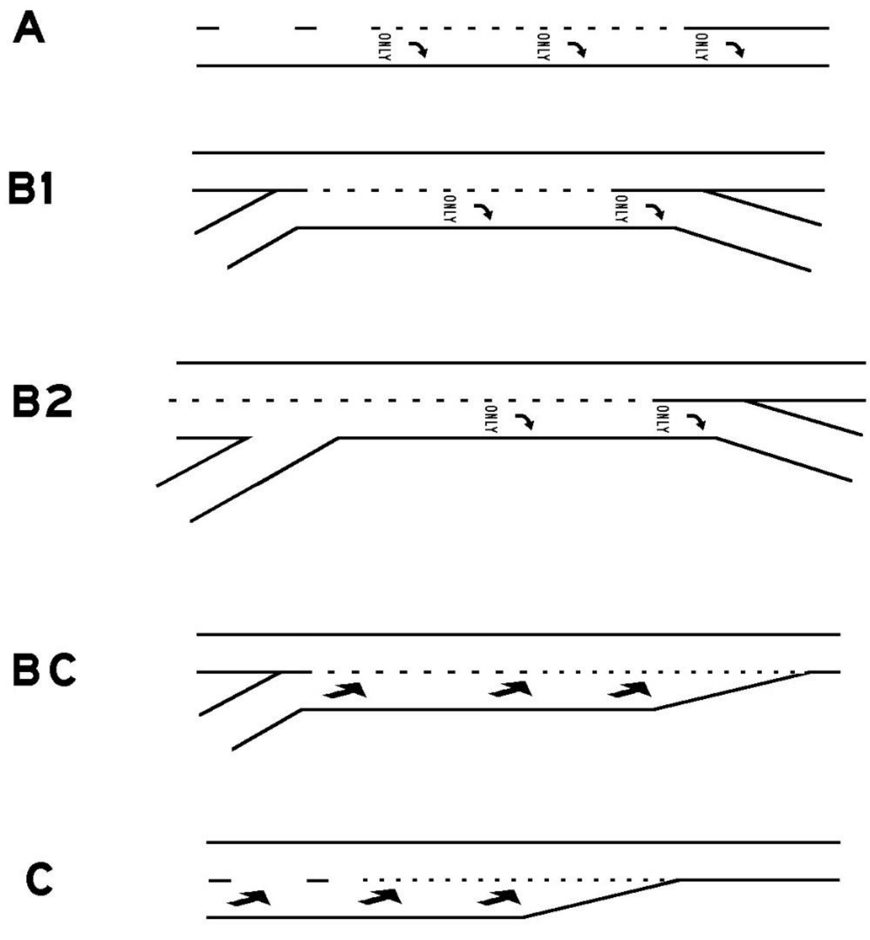
Table 41. Pavement marking patterns and typical uses.

Pattern	Typical Dimension	Use
Broken lane line	10-ft line/30-ft space	Separates two continuing lanes
Wide dotted lane line (drop marking)	3-ft line/12-ft space	Separates a continuing lane from a non-continuing lane subject to a downstream mandatory turn or exit movement
Dotted extension	2-ft line/6-ft space	Separates a full-width lane from an area of transition, such as a lane development taper for a turn lane, continuance of an edgeline through an intersection, or between turning lanes within an intersection
Solid line	Solid	Separates a continuing lane from a non-travel lane, such as a shoulder or, when wider, separates a continuing lane from a non-continuing auxiliary lane such as a turn lane or other mandatory movement lane, or separates lanes designed for restricted use
Double solid line	Solid	Separates lanes where crossing from either side is prohibited
Solid line with broken or dotted lane line	Mixed	Separates lanes where crossing from one side is permitted but crossing from the solid side is prohibited

The typical uses of pavement marking patterns here can be applied to various scenarios of continuing, non-continuing, and terminating lanes, using patterns in conjunction with each other, perhaps in double-line configurations.

In addition to width, color, and pattern, the texture of the pavement marking can also be important. In regions with limited snow removal activities, the use of textured and profiled markings has been used as a replacement for non-reflective raised pavement markers. These profiled markings cause a tactile sensation for road users, and the use of these markings, particularly in conjunction with roadside delineation, can be an effective mitigation against roadway departure crashes.

Figure 19 illustrates five geometric design settings. Depictions A, B2 and C show geometries that are commonly used in many States. An emerging practice observed in many States is the use of the dotted lane line for the geometry in depiction B1 and depiction BC. In heavy traffic, particularly in cases where the acceleration lane taper is of significant length, motorists may mistake the acceleration lane (BC) for an auxiliary lane (B1), and may fail to vacate the acceleration lane. Road users on the major facility may similarly mistake the lane and move into it, not realizing that the lane terminates. Even the use of a lane-reduction warning sign and lane-reduction arrows may be insufficient in heavy traffic, especially if auxiliary lanes are generally provided in locations along a corridor.



Source: FHWA.

Figure 19. Graphic. Configurations of exiting and entering lanes.

Inconsistent Use of Dotted Lane Lines

Preserving a distinction between these two patterns is critical to the effort engineers should undertake to provide consistency among usage cases. Some agencies use the same marking cycle for all dotted lines, regardless of the intended use. Other agencies have preserved the marking pattern for dotted lane lines that specifies a 12-ft gap, as opposed to a 9-ft gap, recognizing the importance of that larger ratio in preserving this distinction between the dotted extension marking pattern and dotted lane line marking pattern, especially when coupled with the use of wider lines for dotted lane line installations.

Comparison of the dotted lane line and dotted extension line applications in depiction BC of figure 19 reveals how the change in pattern is an effective way to indicate that the lane is approaching its termination point. The exclusive use of the dotted extension (i.e., avoiding broadening-usage cases) will ensure that road users interpret it as indicating an area of transition, a taper forming a lane or terminating a lane. In figure 20, the same marking pattern is used along the entire length of the left-hand acceleration lane, a left entrance from another freeway. The lack of advance lane-reduction arrows, roadside delineation, and signing for the lane-reduction taper could be mitigated with a transition in pavement markings, a cue to road users that the status of the lane is changing.

Source: FHWA.

Figure 20. Photo. Left-hand acceleration lane terminating in a lane-reduction taper.

Omission of Dotted Extension Lines

The use of dotted extension lines in lane reductions was identified chapter 2 as a practice of several States. Many other States use dotted extension lines in lane addition tapers, as well, but typically only if the lane is a non-continuing lane. In figure 21, a freeway-to-freeway ramp is shown emerging from a tunnel in a left-hand curve. Added on to the left is a left-hand auxiliary lane, which serves as the deceleration lane for a left-hand exit from the C/D roadway.

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Figure 21. Photo. Overhead view of entering ramp (lower right of image) with asymmetrical widening to the left in a left-hand horizontal curve.[36]

In this location, the dotted extension line is not being used to delineate the edge of the continuing lane. However, in many States, such a marking would be applied in this case. A dotted extension line applied here would help guide left-turning traffic into the through lane, which atypically is to the right. In addition, while guiding traffic out of the left-hand lane, the dotted extension would also allow for visual perception of the widening by means of the increasing distance in the triangular area between the left edgeline and the dotted extension line. In figure 22, the superimposed red line graphic shows the location of the left edgeline in the area of the asymmetrical widening over and beyond a crest vertical curve.

Figure 22. Photo. Location of left edgeline in an asymmetrical widening over and beyond a crest vertical curve.[37]

Observations at this location during free-flow traffic periods indicated that roughly two-thirds of vehicles continuing straight onto the freeway (not taking this left-hand service interchange exit) tracked into the auxiliary lane, such that at least one tire moved across the dotted lane line markings that begin beyond the railway overcrossing.

Omission of Lane-Reduction Arrows

In addition to using a change in longitudinal pavement markings to indicate a lane change, lane-reduction arrows can be particularly helpful at providing another cue to drivers that a lane change is required.

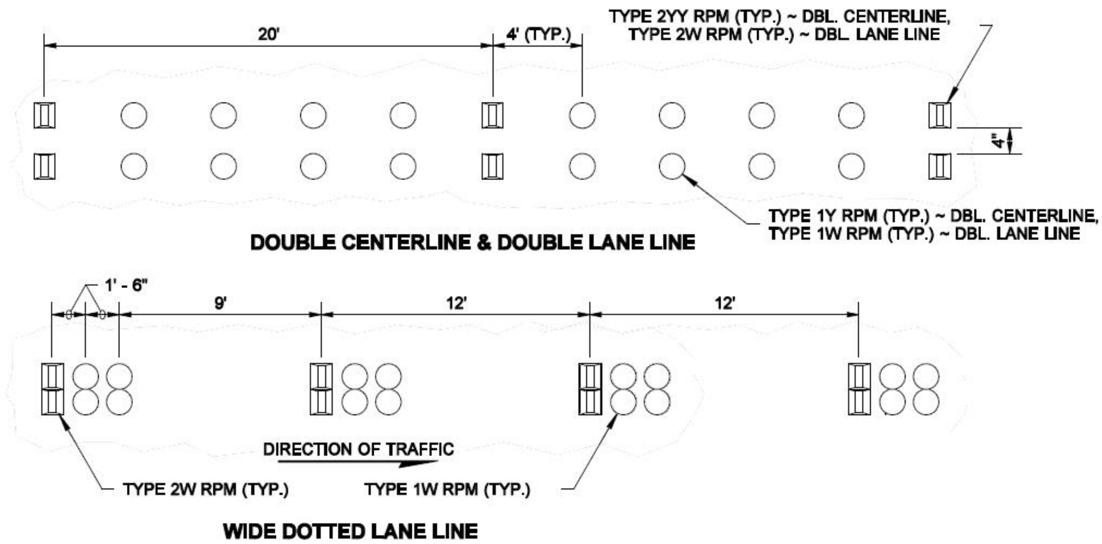
Use of Yellow Delineators

The use of yellow delineation adjacent to white pavement markings may be contributing to guidance task failures, particularly during inclement weather. For example, yellow delineation used on the left edge of a freeway while also being used on both sides of an exit gore (where white delineation should be used adjacent to the mainline lanes) may lead to confusion over the corresponding edge of the roadway.

RRPMs

While a change in marking patterns is useful to road users, a change in the marking patterns may prove detrimental if the change is not progressive. Examining the transition from a broken lane line to a dotted lane line to a dotted extension, for example, leads to the conclusion that the pattern becomes visually more restrictive as the road user moves through the patterns. When RRPMs are placed, their installation cycles typically correspond with the associated longitudinal pavement markings. Longer spacing between RRPMs is logically associated with a less-restrictive marking, missing markers notwithstanding. In fact, most agencies do not use RRPMs in transition areas, those being the development tapers of turn lanes and the termination tapers associated with lane reductions. Even if those areas are marked with dotted extension lines, the markers are omitted, partially to preclude the intensive replacement cycle due to traversing traffic but also because movement across those areas is encouraged, when desired by the navigation and piloting directives of the road users.

WSDOT uses substitutionary markers for pavement markings in certain cases, typically consisting of round, 4-inch, non-reflective, domed markers and RRPMs. Comparison of the double lane line marking pattern (most restrictive) and dotted lane line pattern (intended for information) in figure 23 reveals that the less-restrictive marking (the dotted lane line) features reflectors spaced at roughly one-half the interval of the more restrictive marking (the double lane line). A short drive along any exit-only lane reveals how disorienting and counterintuitive this marking pattern can be, especially in areas of horizontal curvature where edgelines may be supplemented with RRPMs at 20-ft intervals as well.



Source: WSDOT Standard Plan M20.50-02.

Figure 23. Graphic. Excerpt from WSDOT Standard Plan M20.50-02.[38]

INSTITUTIONAL OBSERVATIONS

In addition to examining technical policy and its application in practice, the project team also examined institutional operational and management policies and practices to determine how those might affect the design and operation of complex interchanges. While further examination of these issues is outside the scope of this project, the initial investigation revealed three major policy characteristics.

First, the project team found that, in States with consistent signing practices and where application of TCDs most adhered to the consistency principle, a formal sign design training course was often present and actively provided across all agencies ranging from the State transportation department–level to local agencies and consultants. MnDOT publishes the agency's sign design course online and offers additional content, including sign support selection and the preparation of signing plans. States with strong central traffic sign design expertise, yet lacking the training course, also demonstrated improved consistency in practice. In some of those States, central office staff assisted region staff in reviewing consultant-prepared plans, aiding in consistent design practices and ensuring that State traffic engineering policy was addressed in project development.

Secondly, the project team discovered that States with long-standing traffic engineering expertise and institutionalized funding for traffic engineering activities generally had comprehensive policy manuals and more consistent applications of TCDs, particularly on freeways. Some States have demonstrated statewide consistency in traffic engineering, owing to the centralized nature of the traffic engineering publications and the presence of large urbanized areas with well-developed freeway systems. In States with limited freeway networks, common errors in guide sign design and application were observed far more frequently.

Finally, State transportation departments' central office–level management of large-format sign design, as is the case in Minnesota and Washington State, seemed particularly correlated to a reduction in fabrication errors and incorrect field installations.

CHAPTER 6. SIMULATOR STUDY

To prepare for the simulator study, the project team conducted the tasks outlined in earlier sections of this report. The literature review identified existing research, results, and limitations. The practices evaluation provided insights into the existing practices of agencies throughout the United States and Canada. The identification of attributes contributing to complexity and the development of topic areas provided focus for the simulator study and the selection of sites for the field study. The field study also served to identify issues with merit for further examination in the simulator environment. All of these tasks generated information used to prioritize conditions that make an interchange complex and identify challenges associated with treatments at these locations. For the purposes of this project, *complexity* is defined as follows:

> Complexity occurs when the choice of more than one movement is available from a lane or group of lanes where the decision points occur successively in close proximity.

As part of task 4, a simulator study was conducted to experimentally evaluate driver lane selection in complex interchange situations. Complex interchanges typical of the existing field applications were designed, and multiple alternative approaches to guide signing were developed for each interchange layout. The effectiveness of driver decisionmaking was evaluated in terms of whether drivers made accurate lane choices (i.e., those that led to arriving at the correct location) and in terms of the potential impacts to safety and efficiency associated with the timing of these decisions and with making ULCs because of poor comprehension or inadequate information.

OBJECTIVE

The simulator study was conducted to understand driver behavior at complex interchanges and identify signing characteristics that are related to more effective lane selection. The simulator study results contribute to the literature describing driver behavior in the presence of different signing information and can be used to develop guidance that helps practitioners make effective choices for common complex interchange scenarios.

RESEARCH QUESTIONS

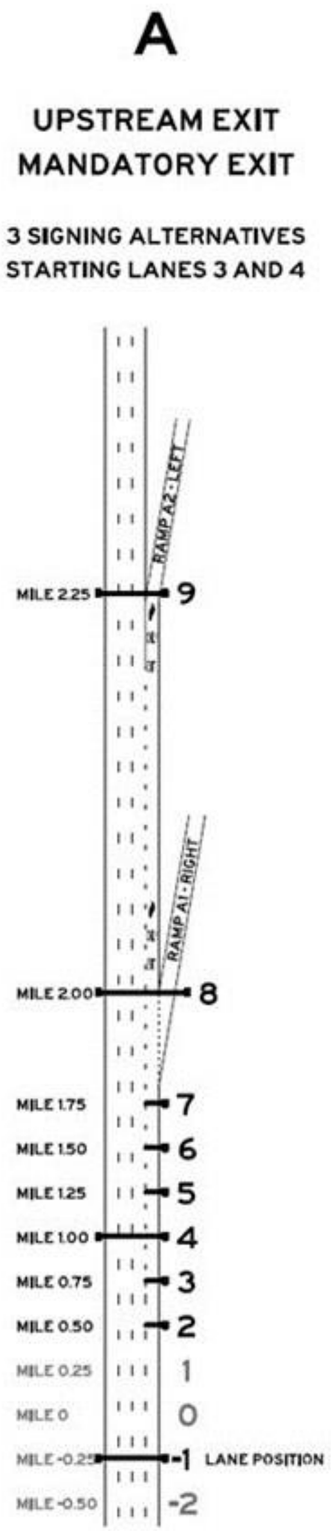
The simulator study addresses the following research questions:

- Which signing alternatives contribute to the fewest number of lane changes?
- Which signing alternatives exhibit the highest number of inaccurate lane changes?
- Do drivers in the option lane leave the option lane as through traffic? As exiting traffic?
- Is option lane use consistent with the downstream exit direction on the exit ramp?

- Do drivers initially react to information upstream of the mainline exit, only to change lanes into an incorrect lane for the instructed destination, either prior to or beyond the exit?

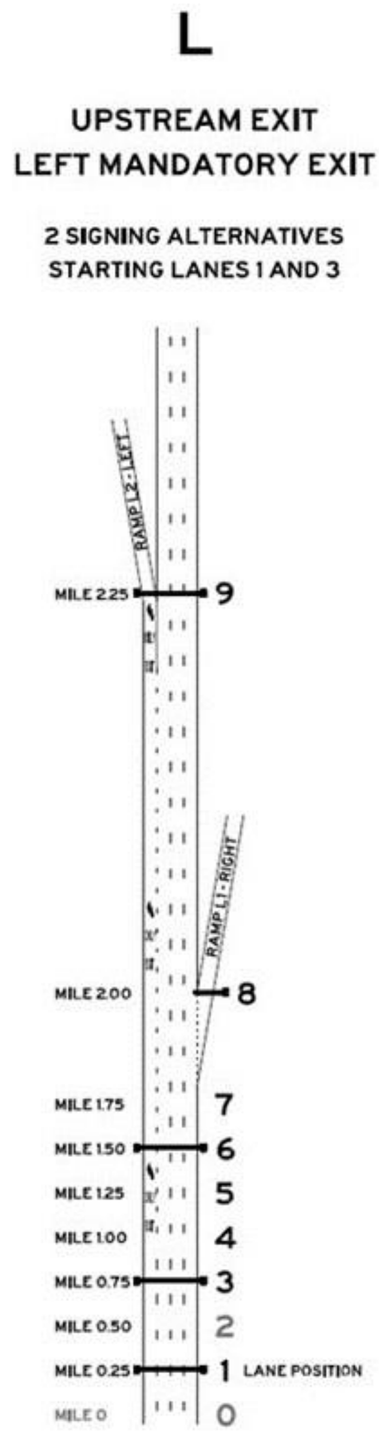
INTERCHANGE DESIGN AND SIGNING APPROACHES

Four interchange layouts were developed to be representative of existing configurations of interchanges exhibiting attributes related to complexity (see figure 24). While two layouts contained similar geometric designs, each consisted of a different exiting lane configuration downstream of the primary exit.



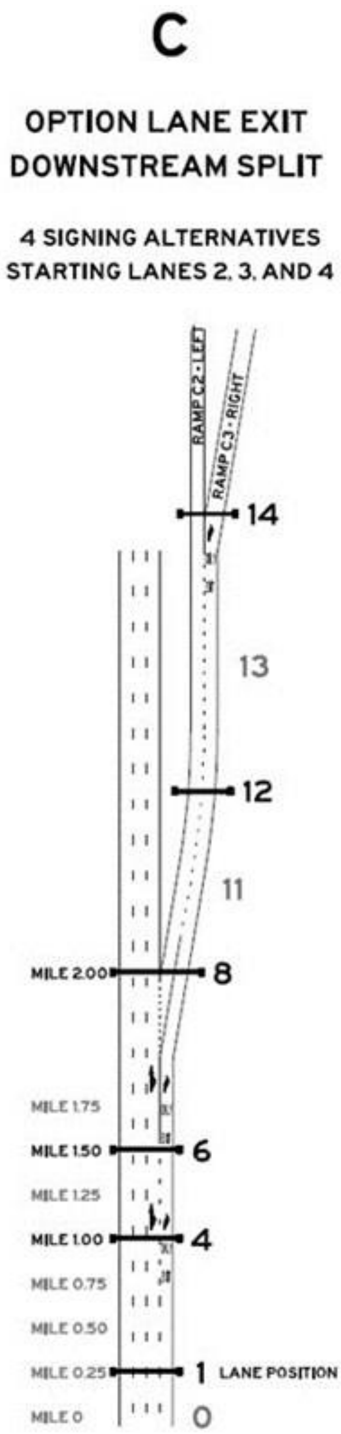
Source: FHWA.

A. Interchange layout A.



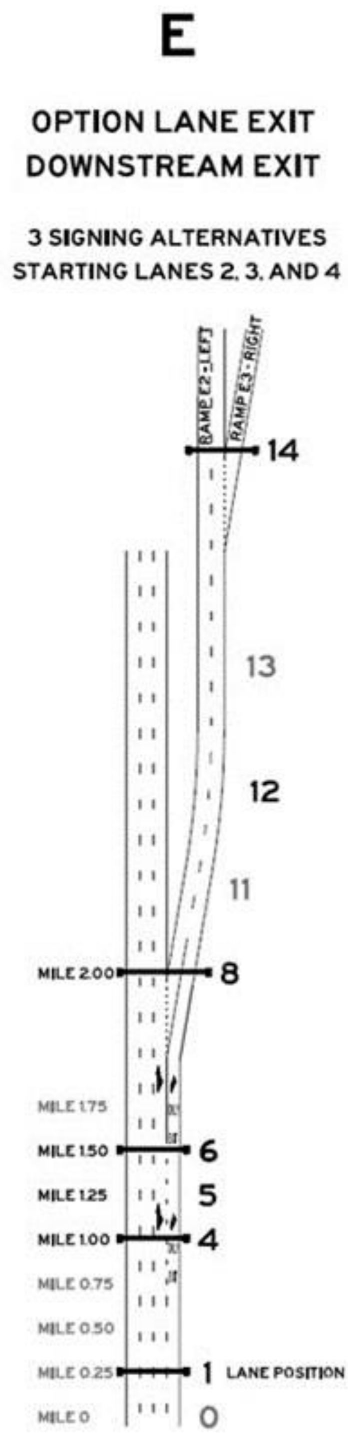
Source: FHWA.

B. Interchange layout L.



Source: FHWA.

C. Interchange layout C.



Source: FHWA.

D. Interchange layout E.

Figure 24. Graphic. Interchange layouts considered in this study.

Table 42 shows how each simulator study layout provided various geometric design features that are present in real-world complex interchanges.

Table 42. Summary of interchange layouts and their relationships to existing interchanges with complexity.

Layout	Analogous Field Study Site	4121 Exit-Only Lanes	4124 Option Lanes	4221 Exit Preceding Downstream Exit Only From Same Lane	4222 Exit With Downstream Split	4232 Left-Side Exits	5132 Discrete Arrow	5133 Blended Arrow	5134 Diagrammatic	5211 Use of Dotted Line	5123 Solid Lines in Advance of Exits
A	I-405 southbound Exits 3 and 2B-A	X	X	X	—	—	X	—	—	X	X
L	Not applicable	X	—	—	—	X	X	—	—	X	X
C	I-35W southbound to TH 62 I-5 southbound Exit 105	X	X	—	X	—	X	X	—	X	X
E	I-4 westbound to US 192 I-4 eastbound to SR 536 I-5 northbound Exit 111	X	X	—	X	X	X	X	—	X	X

X indicates attributes present at the interchange.
—These attributes were not present at the interchange.
TH 62 = State Trunk Highway 62.

Each interchange layout addressed a specific configuration of exiting lanes in one discrete geometric design. A variety of signing alternatives were applied to each layout. These alternatives generally consisted of a single approach to signing for an interchange. In the present simulator study, participants encountered a unique combination of an interchange layout, signing alternative, destination, and starting lane position. An overview of these is provided here, and more detail follows in subsequent sections.

Appendix B provides a complete catalog of the signing alternatives advanced for testing in the simulator in conjunction with diagrams of the geometric layouts associated with each. Each signing alternative was designed to accommodate the three possible destinations for each of the alternatives in a given layout. These movements are considered THRU (T), LEFT (L), and RIGHT (R). Participants were told that their task was to follow the signs toward Greenville; Greenville was always the destination to which they were instructed to drive. For example, a participant might be trying to navigate to Greenville on Route 28 without being told a cardinal direction for Route 28. Using the information provided on overhead guide signs, the participant would either continue THRU to Greenville or would exit the interchange to the RIGHT or the LEFT toward Greenville based on the experimental scenario. As there is no LEFT movement in layout A, a destination of "L" for this layout represents the second RIGHT movement.

Each layout and signing alternative was tested as a discrete exercise with a single starting lane assignment (lanes number 1 to 4 from left to right). As shown in table 43, there was a total of 12 signing alternatives, each of which allowed for between 2 and 9 total possible experiences based on starting lane and destination combinations, for a total of 87 possible discrete simulator experiences.

Table 43. Summary of the possible combinations of interchange layout, signing alternative, and starting lane destination.

Interchange Layout	Signing Alternative	Description	Possible Starting Lane Positions	Possible Destinations	Number of Possible Experiences
A	A1	Single panel	3, 4	T, R (first exit), L (second exit)	6
A	A2	Overhead plus post-mount	3, 4	T, R (first exit), L (second exit)	6
A	A3	Sign spreading	3, 4	T, R (first exit), L (second exit)	6
L	L1	Typical	1, 3	L	2
L	L2	Typical plus pull-through	1, 3	L, T	4
C	C1	Discrete arrow	2, 3, 4	L, T, R	9
C	C2	Hybrid arrow	2, 3, 4	L, T, R	9
C	C3	Separate panels	2, 3, 4	L, T, R	9
C	C4	Combined arrow	2, 3, 4	L, T, R	9
E	E1	Discrete plus ramp advance	2, 3, 4	L, T, R	9
E	E2	Discrete plus mainline advance	2, 3, 4	L, T, R	9
E	E3	Separate panels	2, 3, 4	L, T, R	9
—	—	—	—	**Total possible experiences**	**87**

L = left; R = right; T = thru.
—Not applicable.

Each layout is described in more detail in the subsections that follow, along with the signing alternatives that were evaluated for each.

Layout A

Layout A consists of a limited-access roadway segment with three lanes in one direction and an auxiliary lane on the right. The upstream portion of layout A in advance of the first exit is 13,200 ft long. The auxiliary lane terminates at an exit ramp with an adjacent option lane. The two-lane exit ramp is approximately 1,980 ft in length and terminates in a downstream split, where the left lane continues as the left-hand movement and the right lane exits as a right-hand movement.

Layout A's characteristics may be challenging to the driver because there are two movements available from the right-hand lane. The first movement, a non-mandatory exiting movement, occurs upstream but in close proximity to the second movement, the mandatory exiting movement. Drivers may move out of the right lane anticipating the first exit, depending on signing, reducing segment capacity and increasing conflicts due to lane changes between the two exits. To evaluate what signing would best convey lane selection information to drivers, three signing alternatives were developed for layout A.

Summary of Hypotheses for Layout A

Table 44 summarizes the description and hypotheses for layout A. Alternative A1 is expected to perform poorly for ULCs upstream of the first exit, until downstream of the first exit, destination LEFT for drivers who are taking the second exit. Alternative A2 is expected to perform more poorly than alternative A1 for lane changes into lane 4 in advance of the first exit for vehicles assigned to destination RIGHT. Alternative A3 is anticipated to result in a larger number of vehicles using lane 4 upstream of the first exit for both destination RIGHT and destination LEFT vehicles.

Table 44. Signing alternatives for layout A.

Signing Alternative	Signing Approach	Driver Behavior Hypotheses
A1	Single panel	Alternative A1 uses a single panel approach to provide guidance to the two subsequent exits. It is expected that some drivers who should take the second exit may move from the auxiliary exit-only lane, interpreting the single panel to mean that the "EXIT ONLY" applies to the first exit. It is further expected that drivers may mistakenly take the first exit even if intending to travel to the second exit, although the use of distances on the overhead signs should mitigate this to some degree.
A2	Overhead "EXIT ONLY"/side-post exit	For this alternative, all three destination movements are provided to give drivers a more complete set of expectations for downstream options. Drivers in alternative A2 are expected to have a better understanding of the separate upstream location of the first exit than in alternative A1, although there may be some confusion about the lane choice for the upstream exit. This is anticipated because the signing for the first exit does not explicitly assign drivers to the right-hand lane using action messages such as "KEEP RIGHT" or downward-pointing arrows.
A3	Sign spreading	While similar to alternative A2, it places the advance guide signing for the first exit overhead and adds downward-pointing arrows for additional clarity on lane assignments. For this alternative, all three destination movements are provided. Drivers in alternative A3 are expected to have a better understanding of the separate upstream location of the first exit than in alternative A1 and are expected to exhibit superior lane choice behavior to both alternatives A1 and A2 because of the downward-pointing arrow on the signing for the first exit. The staggered nature of the advance guide signing and the presence of distances on both are anticipated to create a sense of the closing distance to each exit.

Layout L

Layout L consists of a limited-access roadway segment with three lanes in one direction and an auxiliary lane for a downstream left-hand exit. The upstream portion of layout L in advance of the first exit is 10,560 ft long. The first exit ramp is a single-lane exit with a standard tapered departure. The exit gore areas are separated by 1,320 ft. The left-hand auxiliary lane terminates as a single-lane, left-hand exit ramp as the second exit.

The characteristics of layout L are challenging to the driver because left exits are less common, and a disruption in freeway flow characteristics is more likely to occur with left exits because slower traffic will move into the generally higher-speed left lanes. Compounding the issue of left exits, in situations where a continuing lane terminates as the left-hand mandatory exiting movement, significant lane change events will occur as through traffic moves into right-hand lanes. To evaluate what signing would best convey lane selection information to drivers, two signing alternatives were developed for layout L.

Summary of Hypotheses for Layout L

Table 45 summarizes the description and hypotheses for layout L. It is anticipated that drivers assigned destination “LEFT” will perform equally well in both scenarios, because overhead advance guide signing is provided in advance of the exit, depicting both the exiting movement and the distance to the exit. However, for drivers assigned destination “THRU,” it is expected that drivers in alternative L2 will perform better because of the presence of positive guidance directing them into the through lanes ahead of the left-hand exit.

Table 45. Signing alternatives for layout L.

Signing Alternative	Signing Approach	Driver Behavior Hypotheses
L1	Standard left-hand exit without pull-through signs	This alternative is submitted as a distractor scenario, and it is anticipated that the majority of drivers will correctly choose lane 1 when assigned destination “LEFT.”
L2	Standard left-hand exit with pull-through signs	For this alternative, two destination movements are provided: those being destination “LEFT” and destination “THRU.” It is anticipated that the pull-through signs will increase driver confidence in upstream lane selection, leading to correct choices further from the departure point.

Layout C

Layout C consists of a limited-access roadway segment with three lanes in one direction and an auxiliary lane. The upstream portion of layout C in advance of the primary exit (sections 1 and 2) is 10,560 ft long. The auxiliary lane terminates at an exit ramp with an adjacent option lane. The two-lane exit ramp is approximately 1,980 ft in length and terminates in a downstream split, where the left lane continues on as the left-hand movement and the right lane exits as a right-hand movement.

Layout C’s characteristics are challenging to the driver because drivers must first make an upstream lane selection (prior to the mainline exit) that may be predicated on their downstream lane selection, depending on the driver’s driving style. For example, drivers who will correctly exit destination “LEFT” would most expeditiously choose to use the option lane on the upstream segment. However, if upstream information is absent or unclear, drivers may choose to use the right-most lane (in this case, the mandatory movement lane) to obtain some assurance that they are indeed taking the exit. To evaluate what signing would best convey lane selection information to drivers, four signing alternatives were developed for layout C.

Summary of Hypotheses for Layout C

Table 46 summarizes the description and hypotheses for layout C. It is anticipated that drivers will make the highest number of upstream lane changes for the signing in alternative C3 because it makes a clear lane assignment upstream of the exit from the mainline roadway. Alternatives C1, C2, and C3 are expected to perform equally in terms of upstream lane choice, although option lane use for exiting traffic may be higher for alternatives C1 and C2 because the signing in those two alternatives does not indicate a multiple movement from the option lane.

Table 46. Signing alternatives for layout C.

Signing Alternative	Signing Approach	Driver Behavior Hypotheses
C1	Discrete arrows, single panel	On the mainline, it is expected that most drivers will make choices that lead to the correct movement on the mainline, although some drivers are likely to avoid the option lane, consistent with prior research.[39] For downstream decisions, it is anticipated that drivers will not make final lane selections until passing sign location 12 (see figure 24). As drivers experience multiple runs of layout C, they may likely learn that the order of the destinations on the sign (Greenville and Madison as opposed to Madison and Greenville) indicates the desired downstream movement on the C/D roadway. Of particular interest is the behavior of driver lane changes ahead of the overhead signing at location 12, as drivers recognizing the short distance to the exit based on visual cues.
C2	Hybrid arrows, single panel	On the mainline, it is expected that most drivers will make choices that lead to the correct movement on the mainline, and fewer drivers than alternative C1 are expected to avoid the option lane. This is anticipated because the sign has an arrow pointing at the destination legend. Because that arrow (the left-hand arrow on the signs) also has a non-headed shaft, it is further expected that fewer drivers who intend to go through will vacate the option lane than in alternative C1. For downstream decisions, it is anticipated that drivers will not make final lane selections until passing sign location 12 (see figure 24). As drivers experience multiple runs of layout C, they may likely learn that the order of the destinations on the sign (Greenville and Madison as opposed to Madison and Greenville) indicates the desired downstream movement on the C/D roadway. The results for upstream lane position relative to the final movement will likely be similar to alternative C1.

Signing Alternative	Signing Approach	Driver Behavior Hypotheses
C3	Discrete arrows, multiple panel	On the mainline, it is expected that most drivers will make choices that lead to the correct movement on the mainline, and that those drivers will most likely choose the final destination lane while still on the mainline. The lack of the "EXIT ONLY" message on the signs over the option lane is anticipated to produce results similar to alternative C1 for through-movement drivers, although more drivers than in alternative C1 are likely to avoid the option lane because of the presence of the separate panel. For downstream decisions, it is anticipated that drivers will not make final lane selections until passing the sign for location 12 (see figure 24). As drivers experience multiple runs of layout C, they may likely learn that the order of the destinations on the sign (Greenville and Madison as opposed to Madison and Greenville) indicates the desired downstream movement on the C/D roadway.
C4	Shared arrows, single panel	It is expected that some drivers will continue on the mainline when the destination is on the C/D roadway because of the presence of the upward-pointing portion of the shared-movement arrow. The lack of a distance to the exit (which is consistent with numerous implementations observed in the field, including in Atlanta, New York State, and Charlotte) is also likely to lead to some confusion regarding the point of exit. Fewer drivers who intend to follow the through movement are likely to avoid the option lane, however, because the shared-movement arrow points upward and clearly indicates a lane that continues straight, although not clearly indicating the destination of that lane. For downstream decisions, it is anticipated that drivers will not make final lane selections until passing the sign for location 12 (see figure 24). As drivers experience multiple runs of layout C, they may likely learn that the order of the destinations on the sign (Greenville and Madison as opposed to Madison and Greenville) indicates the desired downstream movement on the C/D roadway.

Layout E

Layout E consists of a limited-access roadway segment with three lanes in one direction and an auxiliary lane. The upstream portion of layout E in advance of the primary exit (sections 1 and 2) is 10,560 ft long. The auxiliary lane terminates at an exit ramp with an adjacent option lane. The two-lane exit ramp is approximately 1,980 ft in length and terminates in a downstream split, where the left lane continues as the left-hand movement and the right lane exits as a right-hand movement.

Layout E's characteristics are challenging to the driver because, as in the scenarios for layout C, drivers must first make an upstream lane selection (prior to the mainline exit) that may be predicated on their downstream lane selection, depending on the driver's driving style. In the case of layout E, drivers will be able to access destination "LEFT" from either exiting lane (which could only be done from the left-most exiting lane for layout C), but the destination "RIGHT" movement will require a lane change to the right-most lane. Three signing alternatives were developed for layout E.

Summary of Hypotheses for Layout E

Table 47 summarizes the description and hypotheses for layout E. In general, drivers driving in scenario 3 are expected to exhibit better performance as additional positive guidance elements are added, such as the upstream supplemental guide sign in alternative E2. Despite the incorrect signing of the right-hand lane as solely used for the right-hand movement on the C/D roadway in alternative E3, that signing is expected to produce more upstream lane changes into the right lane for destination "RIGHT" drivers while reducing the utility of the right-hand lane for destination "LEFT" drivers.

Table 47. Signing alternatives for layout E.

Signing Alternative	Signing Approach	Driver Behavior Hypotheses
E1	Discrete arrows without upstream supplemental sign	Drivers are expected to exhibit marginal lane choice for the right-hand movement upstream of the primary exit, while performance downstream is expected to be good on account of the primary guide sign provided at location 12. This guide sign does not indicate the use of the right lane or use the message "KEEP RIGHT."
E2	Discrete arrows with upstream supplemental sign	Drivers are expected to exhibit better overall lane choice behavior in alternative E2, owing to the presence of the "KEEP RIGHT" legend on the sign panel at location 5. Selection of the correct lane upstream of the primary exit is expected to be equal to the performance of alternative E3.
E3	Discrete arrows, multiple panels	Signing in alternative E3 uses the discrete arrow/multiple panel method. For this alternative, only the destination "LEFT" and destination "RIGHT" movements are provided because the destination "THRU" movement is addressed in signing alternative C3, which features an identical upstream condition in advance of the primary exit to the C/D roadway. It is anticipated that a higher percentage of drivers will use lane 3 than lane 4 for destination "LEFT" movements because of the single arrow pointing into lane 3 upstream of the first exit. Likewise, alternative E3 is anticipated to result in the highest number of correct maneuvers.

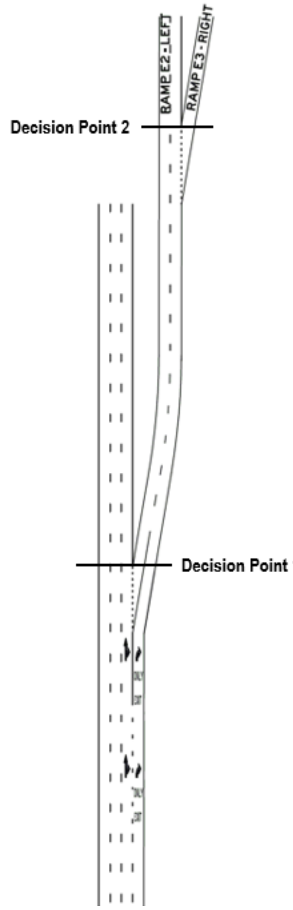
RESEARCH DESIGN

This section describes the key elements of the research design that involved the recruitment of drivers to perform a driving task in a partial cab driving simulator. The details of this study are described in greater detail in the subsections that follow.

Independent and Dependent Variables

Three factors were of particular interest to this study and served in statistical models as dependent variables: accuracy of lane selection, ULCs, and lane selection distance (LSD). These measures were further assessed within different segments of the interchange, separated by decision points, or locations where the participant is presented with options for how to proceed.

Figure 25 shows an example of the two decision points on layout E. A participant’s accuracy is calculated both in terms of overall accuracy (i.e., getting to his or her designated destination) and in terms of accuracy at individual decision points during the simulation. Consider an example where the designated exit was to the right of the downstream split (ramp E3), and the participant successfully exited the mainline, but stayed to the left (ramp E2). In this example, accuracy for the participant would have been recorded as correct at decision point 1 (DP1), incorrect at decision point 2 (DP2), and incorrect overall. A similar approach was used for ULCs and LSD. However, in the case of LSD, no value was recorded for overall LSD.



Source: FHWA.

Figure 25. Graphic. Layout E decision points.

Accuracy

Lane accuracy was measured on a bivariate scale (correct or incorrect). Accurate drives were those in which participants ultimately navigated to the given destination, regardless of intermediate maneuvers. All lanes that allow the participant access to the correct destination were considered correct, and no priority or preferences were assigned (i.e., optimal).

ULCs

For this study, a lane change was defined as the moment when more than 50 percent of the participant's simulated vehicle moved into an adjacent lane. (Directional signals (turn signals) were not enabled during the study.) For a given interchange and destination, a certain number of lane changes were required to reach the correct destination (minimum number of lane changes); those in excess of this minimum were considered ULCs. ULCs were calculated in two ways: (1) across the entire interchange and (2) per the segment of road leading up to each decision point. In both cases, the initial starting lane position is assigned based on the scenario being run. In the latter example, the participant's starting lane position approaching DP2 is not assigned; rather, it is based on the lane the participant selected at DP1. Because of this subtle difference between the starting lane assignments in both approaches, the sum of ULCs in the latter approach (counted per segment) does not necessary equal those in the first approach (counted across the interchange). While the first approach is useful to get an idea of potential navigation issues, in general, with a given layout and signing alternative, the second approach allows further insight into where these ULCs are occurring.

LSD

The location of the participants' final lane change tells us how far in advance of the exit their selection was finalized. This variable was measured in feet from the exit location (the point at which they could not change their mind). This measure will reflect the degree to which participants waited until the last minute to change lanes. However, it cannot precisely describe when participants decided what their lane choice should be.

Accuracy reflects the outcome of each drive; whereas, the ULC and LSD variables reflect the decision process. Signing options that produce more accurate outcomes may improve driving reliability, and those that do so with the least confusion (fewer ULCs, better LSD) could improve safety.

What Signing Alternative Results in the Best Driver Performance for Each of the Four Interchange Layouts?

Driver performance on each of the four interchange layouts was not compared against one another. Instead, the focus of this research was to identify which signing alternative results in the best performance for a particular interchange layout. For instance, in layout A, under what signing guidance do drivers make the most accurate and most efficient lane changes (A1, A2, or A3)?

Table 48 shows the 12 interchange signing alternatives seen by all drivers that create a repeated measures factor.

Table 48. The 12 interchange layout signing alternatives.

A	L	C	E
A1	L1	C1	E1
A2	L2	C2	E2
A3	—	C3	E3
—	—	C4	—

—Not applicable (no additional signing alternatives for this layout).

How Do the Characteristics of the Required Lane Maneuver Affect Performance?

In the real world, drivers approach an interchange from various starting positions based on their origin, driving experience to that point, and personal preferences. To account for this, each participant was exposed to a variety of starting position (1, 2, 3, and 4) and destination (left, right, through/straight) combinations when approaching the interchanges. Based on the interchange layouts and signing alternatives in this study, and as shown in table 48, this resulted in 87 combinations, or 87 possible discrete simulator experiences.

To minimize the amount of time participants used the driving simulator, not every driver could see every one of these 87 discrete simulator experiences. Thus, the 87 combinations were placed into 9 different groups, or scenes, as shown in table 49. For example, A1-3L refers to interchange layout A, signing alternative A1, starting lane 3, and destination LEFT. Not all drivers saw every combination, making each combination a between-drivers variable. Instead, each participant was assigned to one of the nine groups, or scenes, and these groups were designed such that each participant saw every interchange layout and signing alternative, but only saw a subset of starting lane and destination combinations. This process was semi-random so that no one participant would encounter similar combinations of starting lane and destination.

Table 49. Overview of the nine possible scenes (combinations of interchange layout, signing alternative, and starting lane destination).

Scene 1	Scene 2	Scene 3	Scene 4	Scene 5	Scene 6	Scene 7	Scene 8	Scene 9
A1-3L	A1-3R	A1-3T	A1-4L	A1-4R	A1-4T	A1-3T	A1-3L	A1-3R
A2-4T	A2-4L	A2-4R	A2-3T	A2-3L	A2-3R	A2-4T	A2-4L	A2-4R
A3-4L	A3-4R	A3-4T	A3-4L	A3-4R	A3-4T	A3-3L	A3-3R	A3-3T
E1-2L	E1-2R	E1-2T	E1-3L	E1-3R	E1-3T	E1-4L	E1-4R	E1-4T
E2-4R	E2-4T	E2-4L	E2-2R	E2-2T	E2-2L	E2-3R	E2-3T	E2-3L
E3-3T	E3-3L	E3-3R	E3-4T	E3-4L	E3-4R	E3-2T	E3-2L	E3-2R
C1-2T	C1-2L	C1-2R	C1-3T	C1-3L	C1-3R	C1-4T	C1-4L	C1-4R
C2-4L	C2-4R	C2-4T	C2-2L	C2-2R	C2-2T	C2-3L	C2-3R	C2-3T
C3-3R	C3-3T	C3-3L	C3-4R	C3-4T	C3-4L	C3-2R	C3-2T	C3-2L
C4-2R	C4-2T	C4-2L	C4-3R	C4-3T	C4-3L	C4-4R	C4-4T	C4-4L
L1-1L	L1-3L	L1-1L	L1-3L	L1-1L	L1-3L	L1-1L	L1-3L	L1-1L
L2-3T	L2-1T	L2-3T	L2-1T	L2-3L	L2-1L	L2-3L	L2-1L	L2-3T

Note: Each participant was assigned to one of these scenes for the experimental session.

Controlling for Order Effects

Two different interchange layout orders were used to control for potential order or learning effects. An order was generated randomly to produce order A; order B was produced by reversing order A. Table 50 shows the two different orders. Each scene above was then ordered accordingly, creating 18 scenes (scenes 1A/1B, 2A/2B, 3A/3B, 4A/4B, 5A/5B, 6A/6B, 7A/7B, 8A/8B, and 9A/9B). Each order contains the 12 interchange layouts that the study participants encountered.

Table 50. Two possible orders of interchange layouts that participants might see.

Interchange Number	Order A	Order B
1	C	C
2	L	E
3	A	A
4	E	E
5	C	A
6	L	C

Interchange Number	Order A	Order B
7	C	L
8	A	C
9	E	E
10	A	A
11	E	L
12	C	C

Detecting Differences in Driving Performance

The statistical power of the proposed experiment was estimated before data collection began using several assumptions. The standard value of power, $(1 - \beta) = 0.80$, was used, but the familywise error rate, $\alpha = 0.05/6 = 0.0083$, was adjusted for the six pairwise comparisons possible with four signing alternatives. Various samples sizes per interchange-signing combination were calculated separately for the two main variables of interest, with accuracy measured as a proportion and number of ULCs as independent group means.

Statistical power was assessed to determine the optimal number of participants to complete this study and show statistically reliable and valid results. A power analysis showed that, if 120 participants completed this study, this would allow for the detection of accuracy differences as small as 14.4 percentage points. The farther the two groups are from 100 percent, the larger the minimum detectable difference becomes (the less powerful the test becomes). Accuracy is expected to be high overall, but if the best group in a pairwise comparison is 75 percent accurate, the smallest detectable difference with 100 drivers is 23 percentage points.

The power to detect differences in discrete variables (such as the number of ULCs) is calculated differently than with proportions. Participants may only commit a small number of ULCs, perhaps zero ULCs or one to two ULCs. Expressed statistically, these represent two Poisson random variables with means of 0 and 1.5. The common standard deviation between the two groups is 1.1. If 120 participants complete this study, this would allow for the detection of ULC differences as small as 0.51 ULCs (an improvement of 0.05).

The above calculations are at the interchange layout and signing alternative level. Starting lane and destination will be equally represented in each interchange-signage combination; therefore, aggregating over them (for comparisons of signing alternatives within interchange) is appropriate and valid. Examining for effects due to starting lane or destination is not likely to yield strong statistical conclusions regarding accuracy, but substantially small differences in ULCs may still be detectable. Table 51 uses the previously stated assumptions and adjusts the familywise error rates according to the number of potential pairwise comparisons to calculate the minimum detectable difference for each comparison with different total numbers of participants.

Table 51. Overview of power analysis to assess minimally detectable differences in study metrics. Smallest Detectable Difference

Comparison	Total Number of Participants	Participants per Group	Potential Pairwise Comparisons	Smallest Detectable Difference: Number of ULCs	Smallest Detectable Difference: Accuracy (Percentage Points)
Between destinations	100	33	18	1.09	36.00
Between destinations	120	40	18	0.98	32.50
Between starting lanes	100	33	18	1.09	36.00
Between starting lanes	120	40	18	0.98	32.50
Between starting-lane destination combination	100	11	216	2.30	69.00
Between starting-lane destination combination	120	13	216	2.10	65.00
Between starting-lane destination combination	120	13	216	2.10	65.00

METHOD

This section describes the participants, apparatus and materials, stimuli, and procedures used for conducting the study.

Participants

This study included a sample of 121 research participants (60 male and 61 female) in 3 different geographic areas: Orlando, FL; Myrtle Beach, SC; and Gainesville, VA. Participants ranged in age from 18 to 83 yr (mean = 44.9). Each participant possessed a valid U.S. driver's license and passed a vision screening with at least 20/40 vision in at least one eye (corrected if necessary). Participants were paid 70 dollars for their participation.

Of the 121 participants who completed the study, half were in the younger age group (18 to 45 yr, mean = 29.7 yr) and half were in the older age group (46+ yr, mean = 60.4 yr). Each age group (younger and older) was evenly distributed between males and females. Of the 133 participants who began the experiment, 5 were stopped due to issues with the laboratory and/or simulator, 4 were stopped due to simulator sickness, and 3 participants did not complete for other reasons.

Participants were randomly assigned to an experimental condition representing 1 of the 18 scenes described above. However, the project team sought to achieve a balance across gender, age, and location within each condition.

The recruitment process used a variety of advertising methods, including flyers in community centers and at local businesses, online ads, and word-of-mouth. The entire experiment (including instructions, informed consent, questionnaires, and debriefing) took approximately 90 min to complete. Each participant was paid 60 dollars for completing the study as well as a 10-dollar bonus for attempting to make as few lane changes as necessary to complete the driving task accurately.

Apparatus

A Mobile Human Factors Laboratory (MHFL), shown in figure 26, was used to collect data. The mobile laboratory is a cutaway van with dimensions of approximately 7 x 20 ft and includes a comfortable, climate-controlled laboratory space; a high-end, business-grade computer capable of advanced graphics generation; a 65-inch display; specialized software for sign display and testing; and a driving simulator platform that can be added or removed to the mobile device, as required. The interior has been configured to limit the view of the researcher's workstation from the participant space, permitting unobtrusive monitoring. The MHFL is equipped for cross-country travel, enabling the testing of different populations of road users in multiple regions. This vehicle platform has a low operational cost, and the lead time for its deployment is short compared to mobilization of testing at laboratory facilities with large workloads. The facility is comfortable for visiting participants, being outfitted with a climate-controlled waiting area and workspace, including windows in the waiting area for natural light.

Source: FHWA.

Figure 26. Photo. MHFL.

MiniSim™ Driving Simulator

The University of Iowa's National Advanced Driving Simulator MiniSim™ suite is used within the MHFL. The MiniSim™ repackages the framework and technology of the National Advanced Driving Simulator-1 driving simulator into a mobile platform. The MiniSim™ suite includes all of the tools required to completely customize and build a driving simulator study, as well as test and analyze the findings, including:

- Tile Mosaic Tool to develop detailed roadway network databases.
- Interactive Scenario Authoring Tool to author scenarios and program behavior of deterministic and autonomous dynamic objects (i.e., other traffic and pedestrians) as well as TCDs.
- MiniSim™ to run the driving simulation and collect data.
- ndaqTools to assist in reducing the raw MiniSim™ output into measures.

MiniSim™ Development Approach

The MiniSim™ works from a tiled approach, so each segment of the test drive was developed as separate tiles. These tiles were then combined into the appropriate sequences per the direction of the experimental team. Signing was developed by a traffic engineer and placed within the sequences per the direction of the engineer. Special attention was given to ensure data accuracy in conjunction with visual accuracy to maintain data integrity in preparation for data reduction.

Materials

The following materials were developed in paper and pencil format.

Motion Sickness History Screening Form

This screening was administered verbally prior to scheduling a participant for the study to identify people who might be likely to experience simulator sickness. The scoring criteria were used to discourage participation as appropriate.

Record of Informed Consent

The informed consent document describes the study, participant and researcher responsibilities, risks, risk mitigation plan, and participant consent.

Vision Screening Form

The Vision Screening form was used to track participants' visual acuity as determined by a Snellen chart.

Simulator Health Screening

This was used as a secondary screening, after participants arrived for their appointment, to help identify participants who might be likely to experience simulator sickness.

Simulator Sickness Questionnaire

The Simulator Sickness Questionnaire (SSQ) is given before the participant drives in the simulator, during certain breaks between driving sessions, and at the end of the experiment. This questionnaire is also administered whenever a research participant becomes ill and periodically during the recovery period thereafter. The SSQ is designed to detect and monitor simulator sickness.

Instructions

The experimenters used a written guide to provide verbal instructions to participants.

Receipt for Payment

This was completed and signed by participants upon payment to track study funds.

Caution Acknowledgement Release

If a sick participant refused to take the SSQ and/or left the research facility without recovering, she/he was requested to sign a caution acknowledgement waiver.

Debriefing Statement

Participants read a brief debriefing statement that described the goals of the study.

Stimuli

As described in previous sections, multiple signing alternatives were developed for each interchange layout. Each layout consisted of four main sections. In general, the layout lengths within a simulator tile were multiples of 660 ft, and the length of each section was set by those multiples, as ¼-mi intervals are typically observed for signing in practice. The expected legibility distance for the guide signs in this study was based on an anticipated in-simulator legibility distance of approximately 500 ft, consistent with a 30-ft legibility distance for every 1 inch of letter height on the sign. The section coverage was previously described in this report. Based on practice evaluations, field reviews, and field data collection at similar sites, the project team developed eight potential geometric layouts, each representing a segment of motorway-grade facility approximately 3 mi in length. While some layouts were related, each consisted of a different exiting lane configuration. From those initial eight layouts, four were advanced for development in the simulator.

All traffic signing and pavement markings to be used in the simulation scenarios were designed using the principles identified in the MUTCD and the SHS. Specific design details were adapted from the policies of MnDOT, WSDOT, and Florida Department of Transportation.

Appendix B provides a complete catalog of the signing alternatives advanced for testing in the simulator in conjunction with diagrams of the geometric layouts associated with each.

Roadway Segmentation

Section 1 includes the mainline of the roadway upstream of any guide signing. For all layouts, this distance is set at a maximum of 5,280 ft. Within section 1, participants will drive 1,320 ft prior to seeing the overhead sign that assigns them to the starting lane position for that scenario. Subsequent to that, participants will observe a pair of speed limit signs no more than 2,640 ft upstream of the first guide signs for that signing alternative.

Section 2 accommodates the signing upstream of the first exit, beginning with the first guide sign, and this distance varies from 5,280 to 7,920 ft (1½ mi). For layout A, where the maximum distance upstream of the first exit is 1½ mi, the overall length of sections 1 and 2 is 11,880 ft.

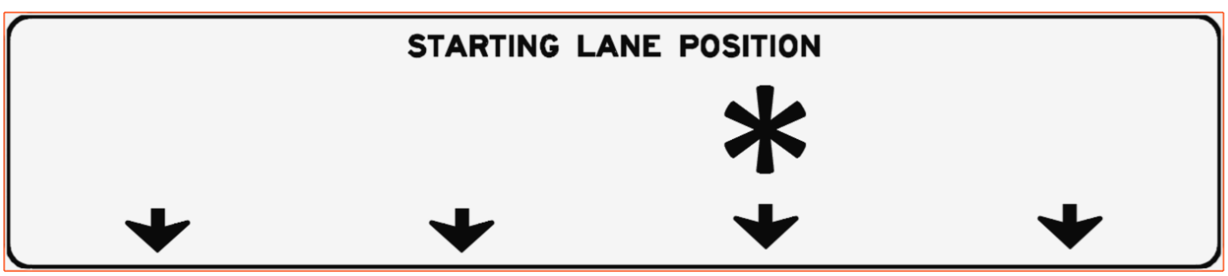
Section 3 covers the distance between the first and second exits. For layouts A and L, that distance is measured along the mainline and is 1,320 ft. For layouts C and E, that distance is measured along the C/D roadway and is 1,980 ft, which includes a 400-ft exit taper, a 600-ft horizontal curve, and approximately 900 ft of distance prior to the split.

Section 4 covers the distance from the final decision point to the end of the tile, where all lanes have rejoined the mainline for a four-lane configuration to match the starting configuration of all of the tiles. This section is typically 3,960 ft long and consists of horizontal curves, tapered lane additions, and lane reductions that provide for participant driving into the four-lane section that will connect to the next tile, for a seamless participant experience.

Starting Lane Indication

All participants encountered each of the 12 layout-signing combinations once, and each participant was assigned to 1 starting lane–destination combination per layout-signing combination (as illustrated in table 49). The participants were directed to a destination and informed of the starting lane position using a sign consistent with figure 27.

The sign was purposely designed to not mimic a guide sign and to avoid providing information with conventional symbols, such as a route marker. A down arrow was provided over each lane so that participants could count lanes and determine which lane to choose based on their position from the right or left edgeline.



Source: FHWA.

Figure 27. Graphic. Overhead sign that directed participants to a starting lane using the asterisk symbol location in one of four lanes.

Procedures

Prior to participation, potential participants were screened for susceptibility to motion sickness. If willing and eligible, participants were then scheduled for participation. Table 52 provides an overview of the participant experience.

Table 52. Summary of participant experimental session activities and approximate duration of each.

Experimental Session Activity	Duration (min)
Intake	**15**
Introduction and general instructions	5
Informed consent	5
Vision screening	3
Baseline SSQ	2
Training	**10**
Practice drive	5
Break/SSQ	5
Test scenarios	**50**
First experimental drive	20
Break/SSQ	10
Second experimental drive	20
Close-out	**15**
SSQ/follow-up questionnaire	10
Debrief	3
Payment	2
Total session duration	**90**

Intake

When participants arrived for their appointment, they were first asked to complete a basic visual screening to ensure a minimum of 20/40 acuity in at least one eye (corrected if necessary). Participants were instructed to stand the appropriate distance from a Snellen eye chart. After receiving instructions and completing the eye chart, the experimenter recorded their visual acuity on the vision screening form. Next, participants were asked to read and sign the Record of Informed Consent. After obtaining informed consent, participants were given a brief health survey; the goal of this questionnaire was to identify participants who might be likely to experience simulator sickness.

Participants were informed that they are participating in a research study to evaluate driving behavior in a driving simulator study of roadway signs. They were given a brief overview of the study process (i.e., they were told there would be a practice drive, two main drives, and a follow-up questionnaire).

Training

Prior to beginning the experimental drives, participants were exposed to a brief 3- to 5-min practice scenario. The experimenters explained the simulator to participants and then had them complete a practice drive to familiarize themselves with the driving simulator. The practice scenario consisted of a four-lane roadway, on which participants practiced accelerating, changing lanes, exiting a roadway, and stopping. The roadway segment used in the practice drive looked similar to those that might be seen in the experimental drives; however, no guide signs were present in the practice drive. A starting lane sign was present at the beginning of the practice drive; this gave the experimenter an opportunity to show to participants what this sign looked like before beginning the experimental drives. Although the practice drive only lasted about 3 to 5 min, this drive was repeated as many times as necessary until the experimenter and participant both felt comfortable moving forward to the experimental drives.

Test Scenarios

Although specific distances may have varied slightly between layouts, each interchange layout should have taken approximately 3 to 3.5 min to traverse. Therefore, the entire experiment (12 runs per participant) consisted of approximately 40 min of driving. The 40 min were divided into two separate drives, each of which consisted of half (six) of the runs assigned to that scene and presented in the orders as discussed in the previous sections of this report. Therefore, each experimental drive lasted about 20 min with a break in between.

For the experimental drives, participants were told that their task for both drives was to follow the signs to continue toward Greenville; Greenville was always the destination that they were to drive toward. In other words, participants' target destination was always Greenville (i.e., they will be instructed to always follow the signs to continue toward Greenville) on Route 28 without being told a cardinal direction for Route 28, which varied between scenarios. The use of a single target destination was undertaken so that participants were not confused by the need to remember a new target destination for each interchange. Using the information provided on overhead guide signs, participants would either continue through to their target destination, or they would exit the interchange to the right or the left toward their target destination. Participants were instructed to maintain the posted speed limit (65 mi/h), drive as they normally would, and determine what to do to reach their destination most efficiently.

Participants were reminded of the starting lane sign and told that they would see these signs occasionally throughout the experimental drives. They were instructed to, whenever they saw one of these signs, enter the lane over which there was an asterisk. Once in the appropriate starting lane, they could then make any lane changes necessary to complete the driving task.

To prevent participants from changing lanes too frequently or too early (such as moving into the right lane out of habit or comfort, rather than necessity), drivers were instructed to avoid making any ULCs (i.e., to only make the lane changes needed to complete the task of driving toward Greenville). To reinforce this, participants had the opportunity to earn the 10-dollar bonus (in addition to the stipend that they were already receiving to complete the study) by using the fewest lane movements possible to complete the driving task accurately and by doing their best to maintain the posted speed limit.

The instructions to participants are located in appendix C.

Close-out

Following the completion of the test scenarios, each participant was debriefed. They were paid their stipend for participating and were excused from the study.

DATA REDUCTION AND ANALYSIS APPROACH

Data captured from the MiniSim™ include 69 variables at 60 Hz and another 66 variables at each change of state (e.g., cruise control: on, off). All variables were captured and recorded for all participants. For this study and the resulting analysis, the set of variables shown in table 53 was extracted from the MiniSim™ data acquisition (DAQ) files for analysis. In some cases, a single variable, as defined by the MiniSim™, contains several arrays of information. As an example, the variable SCC_Lane_Deviation contains information on (1) whether the vehicle is on a road or off-road, (2) the lane or corridor the vehicle is on, (3) the vehicle's deviation from the center of the lane, and (4) the width of the corridor or lane.

Table 53. Variables extracted for analysis.

Variable Name	Definition	Units/Values	Collection Frequency
VDS_Chassis_CG_Position (latitude)	Vehicle position	ft	60 Hz
VDS_Chassis_CG_Position (longitude)	Vehicle position	ft	60 Hz
SCC_Lane_Deviation (lane deviation)	Deviation between vehicle and center of the lane	ft	60 Hz
SCC_Lane_Deviation (lane or corridor ID)	Identifier representing the lane or corridor that the vehicle is on	Identification number	60 Hz
VDS_Veh_Speed	Vehicle speed	mi/h	60 Hz
VDS_Chassis_CG_Accel	Vehicle acceleration	ft/s^2	60 Hz

The Python package undaqTools (version 0.2.3) was used to extract the variables from the MiniSim™ DAQ files into comma-separated values (CSV) files for each participant drive (i.e., string of six interchanges).[39] Quality assurance testing was completed on the raw CSV files before data reduction to confirm that each file was complete without data loss. Data reduction scripts developed by the project team were then used to reduce the raw CSV files into three datasets for analysis: lane selection per decision point, ULCs per interchange, and lane change information. After data reduction, a combination of quality assurance testing and visual inspection was completed to confirm accuracy of the reduced data.

Table 54 shows the scenario details. These data were developed when building each of the driving scenarios and not extracted from the simulation output, but they were critical in developing and analyzing the reduced data. This dataset includes one row of data for each possible simulation configuration.

Table 54. Scenario details.

Variable	Description
File name	Name of the scenario file (.SCN) used
Interchange string	Interchange string that the .SCN file was based on
Interchange number	Interchange number. Each .SCN file includes six interchanges
Layout	Layout of the corresponding interchange (A, L, C, E)
Alt	Signing alternative used for the interchange
SLP	Starting lane position
Destination	Destination (thru, left, or right)

Table 55 shows the variables captured in the first dataset, lane selection per decision point. This dataset included 2 rows of data for each participant, for each interchange, making 24 rows of data for all participants that successfully completed the full procedure.

Table 55. Lane selection per decision point.

Variable	Description
ParticipantID	Participant identifier
SCN_File	The scene order (e.g., Scene1A_pt1)
Int_Num	Intersection number of the given .SCN file
Destination	Destination for the given intersection (e.g., thru, left, or right)
SLP	Starting lane position. If the row pertains to the DP2, this will be the lane the vehicle was at the DP1
Alt	Signing alternative used for the interchange
Decision_Point	The decision point (e.g., first exit, second exit) that the following fields are referring to
Lane_choice	Lane number the driver was in at the decision point
Accuracy	Accuracy of the choice at the decision point (e.g., correct, incorrect)
Selection_Distance	Distance upstream of the decision point where the driver selected their lane. “N/A” is shown if no lane changes were made ahead of the decision point
Num_LC	Total number of lane changes leading up to the decision point. Does not include any lane changes the driver took to get into the startling lane position
Num_ULC	Number of ULCs leading up to the decision point
Veh_Location	Location of the vehicle at the decision point (i.e., mainline or ramp)

Table 56 shows the variables captured in the second dataset, ULCs across the interchange. As discussed under Research Design, the number of ULCs calculated across the interchange does not necessarily equal the sum of ULCs per decision point. This dataset included 1 row of data for each participant, for each interchange, making 12 rows of data for all participants that successfully completed the procedure.

Table 56. ULCs across the interchange.

Variable	Description
ParticipantID	Participant identifier
SCN_File	The scene order (e.g., Scene1A_pt1)
Int_Num	Intersection number of the given .SCN file
Destination	Destination for the given intersection (e.g., thru, left, or right)
SLP	Starting lane position. If the row pertains to the DP2, this will be the lane the vehicle was at the DP1
Alt	Signing alternative used for the interchange
Num_LC	Total number of lanes over the entire interchange. Does not include any lane changes the driver took to get into the startling lane position
Num_ULC	Number of ULCs over the course of the interchange

Table 57 shows the variables captured in the third dataset, lane changes. This dataset includes a row of data for each lane change made within the study area (i.e., once the participant enters their starting lane until the DP2).

Table 57. Lane change data.

Variable	Description
ParticipantID	Participant identifier
SCN_File	The scene order (e.g., Scene1A_pt1)
LC_Num	The participant's lane change number (e.g., if a participant makes two lane changes, their maximum LC_Num would be 2)
DataFrame	The data field from the DAQ file where the lane change occurred
Xcor	The X coordinate where the lane change occurred (ft)
Ycor	The Y coordinate where the lane change occurred (ft)
Int_Num	Intersection number of the given .SCN file
Layout	The interchange layout (e.g., A, L, C, E)
Alt	Signing alternative used for the interchange
Location_Pos	The closest signing position (e.g., A_1) to where the lane change occurred
Location_Type	First or second half of the interchange
Dist_Ahead_Next_DP	Distance in feet to the next decision point
OriginLane	Lane the vehicle left during the lane change
DestinationLane	Lane the vehicle entered during the lane change
LC_Type	Describes if the lane change is necessary or unnecessary (ULC)
Veh_Location	Location of the vehicle at the lane change location (i.e., mainline or ramp)

RESULTS

A statistical analysis of the study results is presented in the following subsections, organized by results for accuracy, ULCs, and LSD.

Accuracy

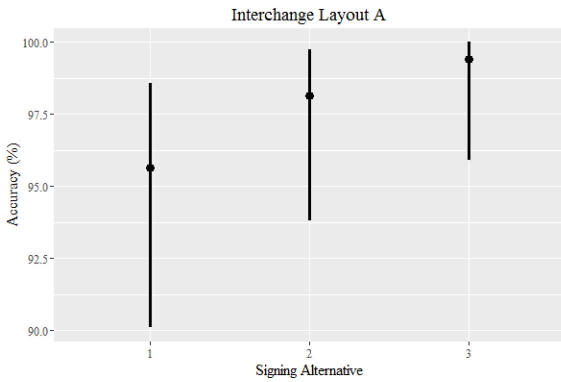
Participants completed their 12 drives each, and their accuracy at each decision point (2 for each layout) was recorded. There were two cases, shown in table 58, where an incorrect maneuver at the DP1 prevented a correct maneuver at the DP2; the accuracy of those DP2 maneuvers was not analyzed.

Table 58. Cases of inaccurate DP1 maneuvers prevented accurate DP2 maneuvers.

Pnum	Age	Gender	City	Interchange_ num	Layout	Sign	Destination	Start Lane
13	Younger	Female	Orlando	1	C	2	L	2
69	Older	Female	Myrtle Beach	1	C	2	R	2

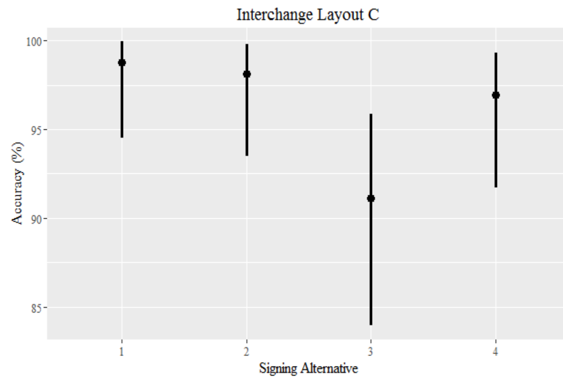
Otherwise, participants were highly accurate across the board. Accuracy was analyzed for each layout separately to determine which signing alternative yielded the best (most accurate) results. Generalized estimating equations—the preferred analysis technique for this setup—are impossible to estimate due to low or zero observations in some experimental conditions. Instead, binomial proportions and exact confidence intervals, adjusted for simultaneous hypothesis testing, were computed and used to detect differences in accuracy among the various experimental conditions.[40,41]

Overall, there was no statistically significant difference detected in accuracy among the signing alternatives of a given interchange layout, as indicated by the overlapping confidence intervals in figure 28.



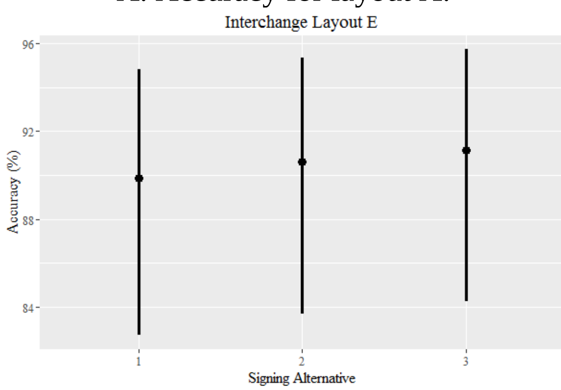
Source: FHWA.

A. Accuracy for layout A.



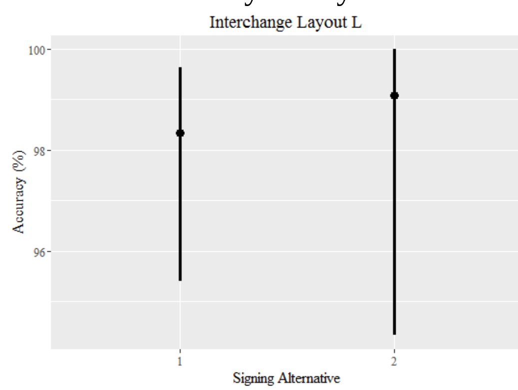
Source: FHWA

B. Accuracy for layout C.



Source: FHWA.

C. Accuracy for layout E.



Source: FHWA.

D. Accuracy for layout L.

Figure 28. Graphics. Participant accuracy for each combination of interchange layout and signing alternative.

Starting lane and destination were also analyzed. Again, no statistically significant differences were detected.

ULCs

The minimum number of lane changes was calculated for each interchange layout, signing alternative, starting lane, and destination combination. All lane changes in excess of this minimum were considered an ULC. Note that this calculation can produce negative values, representative of participants making fewer lane changes than necessary. Ten such cases were observed and are presented in table 59.

In addition, in two cases (see table 60), an incorrect maneuver at DP1 prevented a correct maneuver at DP2; the number of ULCs during those DP2 maneuvers was not analyzed.

ULCs were analyzed for each layout separately to determine which signing alternative yielded the best (fewest ULCs) results. Generalized estimating equations—the preferred analysis technique for this setup—are impossible to estimate due to low or zero observations in some experimental conditions. Instead, Poisson means and confidence intervals, adjusted for simultaneous hypothesis testing, were computed and used to detect differences in ULCs among the various experimental conditions.[42] Figure 29 plots the count of ULCs for each combination of interchange layout and signing alternative to show that ULCs follow a Poisson distribution.

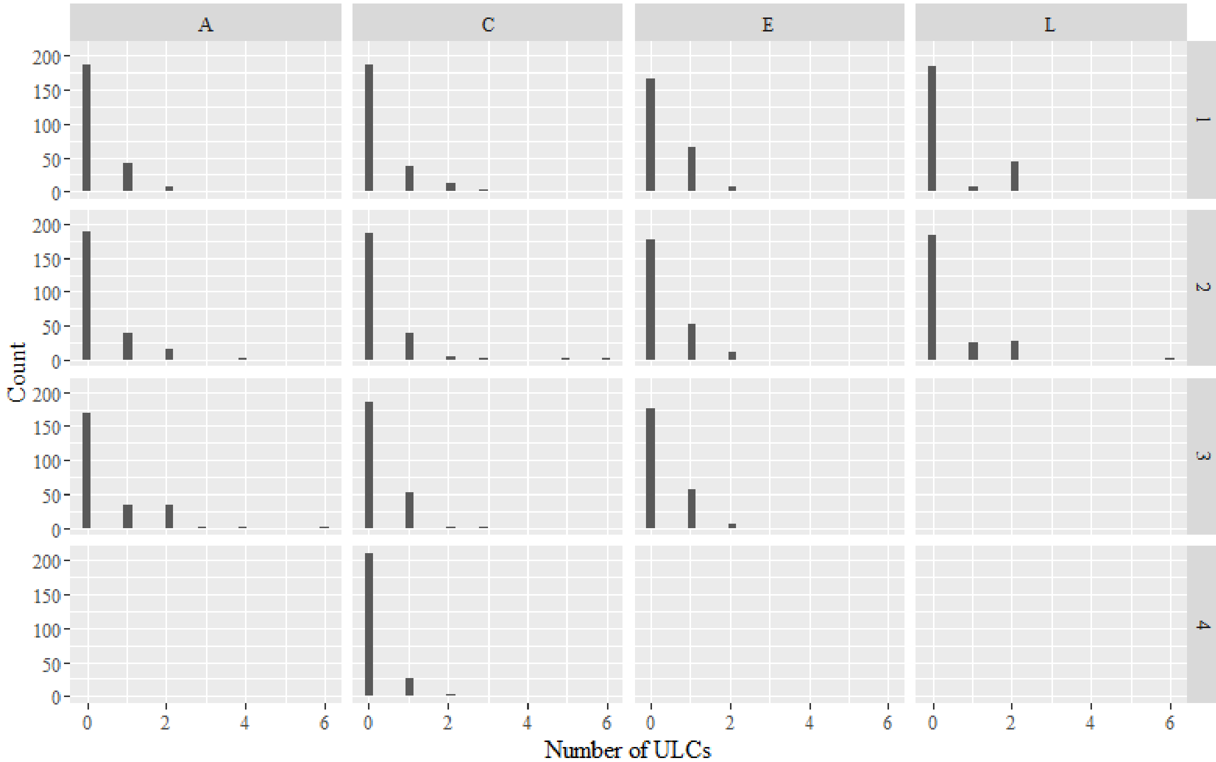
Table 59. Cases of negative ULCs.

Pnum	Age	Gender	City	Interchange_num	Layout	Sign	Destination	Start Lane	Decision_num	Changes_unnec
13	Younger	Female	Orlando	1	C	2	L	2	1	–1
13	Younger	Female	Orlando	5	C	4	R	1	2	–1
49	Younger	Female	Myrtle Beach	8	C	4	R	1	2	–1
51	Younger	Female	Myrtle Beach	1	C	1	R	1	2	–1
69	Older	Female	Myrtle Beach	1	C	2	R	2	1	–1
78	Older	Male	Gainesville	1	C	1	R	1	2	–1
13	Younger	Female	Orlando	2	L	1	L	1	2	–2
49	Younger	Female	Myrtle Beach	11	L	1	L	1	2	–2
80	Younger	Male	Gainesville	7	L	2	L	2	2	–1
105	Older	Female	Gainesville	2	L	1	L	2	2	–1

Table 60. Cases of inaccurate DP1 maneuvers preventing accurate DP2 maneuvers.

Pnum	Age	Gender	City	Interchange_num	Layout	Sign	Destination	Start Lane	Decision_num	Changes_unnec
13	Younger	Female	Orlando	1	C	2	L	2	2	–
69	Older	Female	Myrtle Beach	1	C	2	R	2	2	–

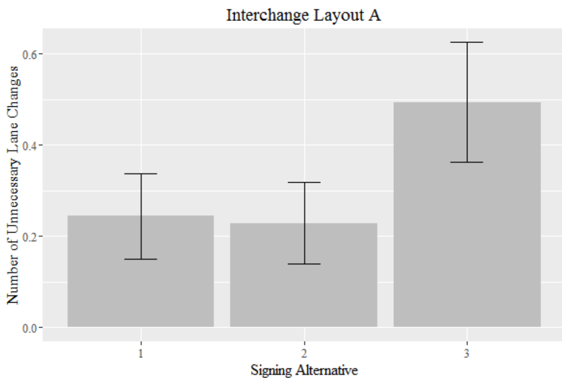
–Not applicable.



Source: FHWA.

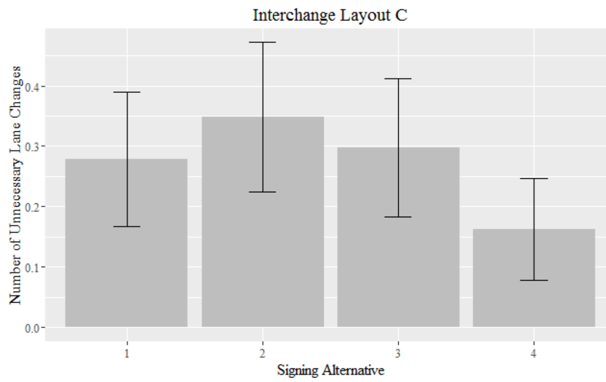
Figure 29. Graphic. Histograms of ULCs for each combination of interchange layout and signing alternative.

As shown in figure 30, there were two statistically significant differences in ULCs due to signing alternatives within a given interchange layout: in layout A, SA3 (mean = 0.49, confidence interval = [0.36, 0.63]) was associated with significantly more ULCs than SA1 (mean = 0.24, confidence interval = [0.15, 0.34]) and SA2 (mean = 0.23, confidence interval = [0.14, 0.32]).



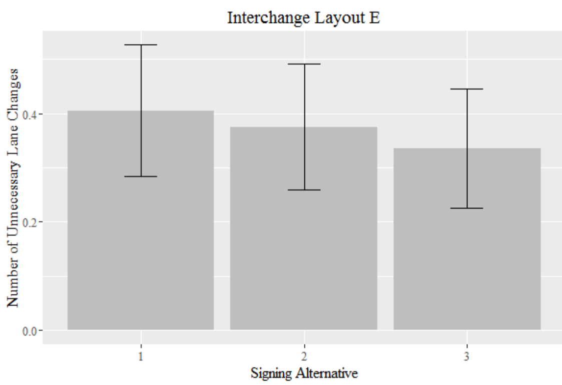
Source: FHWA

A. ULCs for layout A.



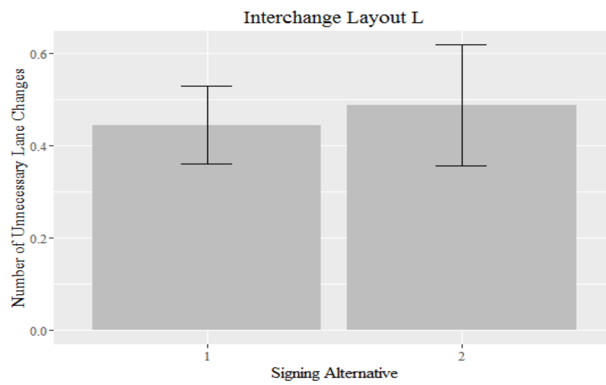
Source: FHWA

B. ULCs for Layout C.



Source: FHWA

C. ULCs for Layout E.



Source: FHWA

D. ULCs for Layout L.

Figure 30. Graphics. Mean and 95-percent (familywise) confidence intervals for ULCs associated with each signing alternative within interchange layout.

LSD

Participants completed 12 drives each, and their lane changes within each decision point (2 for each layout) were recorded. Final lane changes were considered lane selections. LSD (in miles) begins at the legibility point of the first sign in a signing alternative and terminates where the participant makes the final lane change.

Data are formatted such that one row represents one observation, which captures the LSD and number of signs passed up to that point for a given decision point (along with other experimental conditions and demographics). There are up to 2 observations per drive per participant, or 24 observations total per participant; drives involving no lane changes are not represented here. The total number of data points should equal 121 × 12 × 2 = 2904, but one participant (75) failed to complete the sixth drive, and another (111) failed to complete the second set of six drives; therefore, the dataset contains 2904 – 2(1 + 6) = 2890 observations. Of those, 69.6 percent did not change lanes at all, and 1.8 percent did so before encountering any signs. The following analyses apply to the 828 cases in which valid lane changes were made.

Each layout and decision point was considered a distinct survival analysis. Whereas survival analysis is traditionally applied to medical data, the research team use it here to model LSD and use final lane changes as "deaths." The homogeneity of survival curves for each signing alternative was tested using PROC LIFETEST in SAS 9.2. Median LSD and complete survival curves are presented. All reported p-values have been adjusted for multiple comparisons.

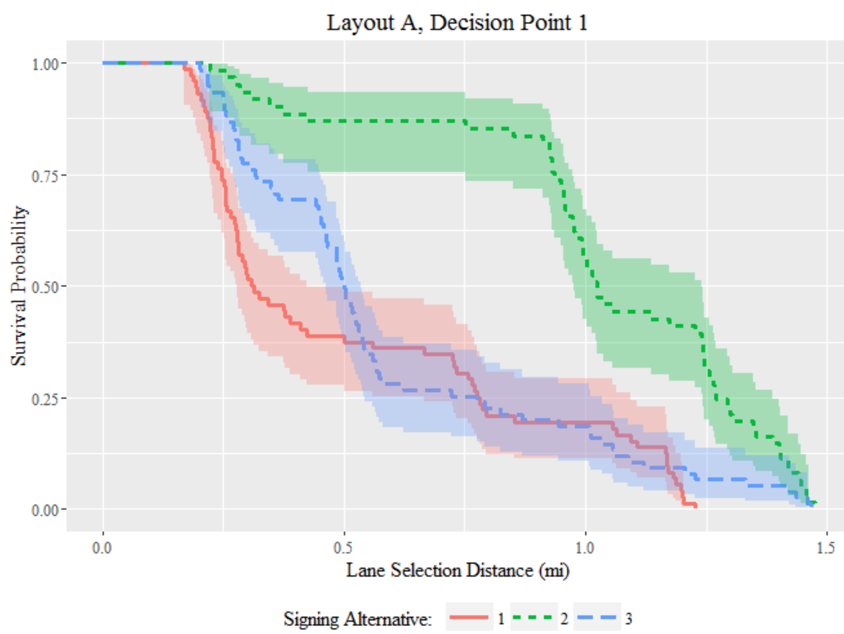
Layout A, DP1

Signing alternatives 1 and 3 were found to differ significantly from signing alternative 2 (Wilcoxon $p_{1,2} = p_{2,3} < 0.01$) but not from one another ($p_{1,3} = 0.42$). The Wilcoxon test is used because the Likelihood Ratio test "assumes that the data in the various samples are exponentially distributed and tests that the scale parameters are equal."(41) Median LSD and simultaneous confidence intervals are shown in table 61.

Table 61. LSD: layout A, DP1.

Signing Alternative	Median	Lower	Upper
1	0.53	0.27	0.56
2	1.02	0.97	1.24
3	0.50	0.45	0.54

Survival curves for each signing alternative are plotted in figure 31 (where "survival" corresponds to not selecting the final lane yet).



Source: FHWA.

Figure 31. Graphic. Survival analysis with 95-percent confidence intervals: layout A, DP1.

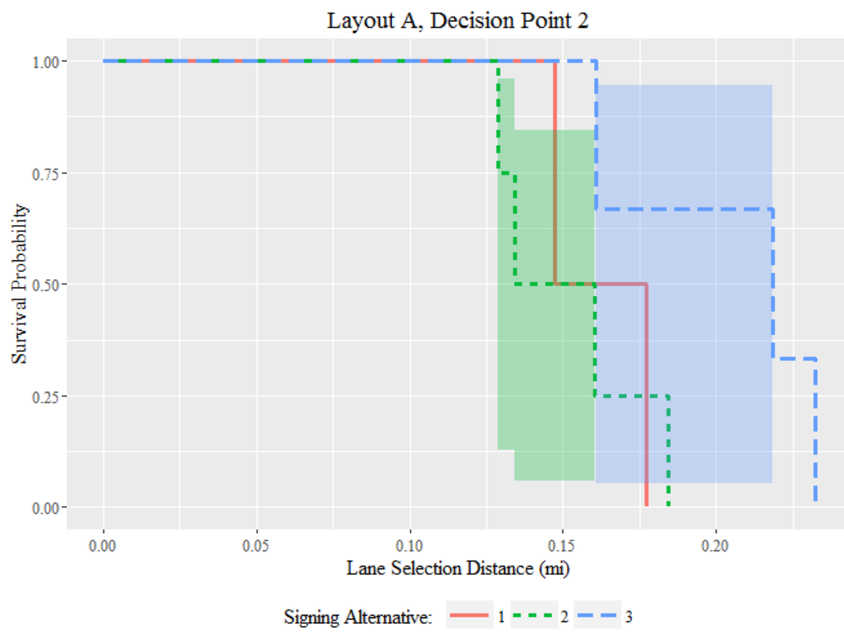
Layout A, DP2

Different signing alternatives did not produce significantly different LSDs in DP2 (all $p > 0.05$). Median LSD and simultaneous confidence intervals are shown in table 62.

Table 62. LSD: layout A, DP2.

Signing Alternative	Median	Lower	Upper
1	0.16	0.15	0.18
2	0.15	0.13	0.18
3	0.22	0.16	0.23

Survival curves for each signing alternative are plotted in figure 32 (where "survival" corresponds to not selecting the final lane yet).



Source: FHWA.

Figure 32. Graphic. Survival analysis with 95-percent confidence intervals: layout A, DP2.

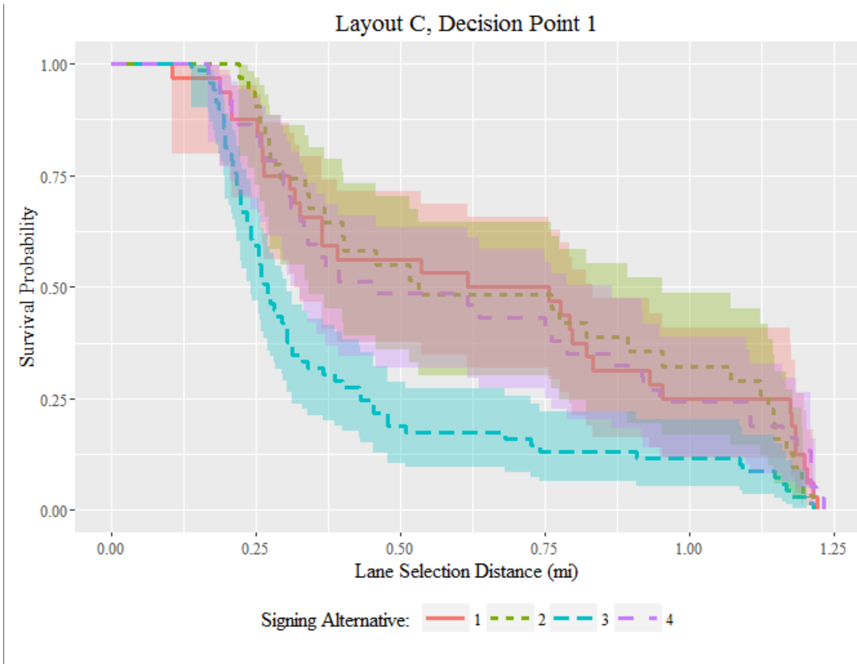
Layout C, DP1

Signing alternatives 1, 2, and 4 were found to differ significantly from signing alternative 3 ($p_{1,3} = p_{2,3} = p_{3,4} < 0.01$) but not from one another ($p_{1,2} = p_{1,4} = p_{2,4} = 1.00$). Median LSD and simultaneous confidence intervals are shown in table 63.

Table 63. LSD: layout C, DP1.

Signing Alternative	Median	Lower	Upper
1	0.69	0.26	0.93
2	0.53	0.29	1.07
3	0.27	0.23	0.31
4	0.46	0.30	0.92

Survival curves for each signing alternative are plotted in figure 33 (where "survival" corresponds to not selecting the final lane yet).



Source: FHWA.

Figure 33. Graphic. Survival analysis with 95-percent confidence intervals: layout C, DP1.

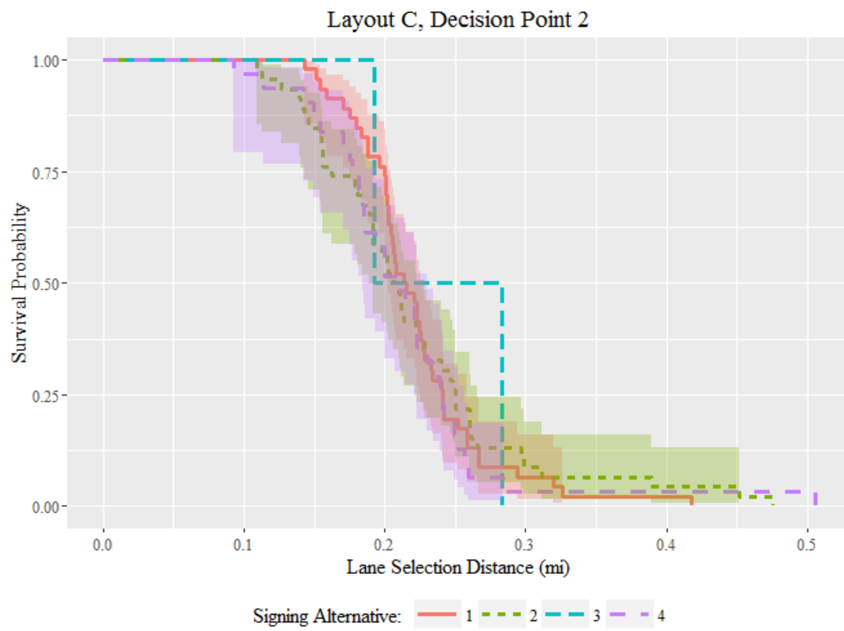
Layout C, DP2

Different signing alternatives did not produce significantly different LSDs ($p > 0.05$) in DP2. Median LSD and simultaneous confidence intervals are shown in table 64.

Table 64. LSD: layout C, DP2.

Signing Alternative	Median	Lower	Upper
1	0.21	0.20	0.23
2	0.21	0.17	0.23
3	0.24	0.19	0.28
4	0.21	0.18	0.23

Survival curves for each signing alternative are plotted in figure 34 (where "survival" corresponds to not selecting the final lane yet).



Source: FHWA.

Figure 34. Graphic. Survival analysis with 95-percent confidence intervals: layout C, DP2.

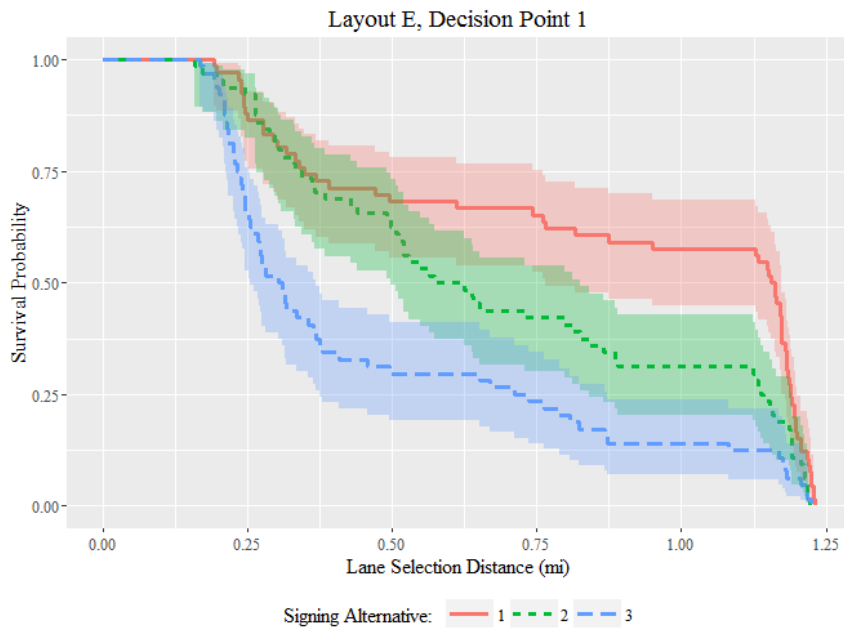
Layout E, DP1

Signing alternatives 1 and 2 were found to differ significantly from Signing alternative 3 ($p_{1,3} = p_{2,3} < 0.01$) but not from one another ($p_{1,2} = 0.21$). Median LSD and simultaneous confidence intervals are shown in table 65.

Table 65. LSD: layout E, DP1.

Signing Alternative	Median	Lower	Upper
1	1.16	0.74	1.18
2	0.60	0.44	0.87
3	0.19	0.12	0.26

Survival curves for each signing alternative are plotted in figure 35 (where "survival" corresponds to not selecting the final lane yet).



Source: FHWA.

Figure 35. Graphic. Survival analysis with 95-percent confidence intervals: layout E, DP1.

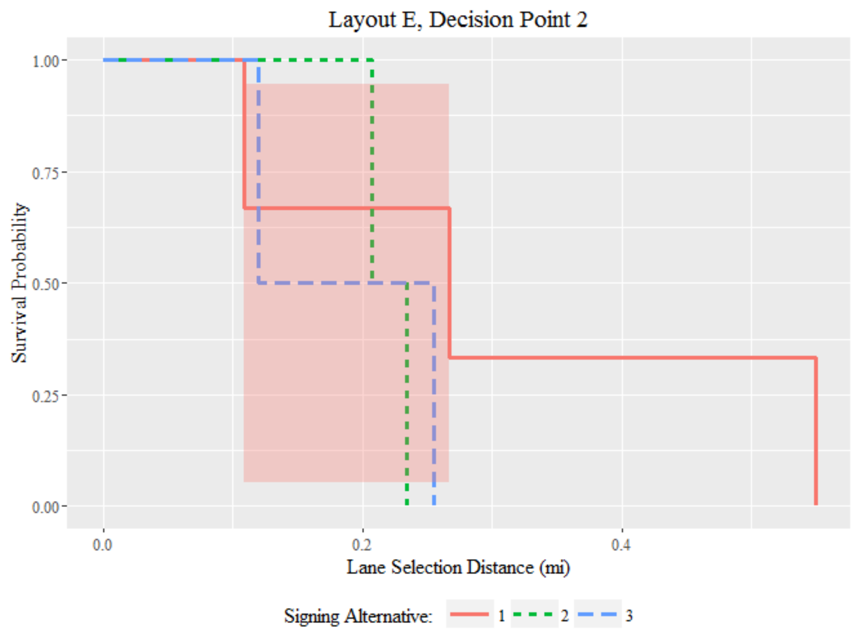
Layout E, DP2

Different signing alternatives did not produce significantly different LSDs ($p > 0.05$) in DP2. Median LSD and simultaneous confidence intervals are shown in table 66.

Table 66. LSD: layout E, DP2.

Signing Alternative	Median	Lower	Upper
1	0.27	0.11	0.55
2	0.22	0.21	0.23

Survival curves for each signing alternative are plotted in figure 36 (where "survival" corresponds to not selecting the final lane yet).



Source: FHWA.

Figure 36. Graphic. Survival analysis with 95-percent confidence intervals: layout E, DP2.

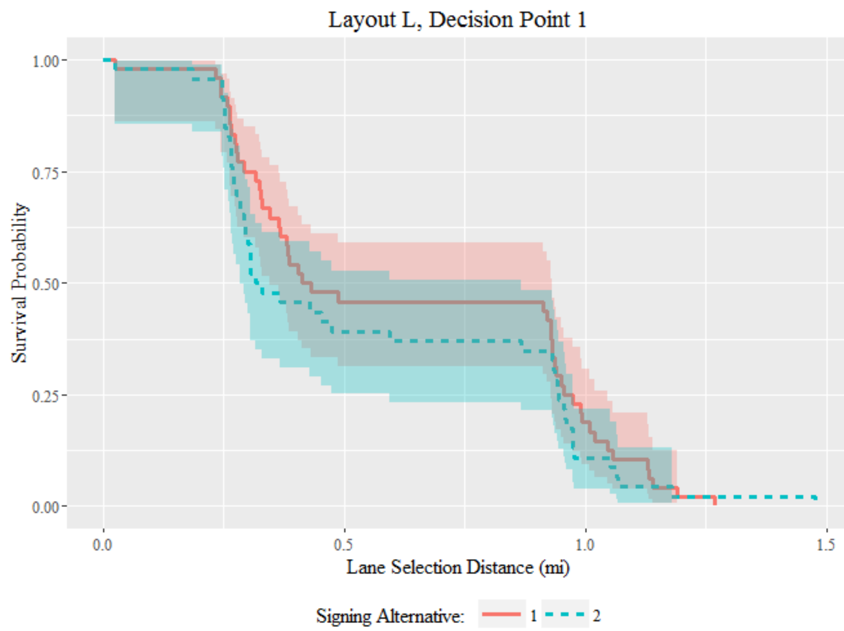
Layout L, DP1

Different signing alternatives did not produce significantly different LSDs ($p > 0.05$). Median LSD and simultaneous confidence intervals are shown in table 67.

Table 67. LSD: layout L, DP1.

Signing Alternative	Median	Lower	Upper
1	0.42	0.33	0.93
2	0.32	0.28	0.93

Survival curves for each signing alternative are plotted in figure 37 (where "survival" corresponds to not selecting the final lane yet).



Source: FHWA.

Figure 37. Graphic. Survival analysis with 95-percent confidence intervals: layout L, DP1.

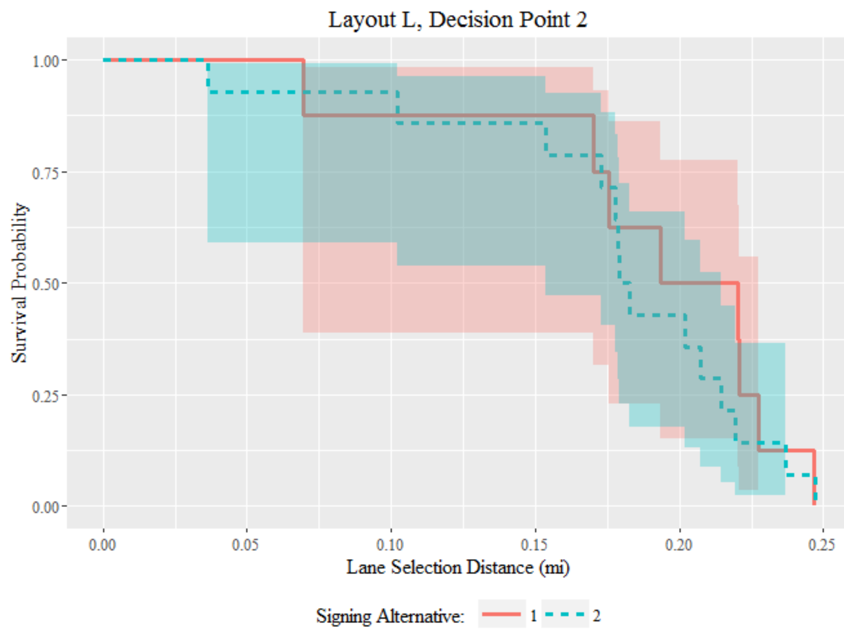
Layout L, DP2

Different signing alternatives did not produce significantly different LSDs ($p > 0.05$). in DP2. Median LSD and simultaneous confidence intervals are shown in table 68.

Table 68. LSD: layout L, DP2.

Signing Alternative	Median	Lower	Upper
1	0.21	0.07	0.23
2	0.18	0.04	0.21

Survival curves for each signing alternative are plotted in figure 38 (where "survival" corresponds to not selecting the final lane yet).



Source: FHWA.

Figure 38. Graphic. Survival analysis with 95-percent confidence intervals: layout L, DP2.

DISCUSSION

The combination of the three analyses (accuracy, ULCs, and LSD) provides better insight into the different signing alternatives. Because the layouts were not compared, the findings that follow focus on comparisons between signing alternatives within a single layout. The analysis found that, when considering signing alternatives within a single layout, no signing alternatives had a statistically significant difference in accuracy; in all cases, participants were accurate in getting to their destination. Other findings include the following:

- **Layout A.** Signing alternative 3 was shown to produce significantly more ULCs than signing alternative 1 and signing alternative 2, and participants made their final lane change earlier in signing alternative 1 and signing alternative 3 than in signing alternative 2. The three signing alternatives for layout A are shown in figure 39.

- **Layout C.** When considering ULCs, no differences were found across the four signing alternatives in layout C. For LSD, the analysis found that participants entered their final lane significantly earlier in signing alternative 3 when compared with signing alternative 1, signing alternative 2, and signing alternative 4. The four signing alternatives for layout C are shown in figure 40.

- **Layout E.** When considering ULCs, no differences were found across the three signing alternatives in layout E. For LSD, the analysis found that participants entered their final lane significantly earlier in signing alternative 3 when compared with signing alternative 1 and signing alternative 2. The three signing alternatives for layout E are shown in figure 41.

- **Layout L.** No significant differences were found for ULCs or LSD in either of the signing alternatives for layout L. The two signing alternatives for layout L are shown in figure 42.

To summarize, the signing alternatives that produced the best (i.e., fewest ULCs, earliest) movement into the final lane are shown in table 69.

Table 69. Signing alternatives with fewest ULCs.

Layout	Signing Alternative
A	Signing alternative 1
C	Signing alternative 3
E	Signing alternative 3
L	Not applicable

A typical driver in the United States has seen many guide signs in various environments and, generally, is able to follow guide signs to his or her final destination. In this study, participants navigated interchanges signed using a variety of approaches, and participants were found to be accurate regardless of the approach used. Similarly, participants seemed to understand the signing alternative as, in general, there was an average of less than one ULC per interchange. Together, the high accuracy presented by drivers and few ULCs indicate that drivers tend to understand a series of guide signs leading up to complex interchanges as long as they are designed consistently and with good signing practices.

Another finding from this study is that the best signing alternative for both layouts C and E was found to be designed where the signs present the driver one destination per lane, even in cases where some lanes may provide access to multiple locations (e.g., layout E). This characteristic is also present to an extent in the best signing alternative for layout A (signing alternative 1). In layout A, signing alternative 1, two destinations sharing a single lane are listed on a single sign, but the sign has a full-width horizontal separator and clearly lists the distance to each exit.

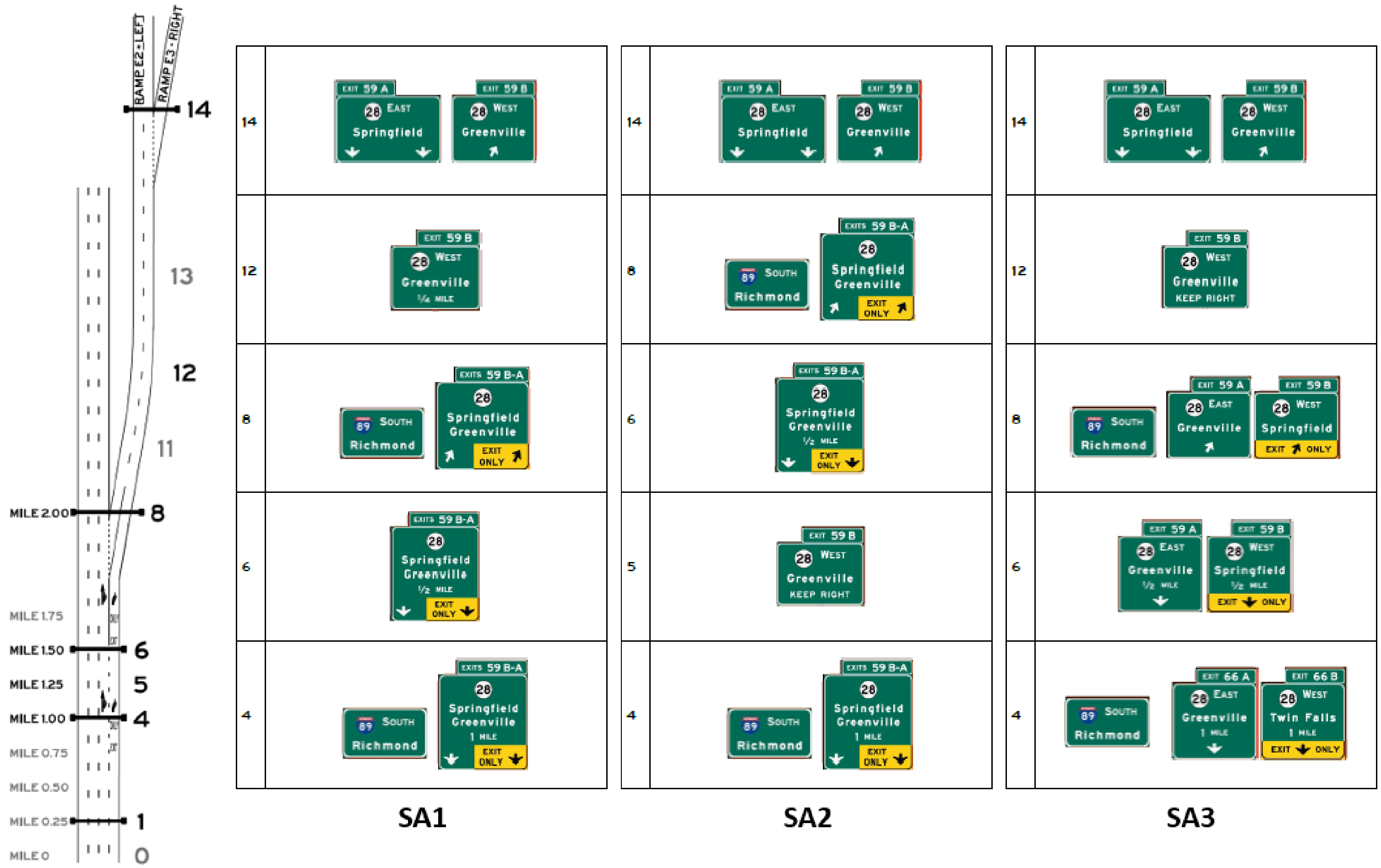
While accuracy, ULCs, and LSD are important measures, it is also important to consider other factors not discussed in this study when designing signs for complex interchanges. For instance, while in layout E, signing alternative 3 was found to perform best; this approach could cause issues with lane use. In this signing alternative, drivers making a left at the downstream split are guided into the option lane on the mainline and the left lane on the C/D roadway, but both the exit-only lane and the right lane on the C/D roadway would lead the driver to the same direction (left at the downstream split). In effect, drivers making a left at the downstream split would be bunched in the left lane on the C/D roadway, potentially leaving unused capacity in the right lane.

Source: FHWA.

Figure 39. Graphic. Layout A signing alternative examples.

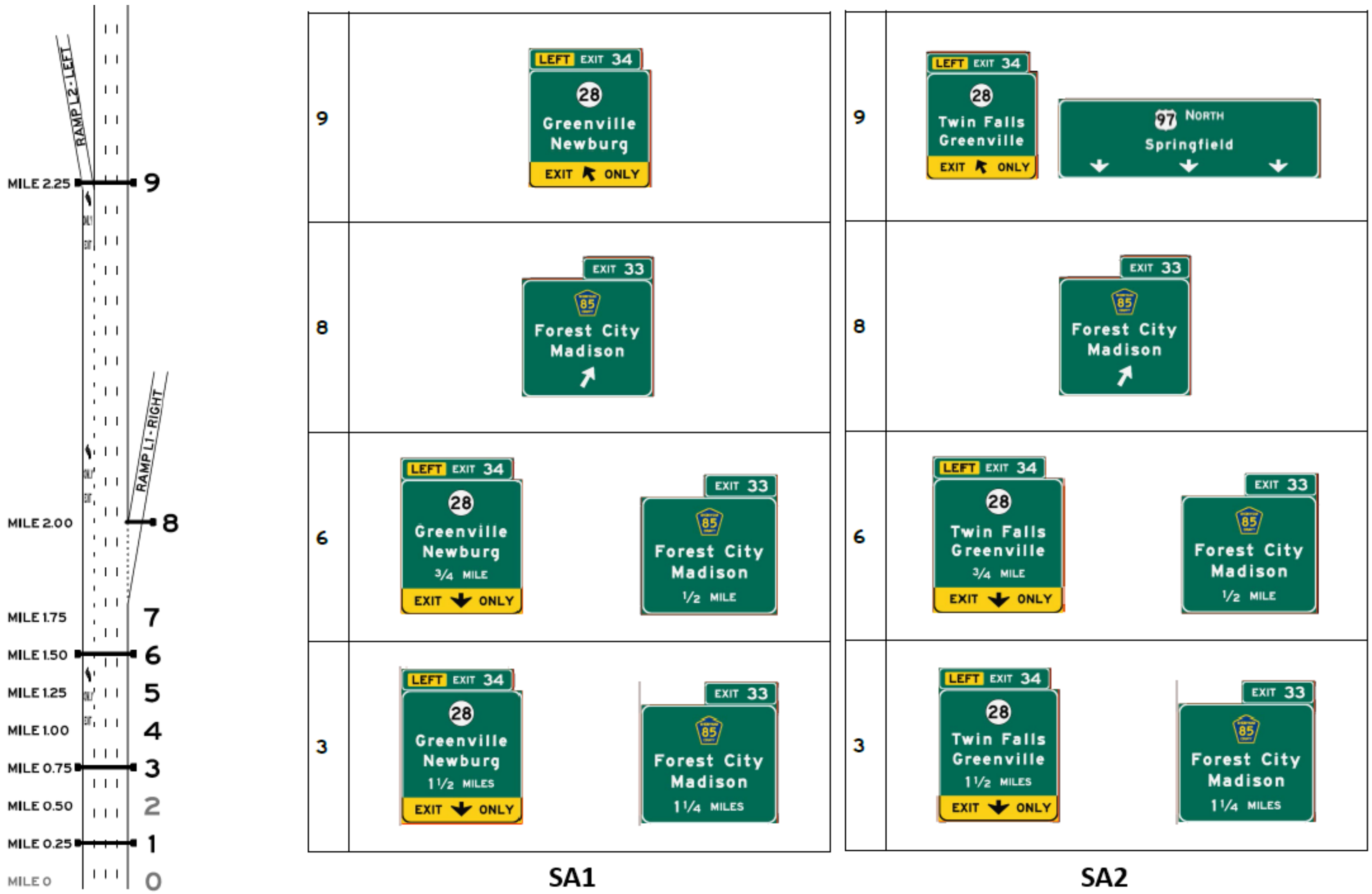
Source: FHWA.

Figure 40. Graphic. Layout C signing alternative examples.



Source: FHWA.

Figure 41. Graphic. Layout E signing alternative examples.



Source: FHWA.

Figure 42. Graphic. Layout L signing alternative examples.

CHAPTER 7. FIELD STUDY

This chapter is organized into four sections: Study Design, Data Collection Process and Methods, Site Descriptions and Results, and Field Study Findings. For each section, individual sites and locations are addressed separately.

STUDY DESIGN

Based on the topics and related attributes identified in previous work products, the project team developed data collection activities for each of the 21 sites considered for field evaluations. The project team considered the collection of video, both aerial and from fixed-location cameras; the collection of photographs and observational notes; and site evaluations consisting of a rudimentary TCD audit and examination of the geometric configuration of the interchange decision points. The initial list was refined to six sites identified for field evaluations (table 70).

Table 70. Selected interchanges for field data collection activities.

Number	State	Location	Data	Municipality
11	Florida	**I-4** US 192 to SR 535	UAV	Kissimmee
26	Georgia	**I-85** I-285 (northeast junction)	Photographs	Atlanta
27	Georgia	**I-20** I-285 (west junction)	Video	Atlanta
31	Minnesota	**I-35W** TH 62	Video	Minneapolis
41	Washington	**I-5** I-405 and Washington SR 518	Photographs	Tukwila
43	Washington	**I-5** US 101 to SR 510	UAV	Lacey, Olympia

TH 62 = State Trunk Highway 62; UAV = unmanned aerial vehicle.

DATA COLLECTION PROCESS AND METHODS

The following subsections discuss the site visit preparation, data collection methods, data reduction, and data analysis.

Site Visit Preparation

In preparation for the site visits, the project team examined all access points along each segment using satellite imagery. The team determined the ideal locations for fixed-position cameras and unmanned aerial vehicle (UAV) hovering in an effort to ensure that data collection methods would produce imagery without gaps or areas out of view. This preparation also enabled the team to write appropriate requests for proposals to vendors, ensuring that each vendor received the same information and that the camera positions were reasonable given the type and quantity of data desired.

Data Collection Methods

Three types of data were collected for this project: photographs, videos from fixed-location cameras, and videos from UAVs.

Photographs

The field data collection for behavioral analysis was limited to representative sites with exceptional complexity. For many sites, the use of fixed-location cameras was cost-prohibitive due to the relative lack of structures for camera mounting and an unfavorable safety risk analysis for camera deployment activities. In the case of site 31, the use of UAVs was explicitly prohibited by the proximity of the Minneapolis-St. Paul International Airport and the instrument approach paths for runways 12L and 12R and departure paths for runways 31L and 31R. To collect photographs, the project team drove through the interchange being studied and captured images at guide signs and pavement markings.

Fixed-Location Camera Video

Fixed-location cameras were deployed at site 11 (supplementing the aerial video), site 27, and site 31 to collect field data. For sites 11 and 27, the project team used high-resolution cameras with a weather-resistant housing and supplemental battery. For site 31, a vendor was selected who provided equipment used for intersection traffic counts, including the installation, removal, data download, and delivery.

For all installations, project team and contractor members used personal protective equipment, including reflective vests, high-visibility headwear, safety glasses, and rated footwear. In addition, project staff conducted a risk analysis, including assessing vehicle parking and site access. No work plans involved the closure of lanes on the freeway or flagging activities related to vehicle diversions.

UAV Video

UAV video data were collected using high-resolution, 4K cameras mounted to professional-quality UAVs. Battery technology limited each UAV sortie to approximately 17 to 20 min, allowing for 15-min data collection intervals separated by approximately 5 min of transit and servicing time. The project team and contractor worked together in advance to create a collection plan, including arranging with property owners for permission to set up launch locations that permitted unobstructed views of the drones to comply with Federal Aviation Administration regulations. In addition, the entire team (operators, spotters, and support staff) met twice each day for a mission briefing, including analyzing risk, assigning and inspecting personal protective equipment, and establishing communications and command protocols.

Data Reduction

The project team reduced all field video to facilitate data analysis. Data reduction activities varied per site and focused on distilling driving behavior (e.g., route choice, lane selection, origin/destination) from the video. In general, the data reduction activities involved viewing each video, selecting vehicles based on a predetermined sampling plan, and noting the lane position of each selected vehicle at screen lines along the route. Those screen lines were chosen based on the position of guide and regulatory signing, the location of pavement markings and pavement marking pattern changes, and other factors that could influence driver behavior relative to navigating to an exit. Where possible, qualitative observations concerning vehicle trajectory, speed, and sudden movements were also recorded and compiled to determine if some locations exhibited a higher frequency of these types of movements.

Data Analysis

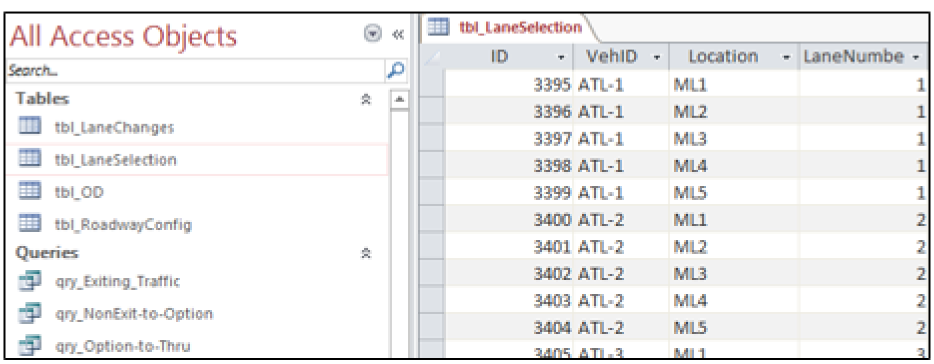
The project team primarily used two approaches to analyze the field data: (1) entering the data into a relational database and manipulating the data through queries and (2) cluster analysis.

The first approach was primarily used to drill down into the data and ask specific questions about how drivers behaved within the captured field video data. Example questions asked through this approach ranged from basic (e.g., what percentage of drivers used the option lane) to more complex (e.g., what percentage of vehicles from any non-exiting lane moved into an exiting lane and ultimately exited). Because the data coders reduced all field data in a uniform format (see figure 43), the use of relational databases allowed the project team to reuse queries at different sites after making minor tweaks to each query.

	A	B	C	D	E	F	G	H	I	J
1	VehID	VehType	Lane (Site	Lane (Site	Lane (Site	Lane (Site	Lane (Site	Vehicle E›	Exit Site	Exit Lane
2	1	PV	1	1	1	1	1	No	N/A	N/A
3	2	PV	2	2	2	2	2	No	N/A	N/A
4	3	PV	3	3	3	3	4	Yes	Site 5	4
5	4	CV	4	4	4	4	N/A	Yes	Site 4	4
6	5	PV	3	2	1	2	2	No	N/A	N/A
7	6	CV	4	4	4	3	4	Yes	Site 5	4
8	7	PV	1	1	1	1	1	No	N/A	N/A
9	8	PV	2	2	2	2	2	No	N/A	N/A
10	9	PV	3	3	3	3	N/A	Yes	Site 4	3
11	10	PV	2	1	1	1	1	No	N/A	N/A

Source: FHWA.

A. Data examples from site 27 as provided by data coders.



Source: FHWA.

B. Site 27 data entered in the relational database.

Figure 43. Graphics. Site 27 data.

The second approach used for the data analysis was a cluster analysis. Cluster analysis is a data mining technique that groups data into clusters, in which the data items within a single cluster are similar, but data items between clusters are dissimilar. The project team used open-source data mining software that included an algorithm for k-means clustering.(43) All cluster analyses performed on the field data were completed using the simple k-means algorithm ranging from 2 to 10 clusters. The final number of clusters was selected by identifying the "elbow" of the curve when the numbers of clusters were plotted against the sum of error within each cluster; this is the point at which additional clusters do little to better explain the dataset. This analysis provided groups of common driving behaviors (i.e., what lanes drivers selected at different locations) witnessed in the field video data.

For this analysis, lane selection per location within a single study site was used on input. Output of the cluster analysis showed what lane best represented driver behavior at each location within the study site. An example of analysis output is shown in figure 44. It is important to note that this method assigns vehicles to the cluster that most closely represents their driving behavior. In other words, while the driver behavior will be similar between drivers of a single cluster, not every driver within a given cluster has the exact same driving behavior.

		Cluster#				
Attribute	Full Data	0	1	2	3	4
	(202.0)	(35.0)	(25.0)	(101.0)	(7.0)	(34.0)
Lane (Site 1)	Lane 4	Lane 2	Lane 3	Lane 4	Lane 2	Lane 3
Lane (Site 2)	Lane 4	Lane 3	Lane 4	Lane 4	Lane 2	Lane 3
Lane (Site 3)	Lane 4	Lane 4	Lane 4	Lane 4	Lane 2	Lane 3
Lane (Site 4)	Lane 4	Lane 4	Lane 4	Lane 4	Lane 3	Lane 3

Source: FHWA.

Figure 44. Graphic. Example cluster analysis results (site 27).

SITE DESCRIPTIONS AND RESULTS

The following sections describe four sites: site 11 in Orlando, FL; site 27 in Atlanta, GA; site 31 in Minneapolis, MN; and site 43 in Olympia, WA.

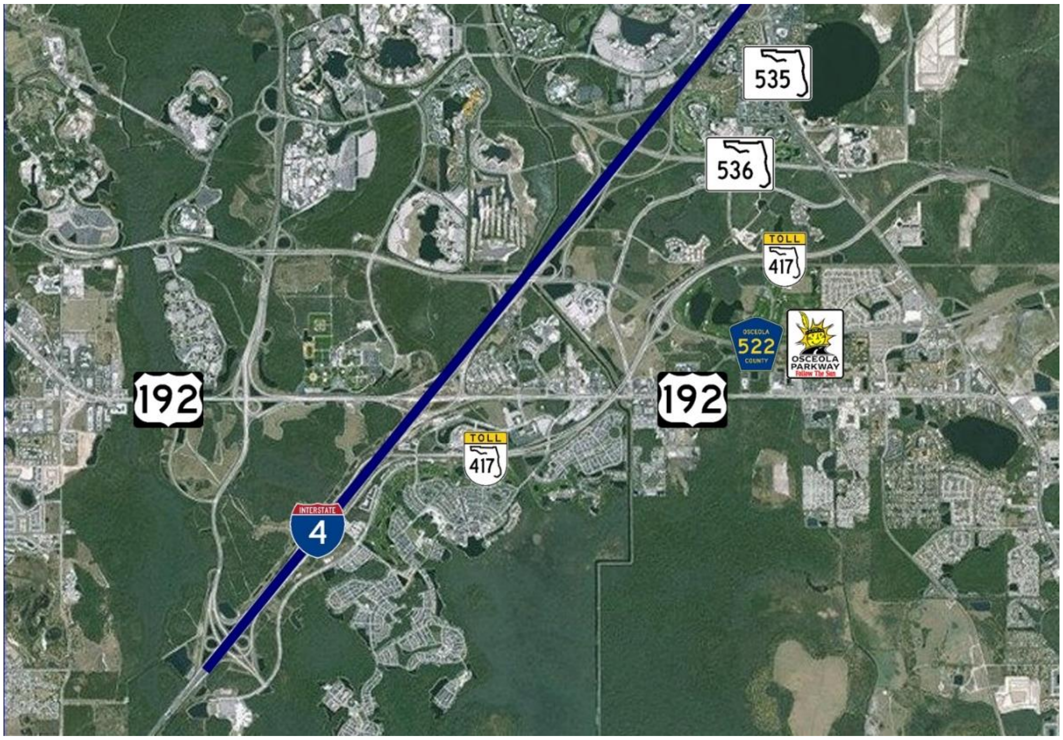
Site 11—Orlando, FL

The following subsections cover the description, observations, and results for site 11.

Description

A total of five UAVs were used to provide coverage of roughly 15,000 linear ft along I-4, between US 192 in the southwest and SR 536 in the northeast. The view of the area is depicted in figure 45. Of particular interest was the behavior of drivers entering from World Drive and US 192 in the eastbound direction and drivers entering from SR 535 and SR 536 in the westbound direction. The area is particularly complicated by the presence of braided ramps between World Drive and US 192, between US 192 and Osceola Parkway (County Road 522), and between Osceola Parkway and SR 536. This means that there is no I-4 access to US 192 from Osceola

Drive in the westbound direction. This site was chosen particularly because it addresses the system design aspects of complexity.



©Esri.

Figure 45. Photo. Area map of Orlando, FL, data collection segment.(44)

The location of the UAVs varied according to the direction being filmed. The composite view of the UAVs provided the ability to track vehicles entering from World Drive southwest of US 192 and exiting as far north as SR 536 in the eastbound direction, while westbound vehicles entering from SR 535 could be tracked to the directional ramps on the US 192 interchange. An example image from the aerial video is shown in figure 46. The data collection took place on Thursday, February 11, and Friday, February 12, 2016.

Source: FHWA.

Figure 46. Photo. Example video still from camera 2 at site 11.

The following attributes were present at the site:

- Auxiliary lanes (attribute 4110).
- Exiting lanes (attribute 4120).
- Exit with downstream split (attribute 4222).
- Guide signs for option lanes (attribute 5130).

Observations

Video was collected from both the eastbound and westbound approaches and will be discussed separately in the Results subsection. In both cases, the sample of vehicles selected for this analysis represents an equal distribution of vehicles across the three lanes of I-4. Approximately 70 min of video per UAV were reviewed for the eastbound video and approximately 50 min of video per UAV were reviewed for the westbound video. Vehicles were sampled at a rate of one sample per minute, with each sample representing one vehicle per lane. Vehicles were tracked across the entire study area using videos from each of the five UAVs, and any vehicle that could not be positively tracked across the entire study area was removed from the dataset. The total sample size resulting from the data reduction was 328 vehicles. More information on the distribution of exiting traffic is shown in table 71 and table 72.

Table 71. Percentage of exiting traffic (site 11, eastbound).

Number of Observations	Number/Percent Remaining on I-4	Number/Percent Exiting at Exit 64	Number/Percent Exiting at Exit 65	Number/Percent Exiting at Exit 67
182	142 (78%)	24 (13%)	6 (3%)	10 (6%)

Table 72. Percentage of exiting traffic (site 11, westbound).

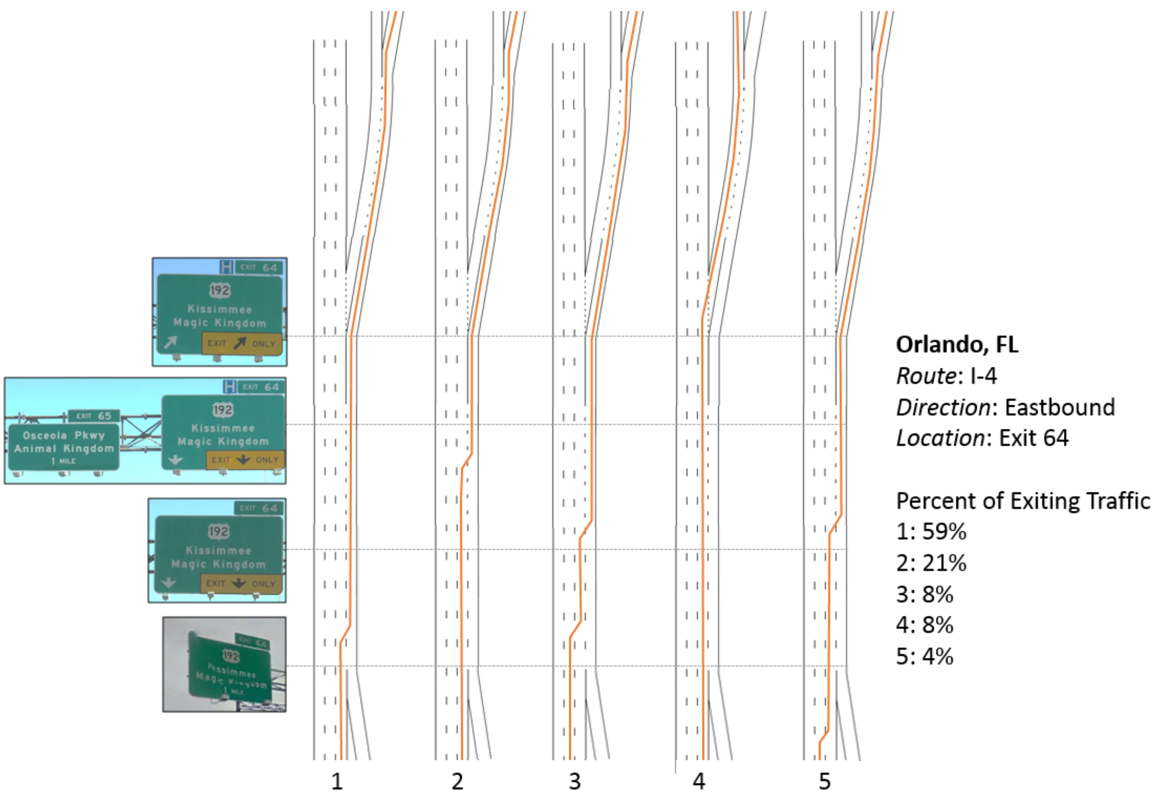
Number of Observations	Number/Percent Remaining on I-4	Number/Percent Exiting at Exit 64	Number/Percent Exiting at Exit 65	Number/Percent Exiting at
146	62 (42%)	26 (18%)	13 (9%)	45 (31%)

Results

Results were obtained from both the eastbound and westbound approaches to site 11.

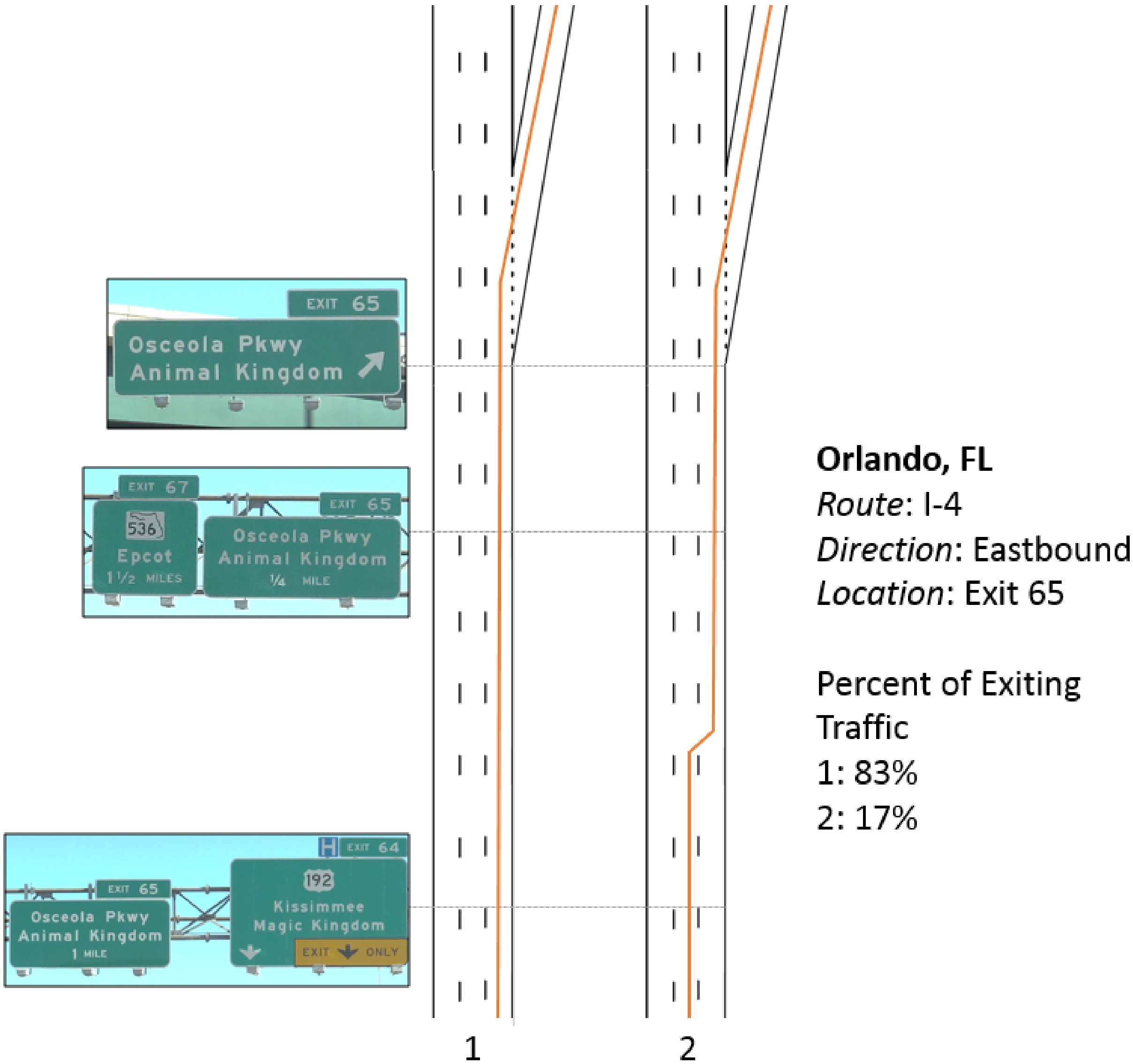
Eastbound

Figure 47, figure 48, and figure 49 illustrate common driver behavior identified at exits 64, 65, and 67, respectively, on eastbound I-4. Depiction 3 in figure 49 illustrates apparent ULCs where drivers move out of the option lane to exit the freeway in the exit-only lane, yet these drivers make a lane change to the left on the C/D roadway to exit left at the downstream split.



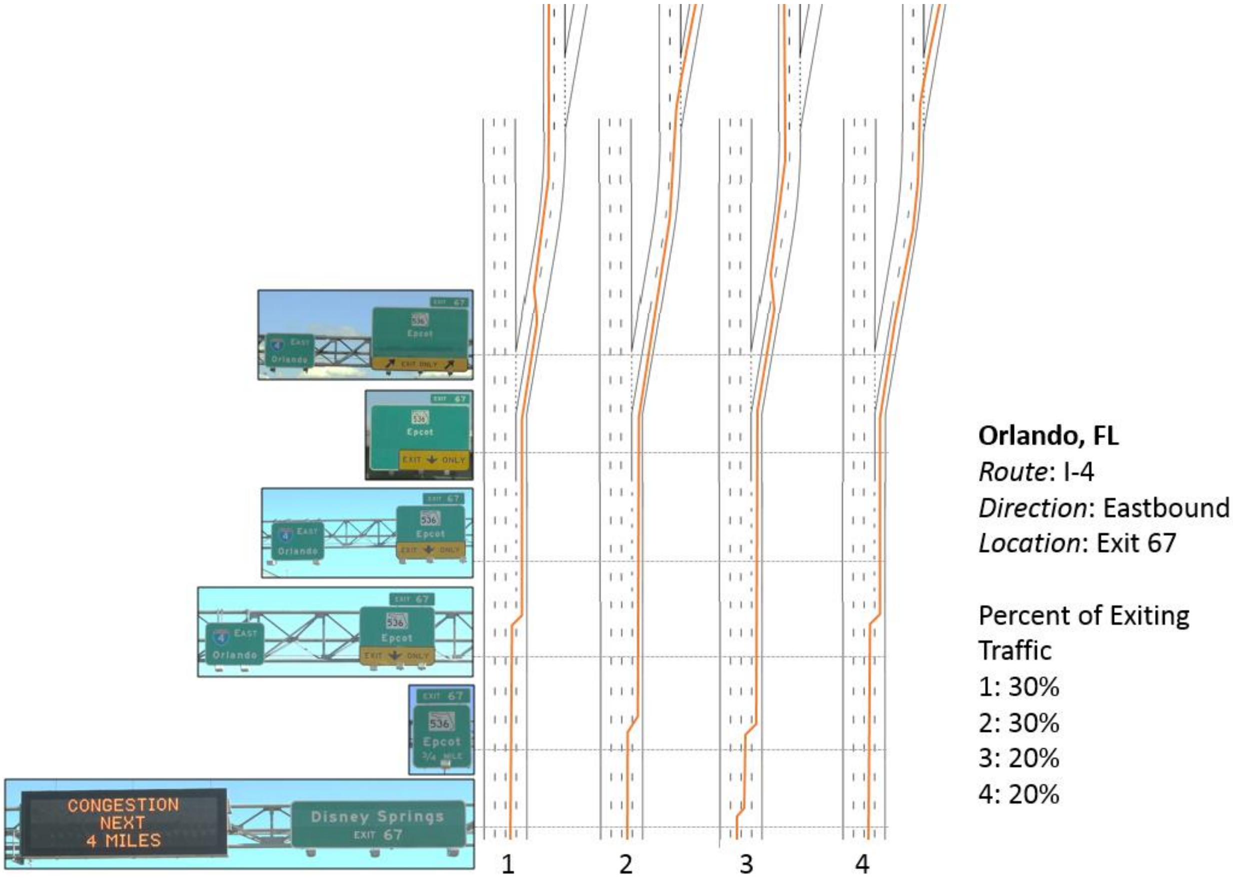
Source: FHWA.

Figure 47. Graphic. Common exiting driver behaviors at site 11, eastbound, exit 64 (*n* = 24).



Source: FHWA.

Figure 48. Graphic. Common exiting driver behaviors at site 11, eastbound, exit 65 (*n* = 6).

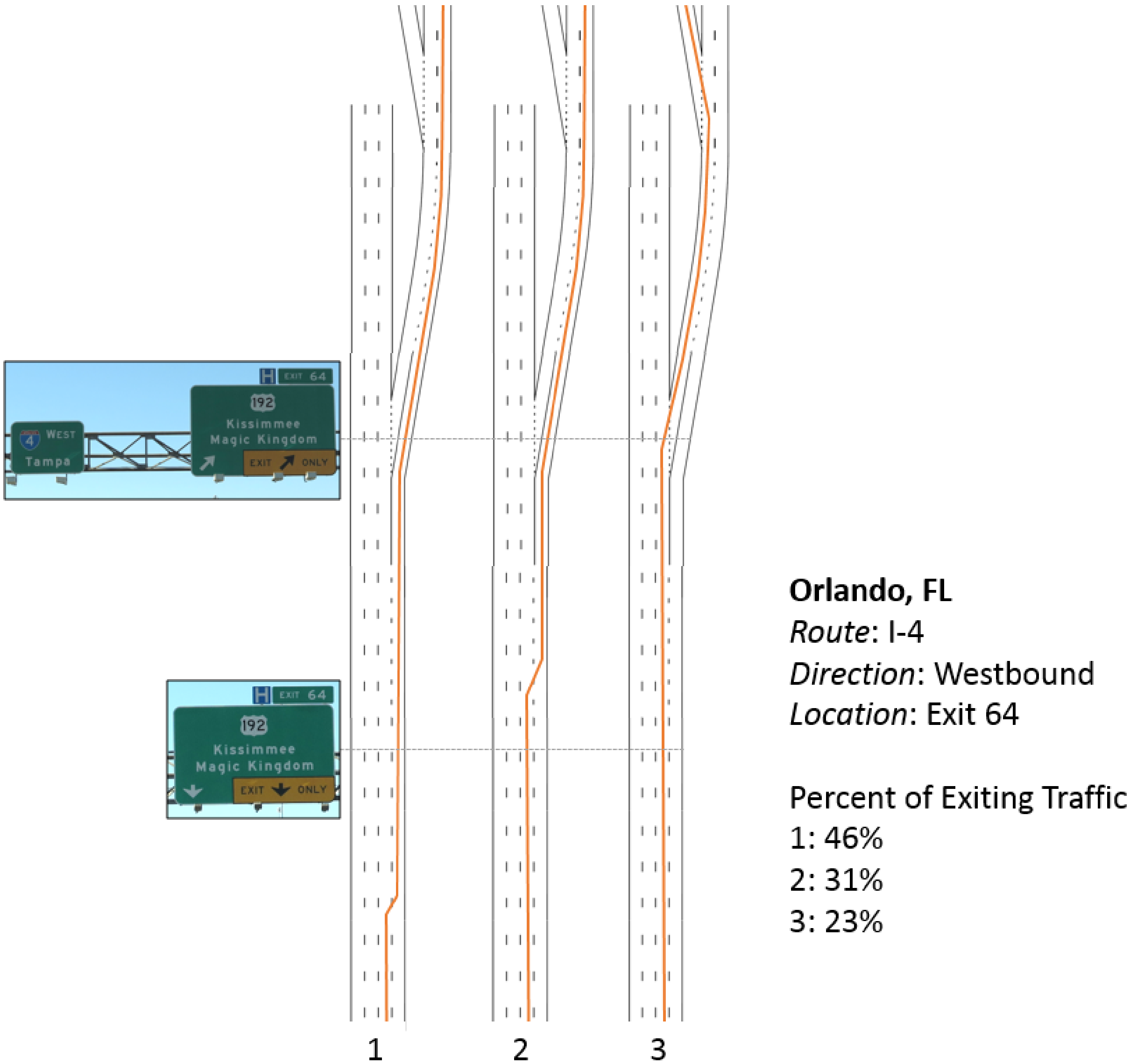


Source: FHWA.

Figure 49. Graphic. Common exiting driver behaviors at site 11, eastbound, exit 67 (*n* = 10).

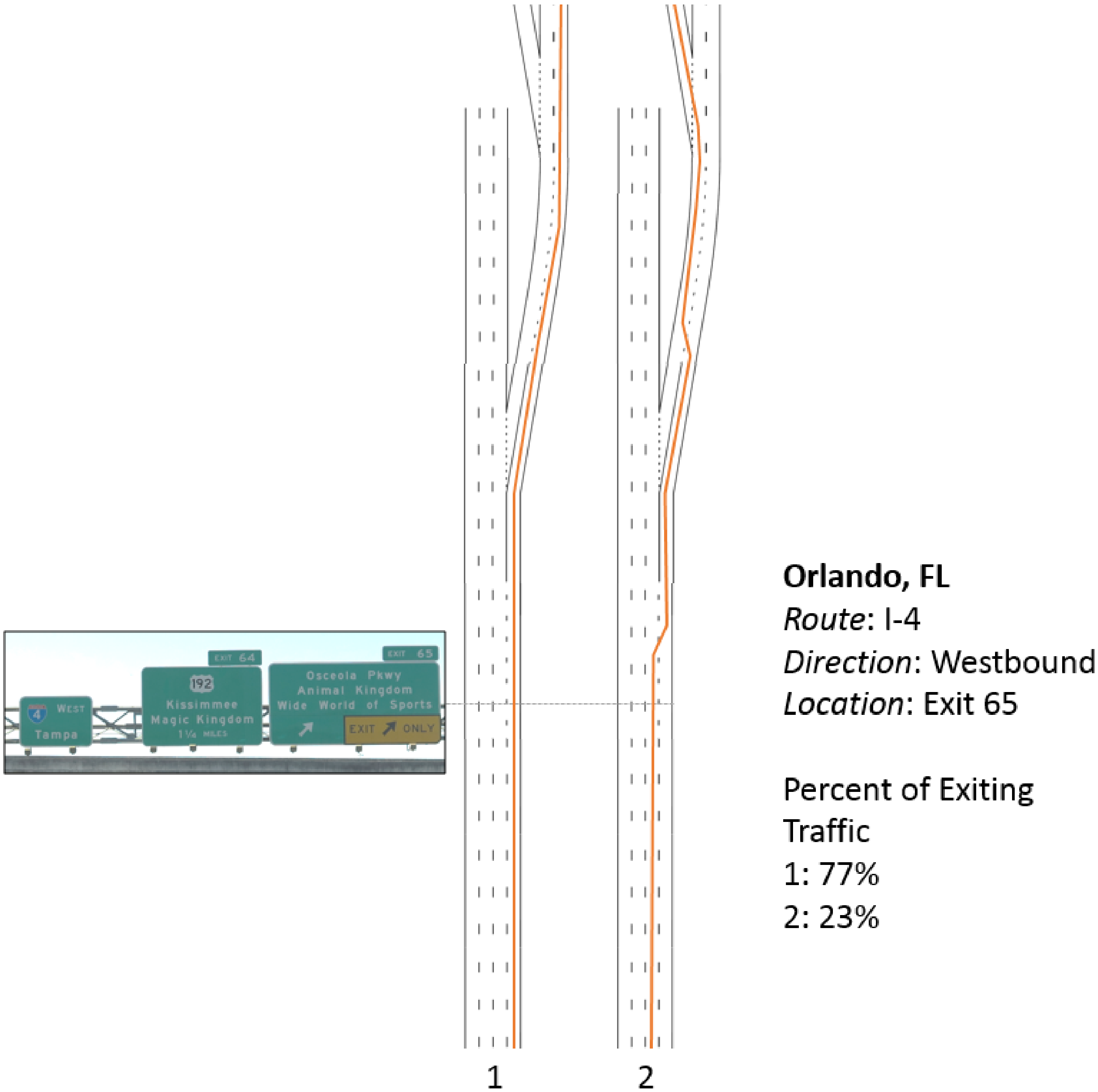
Westbound

Figure 50, figure 51, and figure 52 illustrate common driver behavior identified at exits 64, 65, and 67, respectively, on westbound I-4.



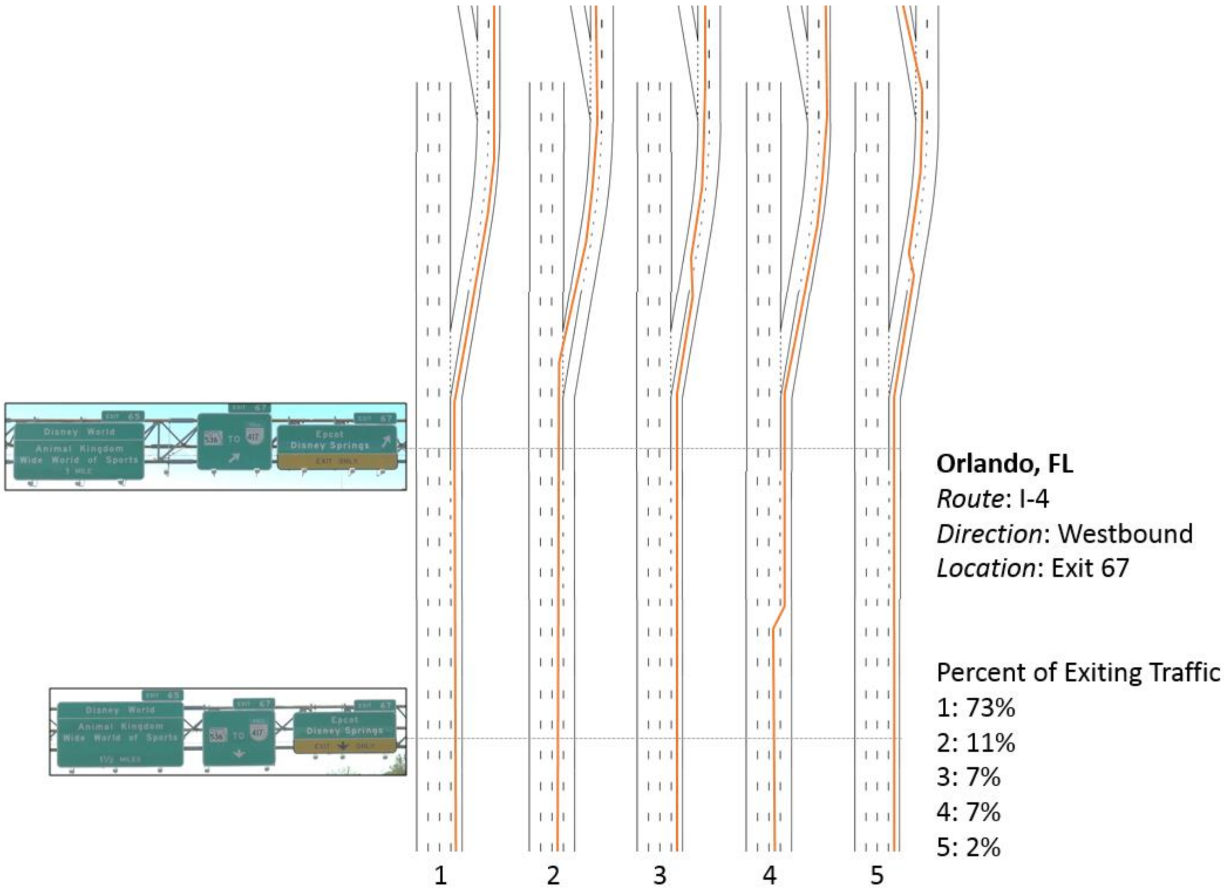
Source: FHWA.

Figure 50. Graphic. Common exiting driver behaviors at site 11, westbound, exit 64 (*n* = 26).



Source: FHWA.

Figure 51. Graphic. Common exiting driver behaviors at site 11, westbound, exit 65 (*n* = 13).



Source: FHWA.

Figure 52. Graphic. Common exiting driver behaviors at site 11, westbound, exit 67 (*n* = 45).

Site 27—Atlanta, GA

The following subsections cover the description, observations, and results for site 27.

Description

The project team deployed five cameras along westbound I-20 near Atlanta, GA, on October 20, 2015. Approximately 4 h of video were collected, beginning approximately at 1:30 PM and ending at approximately 5:30 PM. Cameras were mounted on 20-ft telescoping masts and attached to roadside hardware. Each camera has an internal Global Positioning System (GPS) antenna that records GPS location, time, and date, which allowed the data reduction team to synchronize the collected video, enabling accurate correspondence of multiple camera angles.

Site 27 includes an approximately 1.5-mi stretch of I-20 eastbound leading up to exits 51A and 51B. In this location, I-20 eastbound consists of four lanes, with the rightmost lane an exit-only lane, and the adjacent lane an option lane at both the first (exit 51A) and second (exit 51B) exits. An aerial image of the study site is shown in figure 53, and an example image from the field video is shown in figure 54.

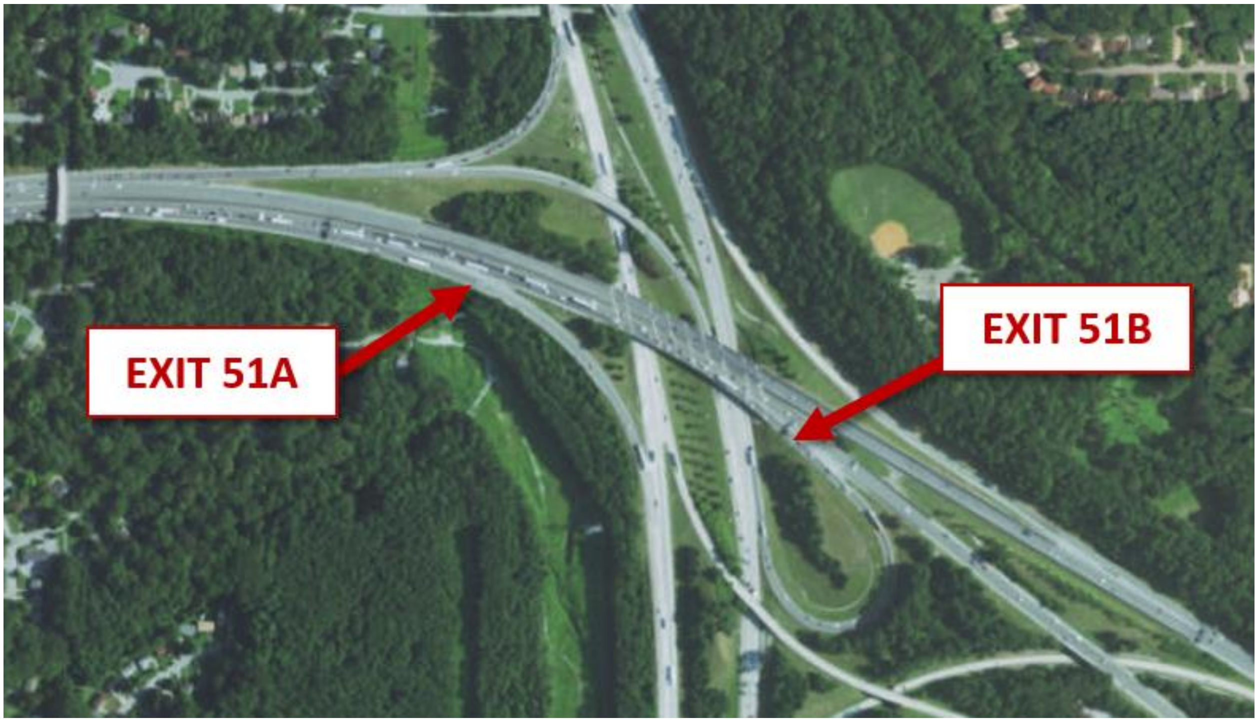


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Figure 53. Photo. Aerial view of the interchange at site 27.(45)


Source: FHWA.

Figure 54. Photo. Example video still from camera 2 at site 27.

The following attributes were present at the site:

- System interchange with sub-optimal geometry (attribute 3131).
- Exiting lanes (attribute 4120).
- Guide signs for option lanes (attribute 5130).

Observations

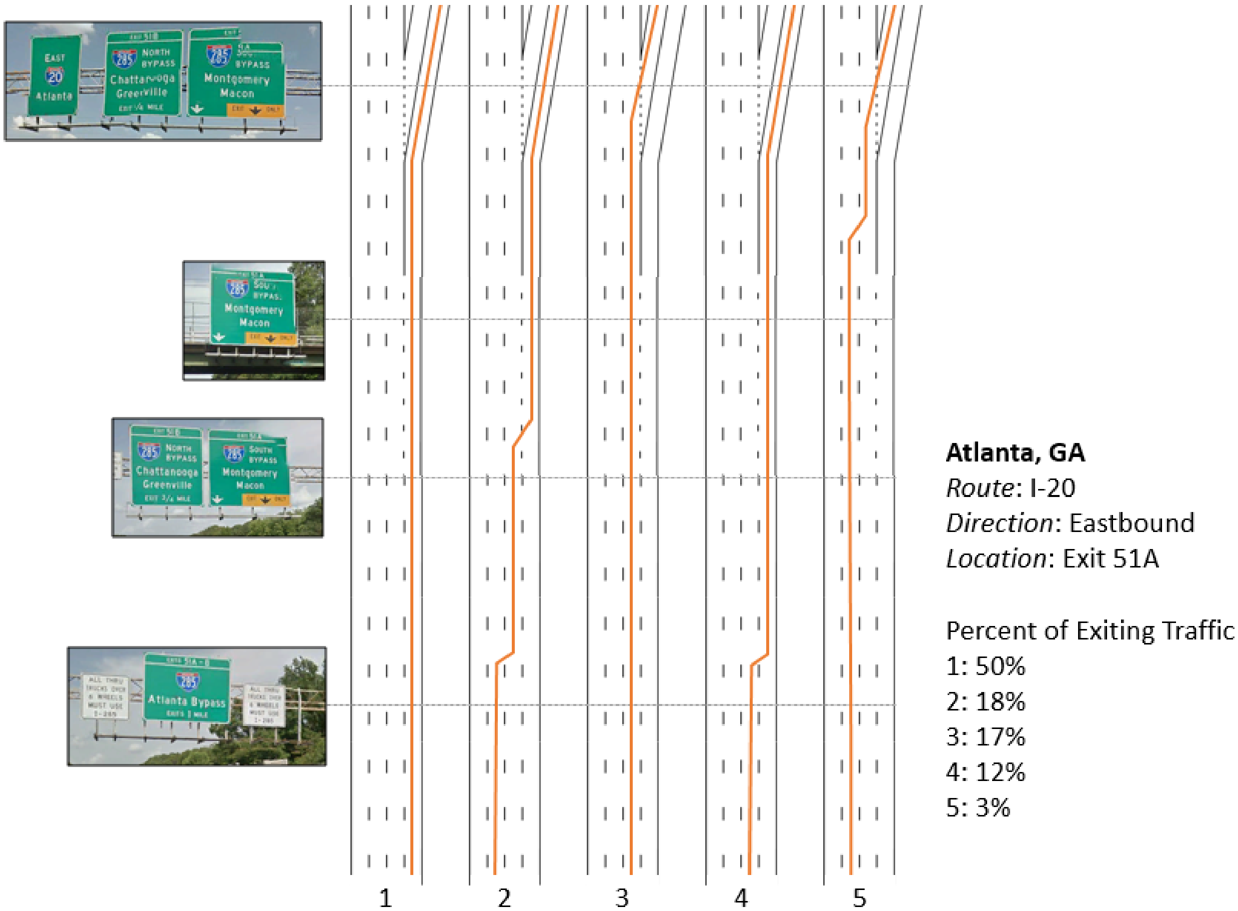
The sample of vehicles selected for this analysis represents an equal distribution of vehicles across the four lanes of I-20. Ninety min of video data were reviewed, beginning at about 4:00 PM. The video was sampled at a rate of two samples per minute, with each sample representing one vehicle per lane, making a total of four vehicles per sample. For instances where a vehicle was not present in a lane through the whole sample interval (30 s), no vehicle was recorded for that sample. The total sample size resulting from the data reduction was 719 vehicles, with 51 percent of the vehicles exiting I-20 over the course of the study area. More information on the distribution of exiting traffic is shown in table 73.

Table 73. Percentage of exiting traffic (site 27).

Number of Observations	Number/Percent Remaining on I-20	Number/Percent Exiting at Exit 51A	Number/Percent Exiting at Exit 51B
719	353 (49%)	202 (28%)	164 (23%)

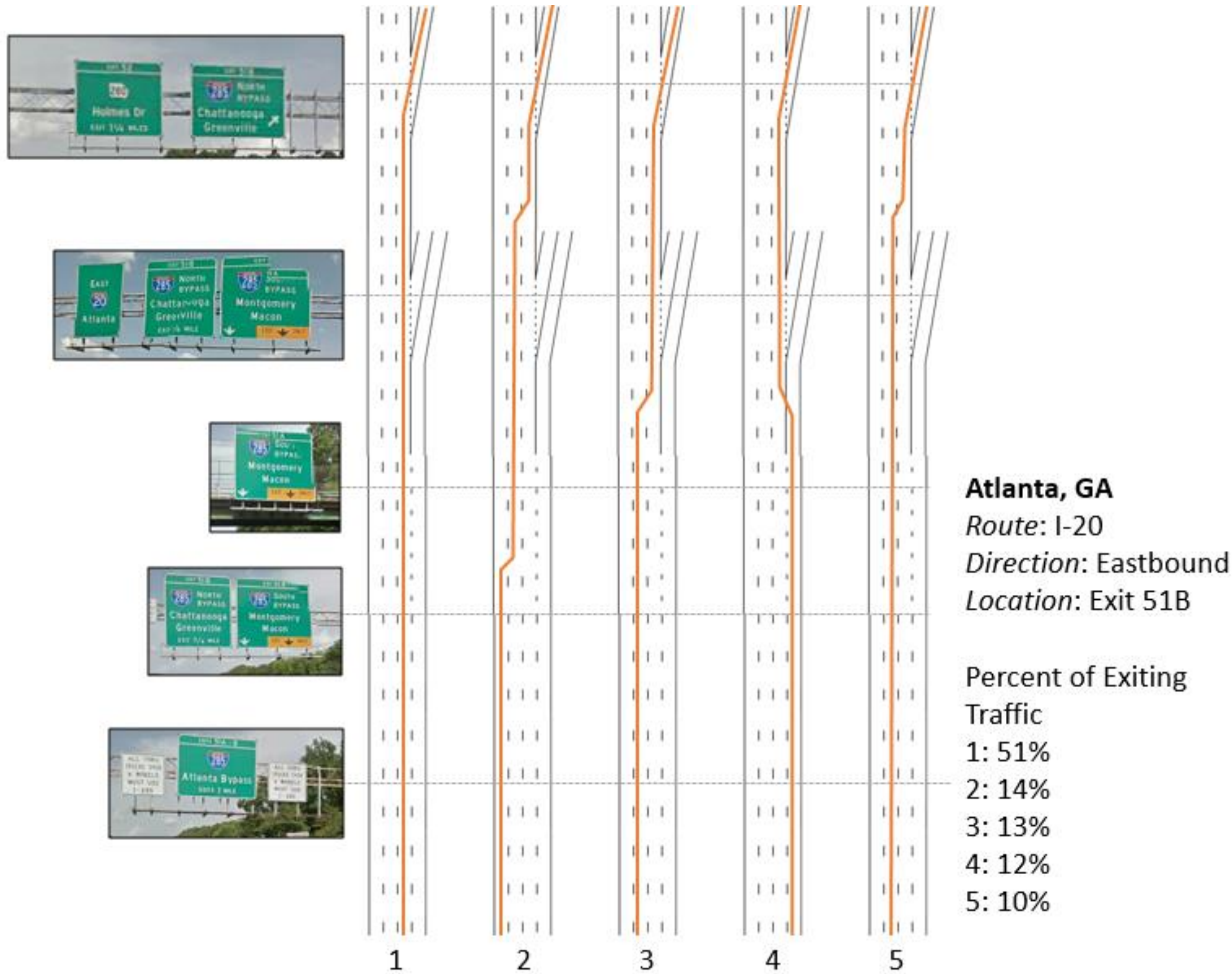
Results

Figure 55 and figure 56 illustrate common driver behavior identified at site 27. In addition, video coders identified several instances of erratic behavior by vehicles near exit 51B. Within the 90 min of field video reduced, two passenger vehicles were observed standing in the exit gore before returning to the freeway, and two commercial vehicles were observed crossing the exit gore. While one passenger vehicles only entered the exit gore briefly, the other remained in the exit gore for more than 2 min, rejecting many opportunities to return to the mainline. One commercial truck began to take exit 51B when the driver crossed over the exit gore to return to the mainline. The second commercial truck came to a complete stop on the mainline adjacent to the exit gore for several seconds before crossing the exit gore to take the exit.



Source: FHWA.

Figure 55. Graphic. Common exiting driver behaviors at site 27, exit 51A (*n* = 202).



Source: FHWA.

Figure 56. Graphic. Common exiting driver behaviors at site 27, exit 51B (*n* = 164).

Site 31—Minneapolis, MN

The following subsections cover the description, observations, and results for site 31.

Description

Site 31 included three approaches to the interchange of I-35W with Minnesota State Trunk Highway 62 (TH 62, the "Crosstown Freeway"). These approaches included southbound I-35W, westbound TH 62, and northbound I-35W, in Richfield and Minneapolis. Of the three approaches, the southbound I-35W approach to TH 62 was the most complicated, with three total splits and a total of four downstream. The three interchanges are summarized in table 74.

Table 74. Selected interchanges for site 31 data collection.

Location	Route	Direction	Interchange
31-1	I-35W	Southbound	TH 62
31-2	TH 62	Westbound	I-35W
31-3	I-35W	Northbound	TH 62

Site 31-1

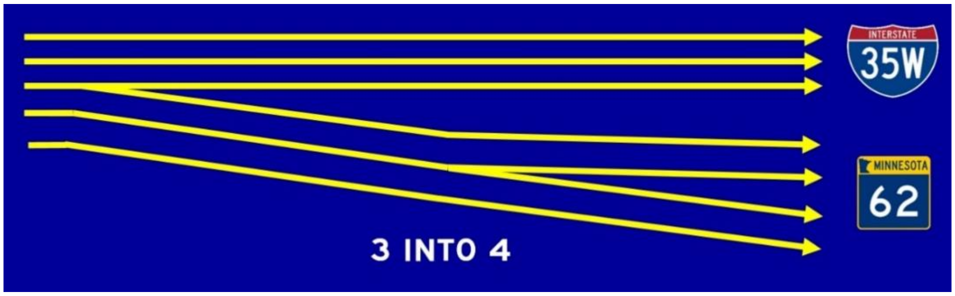
Site 31-1 encompassed a distance of roughly 1½ mi along southbound I-35W. Project contractors deployed three cameras upstream of the split of the three-lane exiting roadway from I-35W southbound. The cameras were deployed according to the information in table 75.

Table 75. Camera locations for site 31-1.

Camera Number	Upstream Distance (mi)	Notes
31-1-1	1.35	Attached to bridge railing/E 50th St overcrossing
31-1-2	0.75	Attached to bridge railing/Diamond Lake Rd overcrossing
31-1-3	0.10	Attached to luminaire pole, vicinity 61st St.

At E 50th St, the northernmost location, cameras were mounted facing both north (against traffic) and south (with traffic, similar to cameras 2 and 3). The camera systems at site 31-1 were adequate to provide identification on vehicle color and type, but generally lacking the resolution necessary to provide positive vehicle tracking over long distances, partly due to the mounting height of the cameras, which was generally within 20 ft of the roadway surface and directly overhead. The data reduction efforts for this location and other locations within site 31 prompted the team to use digital, high-resolution cameras for other sites, as these cameras produced standard National Television System Committee imagery.

The first downstream split involves five lanes diverging into six (see figure 57), with the center lane serving as an option lane for the exit. The signing in advance of all these locations consisted of discrete arrow signing using a vertical divider above the option lane arrow, depicted in figure 58. The arrows at the departure location are angled to better emphasize the point of departure.



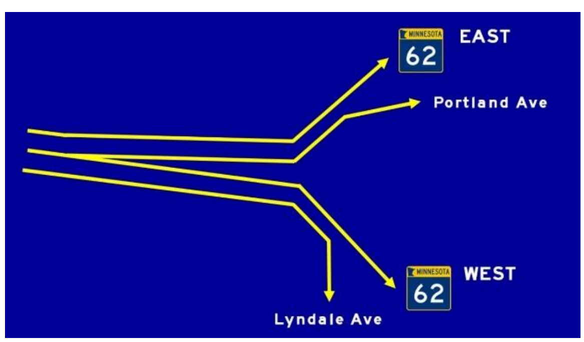
Source: FHWA.

Figure 57. Graphic. Splits 1 and 2 at site 31-1.

Source: FHWA.

Figure 58. Photo. I-35W southbound approaching split 1, the three-lane ramp to the Minnesota TH 62 exits.

The three-lane exit ramp diverges downstream (approximately 1,700 ft) into two two-lane ramps, as depicted in figure 59. This second divergence is referred to as split 2. Each of those two ramps further splits, with exclusive-lane exits to Portland Avenue (the left-hand ramp) and Lyndale Avenue (the right-hand ramp) and are built to accommodate two-lane entrances to TH 62 as the Crosstown Freeway is expanded in the future.



Source: FHWA.

Figure 59. Graphic. Splits 3L and 3R at site 31-1.

The project was primarily concerned with the behavior of drivers at split 1 and at split 2. While the behavior of drivers between the upstream guide sign and splits 3L and 3R is also of interest, the signing for those exits and pavement markings are thorough and conventional.

The following attributes were present at the site:

- Auxiliary lanes (4110).
- Exit with downstream split (4222).
- Guide signs for option lanes (5130).

Site 31-2

An illustration of the camera installation locations is shown in figure 60. The first camera upstream (camera 31-2-1) was attached to the bridge railing on the Portland Ave. S overcrossing, and the second camera (camera 31-2-2) was attached to a ramp meter signal post in the vicinity of the ramp to I-35W northbound. Video from camera 31-2-1 depicts vehicles' behavior at the section of TH 62 where an additional lane is added on the right, creating three lanes. Video from camera 31-2-2 depicts drivers' destination selection (i.e., remain on TH 62 or exit to I-35W northbound).

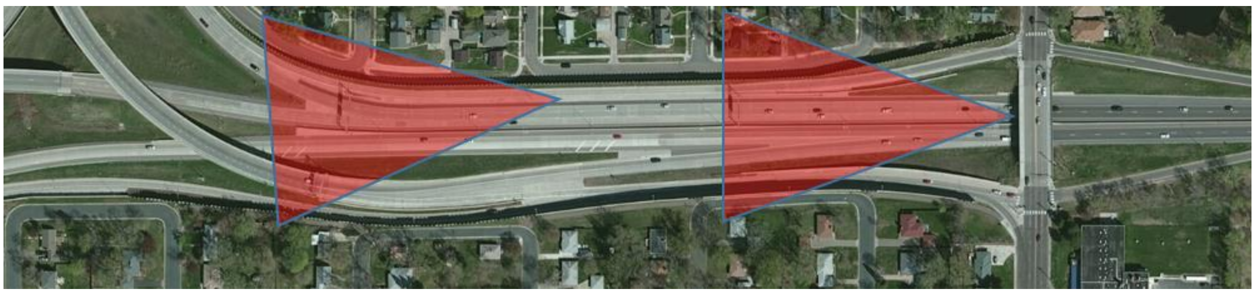


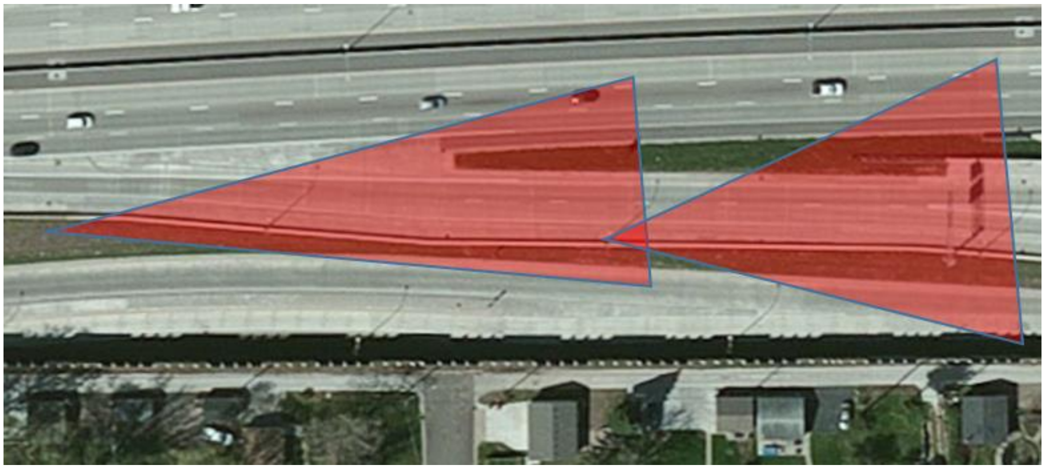
Figure 60. Photo. Camera locations at site 31-2 (Minnesota TH 62 approaching I-35W).[(46)]

The following attributes were present at the site:

- Auxiliary lanes (4110).
- Guide signs for option lanes (5130).

Site 31-3

Two ground-mounted cameras were installed adjacent to an exit gore at exit 11 on I-35W near Richfield, MN (figure 61). Field video collected traffic behavior of vehicles as they exited I-35W and traveled on the exit ramp to TH 62.



©Esri.

Figure 61. Photo. Camera positions at site 31-3 (I-35W northbound approaching Minnesota TH 62).[(47)]

The single-lane exit ramp expands into two lanes after approximately 400 ft from exiting I-35W, and the ramp splits with the exit on the left bringing the driver to TH 62 westbound and the exit on the right bringing the driver to TH 62 eastbound.

The following attributes were present at the site:

- Exiting lanes (4120).
- Exit with downstream split (4222).

Observations

The following observations were made at site 31-1, site 31-2, and site 31-3.

Site 31-1

For the video data reduction, the video was sampled twice a minute, and one vehicle from each lane was selected in each sample, resulting in the capture of driver behavior from 95 vehicles from the approximately 20 min of video. Video was sampled once per minute, collecting information on one vehicle per lane across the five lanes of I-35W, totaling 100 vehicles. Five vehicles were removed because they could not be positively identified at the second camera location. Basic information on the sample is shown in table 76.

Table 76. Site 31-1—percentage of exiting traffic.

Number of Observations	Number/Percent Remaining on I-35W	Number/Percent Exiting I-35W
95	62 (65%)	33 (35%)

Site 31-2

For the video data reduction, the video was sampled twice a minute, and one vehicle from each lane was selected in each sample, resulting in the capture of driver behavior from 474 vehicles from the approximately 2 h of video. Approximately 1 h of video was recorded during the AM peak period, and approximately 1 h was recorded during the PM off-peak period. Basic information about the traffic during the two times is included in table 77.

Table 77. Site 31-2—percentage of exiting traffic.

Time Period	Number of Observations	Number/Percent Remaining on TH 62	Number/Percent Exiting TH 62
AM peak	234	155 (66%)	79 (34%)
PM off-peak	240	142 (59%)	98 (41%)
Total	474	297 (63%)	177 (37%)

This site focused on understanding vehicle behavior at a location upstream of an exit where the freeway expands from two to three lanes. The project team recorded vehicle position immediately prior to the addition of the third lane and after the third lane was fully established. Finally, the vehicles' destinations (e.g., remain on the roadway or exit the freeway) were recorded.

The hypothesis was that drivers intending to exit to I-35W north would avoid use of the right-hand lane until the overhead signing was visible. Some drivers may use the lane immediately in heavy traffic or because their intended destination is the next right-hand exit on I-35W north.

Site 31-3

Driver behavior of 2,144 vehicles was captured from approximately 3 h of field video. One h of video was reviewed during the AM peak, 1 h was reviewed during the PM off-peak, and 1 h was reviewed during the PM peak. Basic information about the driver route selection during the three time periods is included in table 78. PM off-peak and PM peak times were selected to maximize the percent of traffic exiting to TH 62 East.

Table 78. Site 31-3—percentage of exiting traffic.

Time of Day	Number of Observations	Number/Percent Toward TH 62 West	Number/Percent Toward TH 62 East
AM peak	625	554 (89%)	71 (11%)
PM off-peak	781	637 (82%)	144 (18%)
PM peak	738	566 (77%)	171 (23%)
Total	2,144	1,757 (82%)	386 (18%)

The study area was divided into three regions to observe how vehicles behaved when approaching the split. The first region captured the vehicle's orientation as it entered the study area; the second and third regions approximately divide the remaining exit ramp in two, with the first region (region 2) being before the driver encounters the lane designation pavement markings. Finally, the project team recorded the destination selected by each driver.

The hypothesis at this location was that vehicles exiting to TH 62 eastbound would move into the formed right-hand lane further down than the beginning of the lane addition taper, owing to the lack of upstream guide signing with route marking. Further, it was hypothesized that vehicles would drift toward the right, following the right white edgeline, on account of the lack of dotted extension lines providing positive guidance and indicating to drivers the lane addition taper and the path for those wishing to remain in the left-hand lane. This anticipated drifting is a characteristic behavior on wider freeway exit ramps and, without information concerning the arrangement of the lanes, can occur with symmetrical and asymmetrical widenings.

Results

Figure 62 illustrates common driver behavior identified at site 31-1.

Source: FHWA.

Figure 62. Graphic. Common exiting driver behaviors at site 31-1, exit 11 (*n* = 33).

Findings from site 31-2 show that fewer drivers exiting the freeway entered the newly formed exit lane near the beginning of the lane (i.e., once it first became available) than those that entered it later. This finding could indicate that exiting drivers are changing lanes further downstream (i.e., closer to the exit) because of uncertainty in identifying the proper lane to navigate the exit.

Findings from site 31-3 found that traffic exiting to the left (westbound) displayed more uniformity than the traffic exiting to the right (eastbound). Eastbound traffic exhibited three typical behaviors. The most common behavior for the eastbound traffic was to enter the study area in the center of the lane, maintain the position in the center of the lane, and then move to the right side of the lane near the exit. Fewer eastbound vehicles entered the study area on the right side of the lane and maintained that position before exiting to the right.

In addition to the findings from the cluster analysis, the video reviewers provided qualitative descriptions of the field video from site 31-3. In the 3 h of video, several instances of erratic or uncertain behavior were identified. During the PM off-peak time period, five vehicles were observed exiting the freeway by crossing the exit gore. During the same time period, one vehicle was identified crossing the exit gore at the downstream split. During the PM peak time period, one vehicle was observed crossing the exit gore, and another vehicle was observed missing the exit, pulling over to the shoulder, and backing up to take the exit.

Site 43—Olympia, WA

The following subsections cover the description, observations, and results for site 43.

Description

Similar to site 11, site 43 featured a length of urban freeway with longer spacing between exits, across a distance of 7 mi. Along I-5, three interchange locations were selected, summarized in table 79. Each exit features an option lane from the mainline roadway.

Table 79. Selected interchanges for site 43 data collection.

Location	Direction of Travel	Exit Number	Interchange
43-1	Southbound	105 B-A	14th Ave SE/Capitol and Plum St SE/Port of Olympia
43-2	Southbound	104	US 101
43-3	Northbound	111	SR 510 / Martin Rd

Two UAVs were launched for each sortie on Tuesday, November 5, 2015, for each of the three interchange locations in site 43. Because of favorable weather and lighting conditions, field video captured driver behavior on roughly more than 4,000 linear ft of I-5 in advance of each of the three selected interchanges. The field video captured the behavior of drivers as they approached each individual interchange.

Site 43-1

Site 43-1 includes slightly less than 1 mi of I-5 southbound focusing on exit 105B and exit 105A. In this location, I-5 southbound consists of four lanes, with the rightmost lane an exit-only lane, and the adjacent lane an option lane. An aerial image of the study site is shown in figure 63, and an example image from the aerial video is shown in figure 64.

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Figure 63. Photo. Aerial view of the interchange at site 43-1.[48]

Source: FHWA.

Figure 64. Photo. Example video still from UAV at site 43-1.

The following attributes were present at the site:

- Auxiliary lanes (4110).
- Exit with downstream split (4222).
- Guide signs for option lanes (5130).

Site 43-2

Site 43-2 includes slightly less than 1 mi of I-5 southbound focusing on exit 104. In this location, I-5 southbound consists of four lanes, with the rightmost lane an exit-only lane, and the adjacent lane an option lane. An aerial image of the study site is shown in figure 65, and an example image from the aerial video is shown in figure 66.

Figure 65. Photo. Aerial view of the interchange at site 43-2.[49]

Source: FHWA.

Figure 66. Photo. Example video still from UAV at site 43-2.

The following attributes were present at the site:

- Auxiliary lanes (4110).
- Exit with downstream split (4222).
- Guide signs for option lanes (5130).

Site 43-3

Site 43-3 includes slightly less than 1 mi of I-5 northbound focusing on exit 111. At this location, I-5 northbound consists of three lanes. Approximately halfway through the study area, a fourth lane is added with the rightmost lane an exit-only lane, and the adjacent lane an option lane. An aerial image of the study site is shown in figure 67, and an example image from the aerial video is shown in figure 68.

Figure 67. Photo. Aerial view of the interchange at site 43-3.[(50)]

Source: FHWA.

Figure 68. Photo. Example video still from UAV at site 43-3.

The following attributes were present at the site:

- Auxiliary lanes (4110).
- Exit with downstream split (4222).
- Guide signs for option lanes (5130).

Observations

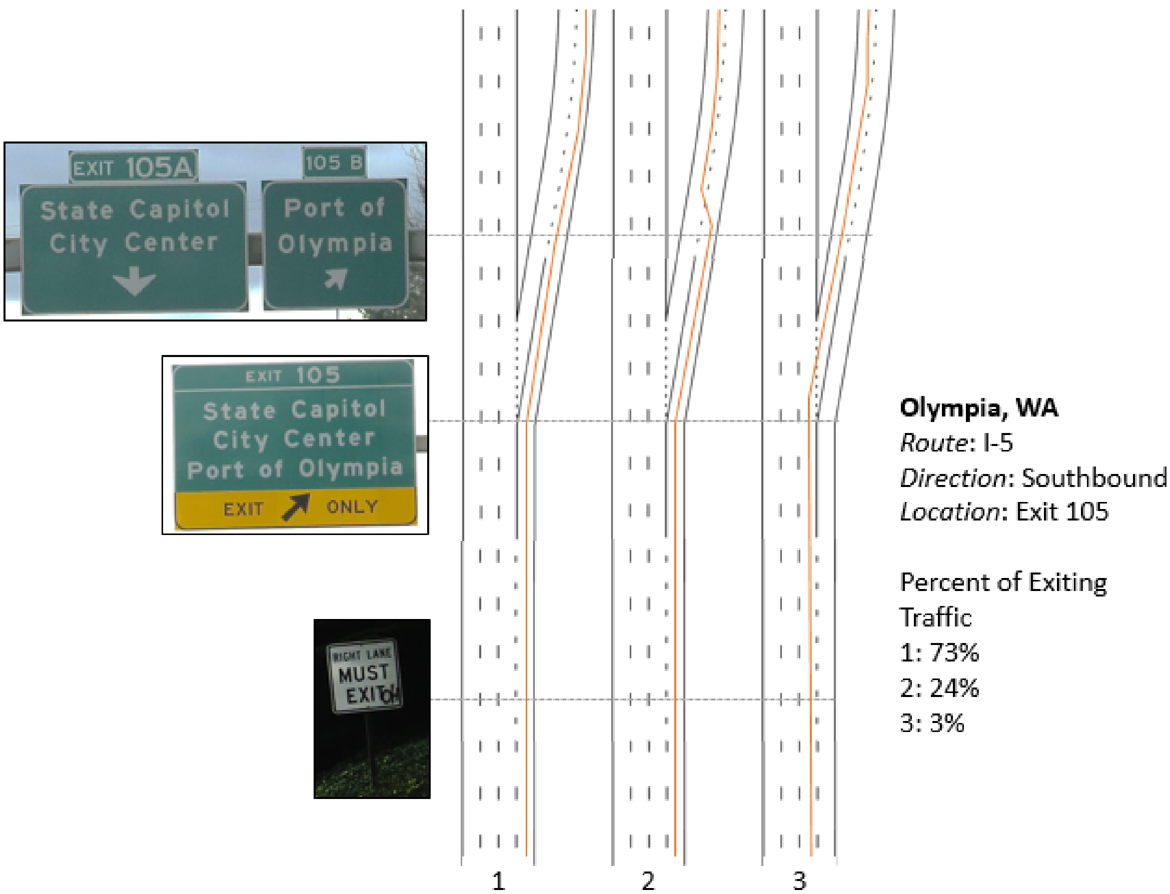
Driver behavior was captured at three locations at site 43. Basic information on driver route selection at each location is presented in table 80.

Table 80. Site 43—percentage of exiting traffic.

Location	Field Video Data Reduced (m)	Number of Regions Within Study Site	Number of Observations	Number/ Percent Remaining on I-5	Number/ Percent Exiting I-5
1	28	7	434	337 (78%)	97 (22%)
2	20	7	334	193 (58%)	141 (42%)
3	30	5	346	262 (76%)	84 (24%)

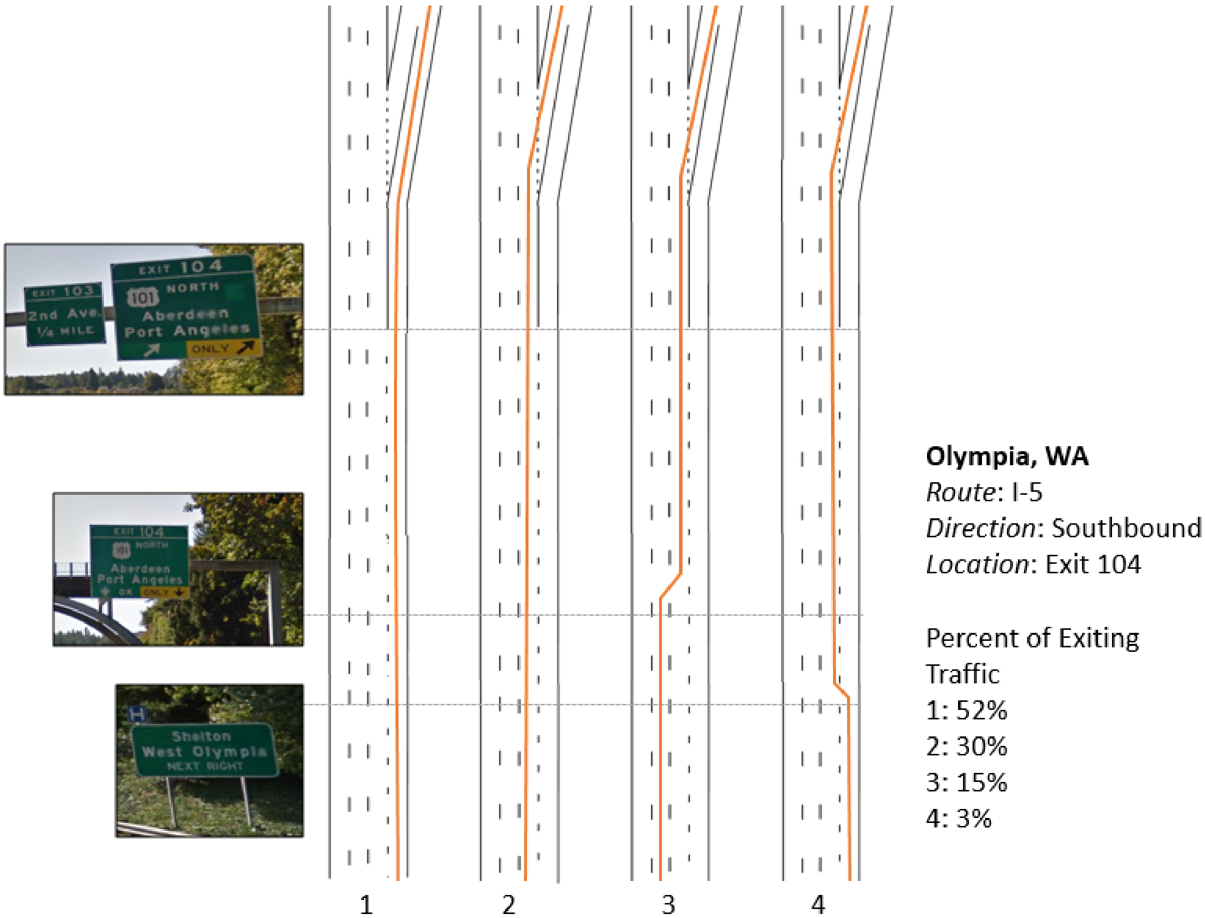
Results

Figure 69, figure 70, and figure 71 illustrate common driver behavior identified at site 43.



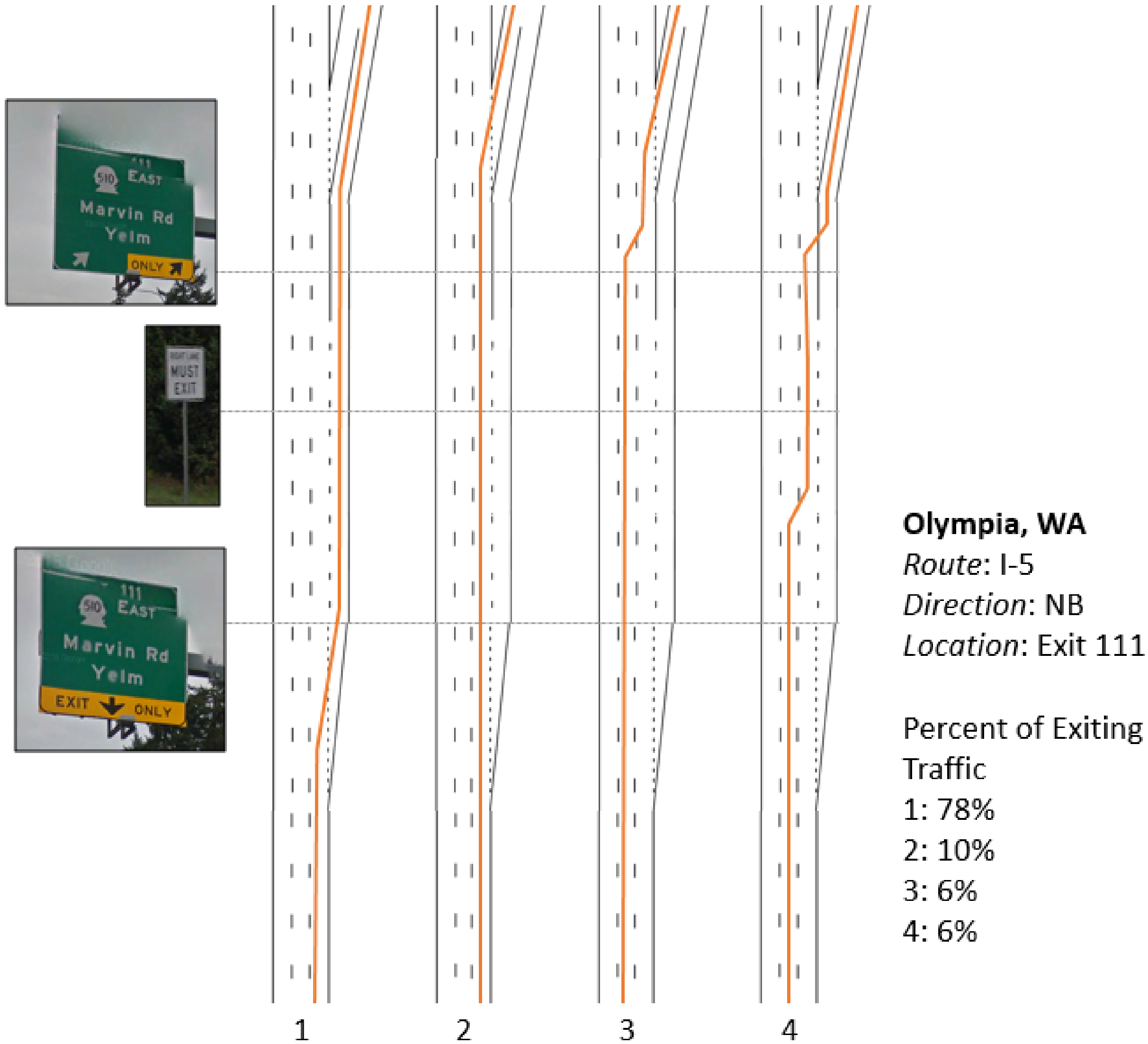
Source: FHWA.

Figure 69. Graphic. Common exiting driver behaviors at site 43-1, exit 105 (*n* = 97).



Source: FHWA.

Figure 70. Graphic. Common exiting driver behaviors at site 43-2, exit 104 (*n* = 141).



Source: FHWA.

Figure 71. Graphic. Common exiting driver behaviors at site 43-3, exit 111 (*n* = 84).

FIELD STUDY FINDINGS

The field study explored driver behavior at complex interchanges in several areas across the country. Field video data were collected at 13 interchanges spanning 4 States through the use of both fixed-position cameras and UAVs. For each interchange studied, field video was reduced to track vehicle paths throughout the study site. While data were captured on both through and exiting traffic, the focus of this review was on the exiting vehicles. Because exiting vehicles served as the focus of the analysis, in many cases, sample sizes were relatively small and data coding was time consuming, particularly when combining several camera views.

One common finding across sites is that exiting traffic was found to most commonly use the exit-only lane rather than the option lane. The cluster analysis found only one site where the most common group of driver behavior did not include moving to the exit-only lane before, or near, the first guide sign with a yellow "EXIT ONLY" panel. The analysis also identified examples where drivers would use the exit-only lane and, ultimately, make a lane change on the C/D roadway. These instances include signing that does not indicate the presence of an option (e.g., site 11 eastbound) lane or groups several destinations on a single sign (e.g., site 43-1). Conversely, the cluster analysis did not find any instances of common behavior where drivers exited using the option lane, and then changed lanes on the C/D roadway.

The site with the highest option lane use was found to be Washington State site 43-2. At this site, nearly half of the drivers were observed using the option lane. This site also included a guide sign configuration not seen in any of the other sites. On the advance guide sign, the option lane is signed with the standard downward white arrow on a green background; however, the guide sign also includes the letters "OK" adjacent to the downward arrow.

Few common behaviors identified through the field video show last-minute lane changes. Behaviors with last-minute lane changes were found in the Atlanta, GA, site (both exits 51A and 51B), as well as Washington State site 43-3. In all cases, the percentage of vehicles completing these lane changes was small. Further, for the case of exit 51B in Atlanta, these lane changes may be influenced by interchange geometry as well as (or in lieu of) signing because exits 51A and 51B are separated by slightly more than ¼ mi.

There was one instance of a common behavior found that could be interpreted as a misunderstanding of the guide signs. In the Atlanta, GA, site, about 12 percent of the drivers exiting at the second exit (51B) were classified in a cluster of driving behaviors that showed the drivers traveling in the exit-only lane for the first exit (51A) before changing out of the lane near the exit ramp for exit 51A to proceed to exit 51B. Drivers who followed this behavior passed two sign gantries where the sign designated the lane as an exit-only lane for exit 51A, with the first gantry also having a separate advance guide sign for exit 51B.

CHAPTER 8. KEY FINDINGS

In chapter 1 of this report, the basis of the following recommendations is outlined. Each of these research activities (data collection, analysis, and interpretation) generated results. Based on those results, the project team developed key findings, which are used to prepare the recommendations in chapter 9.

PRACTITIONER INPUT

The practitioner perspective was obtained from interviews with participants of the working group, from National Committee on Uniform Traffic Control Devices members, and from a topical search of webinars provided by the ITE and similar organizations.

Practitioners shared ideas on staffing, policy initiatives, quality management, and sign fabrication in contract delivery. In general, agencies prefer central office management of sign design practices and policy, but personnel without significant training and experience in freeway signing are often appointed to positions that demand HFs expertise. There is increased desire to provide training for distributed staff and to ensure that traffic engineering personnel have contract oversight in the project delivery process.

LITERATURE AND TECHNICAL POLICY REVIEW

The literature and policy review found that some gaps exist in technical literature related to specific sign design standards. In addition, many agencies do not publish a large-format sign design manual, typically intended for guide signing on freeways, expressways, and primary highways, and the MUTCD and SHS are the sole source of large-format sign design policy for agencies.

MnDOT publishes a *Traffic Guide Sign Design Manual* (most recently published in 2015) that includes substantial information about specific design practices (e.g., fraction layout, legend arrangements, and arrow selection and use).(34) WSDOT also publishes specific practices related to large-format signing in chapter 2 and the appendix of the WSDOT's *Traffic Manual* (publication M55-02).(51) The practices evaluation revealed that States with a history of deliberate policy development generally exhibited fewer sign errors in field installations and that signing approaching interchanges was more consistent between geographic regions and among signing of various agencies.

PRACTICES EVALUATION

The outcome of the practices evaluation was a summary of practices in partnership States and throughout the United States. In general, these practices were identified as being related to attributes contributing to complexity and were evaluated on the basis of conformance to the consistency principle, which was introduced in chapter 5.

The practices evaluation identified nine areas where conformance to the consistency principle was either uniformly observed or was not observed:

- Option lane signing, including policy in the MUTCD.
- Placement of exit-direction signs.
- Legend arrangement on sign panels.
- Use of guide sign arrows.
- Use of distances on all primary advance guide signs.
- Separation of sign panels for separate movements.
- Differentiated use of broken lane lines, dotted lane lines, and dotted extension lines; use of solid lane lines for lane separation and within exit ramp terminal areas.
- Delineation of exit ramp terminal areas.
- Signing of lane reductions, for both entering lanes and continuing lanes terminating at a downstream location.

While many of these practice areas have been addressed in the literature, some existing practices that were observed as highly correlated with consistency have been justified on the basis of heuristics. For example, some States use only one arrow per lane while others mix the use of arrows depending on regional preferences. The consistency principle provides the logical framework for evaluating the use of these TCDs and indicating where evaluation of the effectiveness may be warranted.

SIMULATOR STUDY

The simulator study analysis examined lane choice selection accuracy, ULCs, and the distance over which a subject traveled prior to making the final lane selection for a given simulator scenario. The results of the analyses indicated that the performance of subjects for most scenarios was statistically indistinguishable.

Two variables indicated statistically significant deviation. The first was the performance of subjects in terms of ULCs for signing alternatives in layout A. The second was the performance of subjects in terms of "survival," or upstream final LSD, for signing alternatives in layout E.

Layout A

The data analysis for layout A indicated that subjects made fewer ULCs in signing alternatives A1 and A2 than subjects in signing alternative A3. The analysis also indicated that subjects in alternative A1 made final lane selections further upstream than those subjects in signing alternatives A2 and A3. By both metrics, the simulator study results suggest that signing alternative A1 exhibits better performance in terms of securing early final lane selection and limiting lane changes.

While signing alternatives A2 and A3 do uphold the principle of separated sign panels for separate movements, it is clear that, in this laboratory test, the signing for alternative A1 was associated with better performance for increasing early confidence in lane selection. Minor changes to the design of the signs in alternative A1, which were created to duplicate field conditions, will maintain the single-sign-panel/single-arrow approach while clearly indicating that there are two subsequent exits. The designs in signing alternative A1 already include distances to the exits and, in addition, separating out the exit numbers into the two separate segments of the sign panel will also clarify that there are two separate exits, even though a single panel is used.

Layout E

The data analysis indicated that subjects made a final lane selection in signing alternative E3 nearly twice as far away from the mainline exit as subjects in signing alternatives E1 and E2. Signing alternative E3 differs from signing alternatives E1 and E2 in that it provides separate sign panels for each exiting lane, including the option lane. The left lane is signed with the destination of both lanes of the distributor ramp, and the right lane is signed with the exiting destination for the downstream exit.

In layout E, each of the two exiting lanes in the distributor roadway is assigned discretely to a downstream exit; the left lane is a dedicated lane for the left-hand movement, and the right lane is a dedicated lane for the right-hand movement. This means that signing alternative C3 is directly applicable to the geometric design in the interchange layout and does not violate motorist expectation. In layout E, however, both exiting lanes are dedicated to the left-hand movement, and the right-hand movement is provided by means of a single exiting lane from the right-hand lane of the distributor roadway.

The signing in alternative E3 does not, therefore, adhere to the consistency principle. This is an example of broadening application, where the functional case that is applicable to layout C is applied to layout E, despite the difference in geometric design. Alternative E3 does not adhere to the consistency principle for the configuration of the downstream distributor roadway. Moreover, alternative E3 does not explicitly indicate to road users that both lanes are available for the left-hand movement, which could have significant impacts on traffic operations, including the potential starvation of the right lane and problems related to road-user inability to access the right lane because of congestion in the second lane from the right.

FIELD STUDY

The field study explored driver behavior at complex interchanges in several areas across the country. One common finding across sites is that exiting traffic typically used the exit-only lane rather than the option lane. The cluster analysis found only one site where the most common group of driver behavior did not include moving to the exit-only lane before, or near, the first guide sign with a yellow exit-only panel. The analysis also identified examples where drivers would use the exit-only lane and, ultimately, make a lane change on the distributor roadway. These instances include signing that does not indicate the presence of an option (e.g., eastbound I-4, exit 67) lane or groups several destinations on a single sign (e.g., southbound I-5 at exits 105 B-A). Conversely, the cluster analysis did not find any instances of common behavior where drivers exited using the option lane and then changed lanes on the distributor roadway.

The site with the highest option lane use was found to be Washington State site 43-2, southbound I-5 approaching the US 101 exit. At this site, nearly half of the drivers were observed using the option lane. This site also included a guide sign configuration not seen in any of the other sites. On the advance guide sign, the option lane is signed with the standard downward white arrow on a green background; however, the guide sign also includes the letters “OK” adjacent to the downward arrow.

In the Atlanta, GA, site, approximately 12 percent of the drivers exiting at the second exit traveled in the exit-only lane for the first exit before changing out of that lane near the exit ramp for the first exit, ultimately using exit 51B. This behavior occurred despite the presence of “EXIT ONLY” signing over the lane for the first exit.

SUMMARY OF KEY FINDINGS

Overall, the project team’s efforts in the various activities led to the following six key findings (many of which align with the strategic emphasis areas of FHWA’s Office of Safety, particularly roadway departure crashes):

- Consistent application of signing principles, both among locations and within various geometric design scenarios, leads to correct driver response.
- The existence of explicit technical policy typically results in improved consistency in signing, pavement markings, and geometric design.
- A well-developed pavement marking and delineation policy generally results in appropriate application of pavement marking patterns.
- The consistent use of arrows on guide signs appears to correspond with a design that correlates with intention in the signing of freeway-grade facilities and is generally indicative of fewer design and fabrication errors in the field.
- Providing specific guide signing with corresponding appropriate delineation appears to reduce the likelihood of roadway departures and abrupt lane changes.
- A uniform application of warning signs for lane reductions, for both mainline lanes and entering lanes, is lacking in many jurisdictions.

Option lane signing may take multiple forms, but the basic concepts of signing for the option lane and differentiating between upstream and point-of-departure signs should be incorporated into option lane signing policy. The overall finding of this research is that consistency in TCD applications is the key principle in facilitating road-user navigation and guidance tasks within complex roadway environments, including interchanges. Signing, pavement markings, and geometric design should be applied consistently among interchanges, and even within the components of a system, to support road-user expectancy. Consistent application of TCDs, including the discrete and differing treatment of various configurations along the approach to an interchange, ensures road-user expectancy is not violated.

CHAPTER 9. PROPOSED TREATMENTS

INTRODUCTION

In the development of recommendations, the project team identified six categories of recommendations, referred to in this report as treatments. The treatments selected for the development of practice-ready recommendations are those that emerged from applying the working definition of complexity to each of the selected topics in development of the research activities. Each treatment, listed in table 81, is the result of understanding the interrelationships of various attributes within each research topic and the application of those relationships to practice outcomes, including those being evaluated in the field study and simulator study.

Table 81. Selected treatments for practice-ready recommendations.

Treatment Number	Treatment Description
1	Ramp terminal arrangements
2	Sign layout—sign legend arrangement and panel configuration
3	Sign placement—arrows, distances, and relationship to geometric design
4	Delineation for exiting lanes and special use lanes
5	Lane-reduction methods, signing, and delineation
6	TCD education and design review workshops

Each treatment is addressed using the format outlined in table 82.

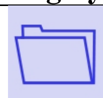
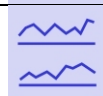
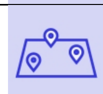
Table 82. Organization of treatment summaries.

Section Title	Section Content
Introduction	Describes the treatment with examples of undesirable practices and anticipated and observed outcomes
Design guidelines	Provides existing design guidelines with a general perspective on implementations in multiple jurisdictions
Research findings	Outlines the primary principles of the concept and provides application examples
Recommendations	Provides specific recommendations to address undesirable practices
Implementation	Summarizes the breadth and depth of implementation options

The discussion of each treatment will describe the purpose and need of the treatment; present observed practices from chapter 5 of this report with sample case descriptions, as appropriate; discuss existing guidelines and research findings from chapters 2 and 5 of this report; and describe the specific treatment applications recommended for implementation.

Each recommendation is numbered according to the six topic areas and then assigned a sequential number within that topic area for ease in referencing the recommendations. Above the heading for each section in which a recommendation is described, applicable indexing symbols, matching those used throughout this report and introduced in chapter 1, are included to aid in quickly identifying the basis of the recommendation (see table 83).

Table 83. Recommended source legend per indexing symbol.

Indexing Symbol	Source of Recommendation
	Literature and policy review
	Practitioner input and insights
	Practices evaluation with consistency principle
	Simulator study
	Field study

Some recommendations in this report are justified on the basis of the consistency principle, when implementations of the TCDs were observed to be consistent within an agency, among locations, and with the general principles laid out in part 1 and part 2A of the MUTCD. While all the recommendations are considered valid on the basis of research conducted in this report or other literature, the consistency principle provides a means of identifying logical TCD applications and determining, in the absence of data and analysis of outcomes such as comprehension and driver performance, which applications are suitable for immediate implementation, field experimentation, or future research efforts. Practice-ready implementations explicitly validated by research should be considered suitable for inclusion in the MUTCD.

TREATMENT 1—RAMP TERMINAL ARRANGEMENTS AND DESIGN

Treatment 1 covers the following topics:

- Traffic volume and density impacts.
- Confusion related to ramp terminal placement and sequence.
- Upstream non-mandatory exiting movement precedes mandatory exiting movement.
- Impacts of violation of expectations.
- System design characteristics.
- Auxiliary lanes and option lanes; signing and marking for option lanes.
- Pavement markings.

Introduction

In conducting the practices evaluation and literature review, the project team identified practices related to interchange configuration and geometric design that can lead to undesirable driver behaviors (e.g., sudden lane changes and reduced speed). The most notable undesirable practices are summarized in table 84.

Table 84. Practice and case summary for treatment 1.

Practice	Sample Case Description
Ramp terminals are placed in close succession with access from a single lane	Without progressive guide signing with distances or a diagrammatic guide sign, driver misunderstanding of the exit locations can lead to undesirable behaviors and missed exits
Access to downstream exits is provided upstream of a preceding exit	Drivers proceeding with the advancing exit numbers wishing to take exit 64 might find that the exit ramp for that exit is placed in advance of exit 63
Inconsistency exists in the use of auxiliary lanes and acceleration lanes	One interchange adds an auxiliary lane, while a subsequent interchange adds a basic lane; without adequate delineation and signing, driver behavior may show a lack of optimal lane use
Unusual ramp designs are inconsistent with the principles of lane balance	A two-lane entrance ramp enters a freeway with the tapered design, and no clear driver expectancy exists for yielding behavior and avoiding conflicts

Design Guidelines

While AASHTO's Green Book addresses exit ramp placement, entrance ramp design, and other design criteria related to interchange design, agencies struggle to retrofit older interchanges.[16] In addition, agency practices for guide signing are often insufficient to address unique and complicated cases and, often, no mechanism exists to retain HFs professionals with experience in freeway sign design and TCD evaluation.

Research Findings

Research findings from the practice evaluation, field study, and simulator study identified practices related to ramp terminal design associated with the attributes in category 4200 and category 4300. Retrofitting existing interchanges to optimize the TCD implementations is a cost-effective means of improving the visibility of ramp terminals and providing explicit, specific guidance related to the navigation task.

Principles

Five basic principles of ramp terminal arrangements and design were identified in practice and policy:

- Spacing of ramp terminals is consistent with AASHTO policy.
- Avoid multiple exits in succession from a single lane.
- Avoid mixing mandatory and non-mandatory exits in succession.
- Provide deceleration lanes beyond what is required by design speed, volume, or simulation modeling, to permit additional overhead signing in complex situations.
- Provide acceleration lanes designed to the maximum length, particularly in areas where heavy entering or mainline truck volumes exist.

The primary principle for ramp terminal arrangements is, concisely, to provide clarity for lane assignments and ample time for lane changes approaching interchanges. The anticipated outcome of implementing these principles is a reduction in crashes related to abrupt lane changes associated with uncertainty in the navigation task.

Application Examples

The following subsections provide examples of ramp terminal arrangements and design in two states: Washington State and Minnesota.

I-5 at SR 18 in Federal Way, WA

This interchange was reconstructed between 2010 and 2012. The project included the construction of direct-access flyover ramps connecting SR 18 to I-5 for the left-hand movements from SR 18. The entrances to I-5 northbound form two lanes, and the lane reductions occur immediately before an existing structure that was not included in the project scope. The acceleration lane for the eastbound to northbound movement is nearly 4,000 ft in length, despite the design speed of the flyover ramp being set at 40 mi/h. The benefits of increased acceleration lane distance include reduced driver workload, improved flow characteristics, and a more-resilient transportation system.

I-35W at TH 62 in Minneapolis, MN

When this interchange was reconstructed, separation of movements was accomplished with C/D roadways and the design of subsequent splits with distance for multiple overhead sign structures. For example, traffic on I-35W southbound bound for Lyndale Avenue S follows TH 62 westbound by using one of the two right-hand lanes. Further downstream, subsequent to the second split (for eastbound and westbound TH 62), overhead signs and “EXIT ONLY” pavement markings indicate to road users that the right lane is an exit-only lane for Lyndale Ave S. An appropriate sequence of signs with all primary destinations indicated, including on upstream signing, is particularly important in these applications.

Recommendations

Addressing ramp terminal design, ramp arrangements, and complexity caused by contributing attributes related to ramp terminals can be costly. On the other hand, even small changes to signing or ramp terminal characteristics can provide significant improvements in safety performance and traffic operations.

Recommendation 1-1: Provide Overhead Signing

Where ramps occur in close succession, overhead signing and the use of lane assignment arrows (a white arrow on a green background) can address driver-expectancy issues and improve lane use, improving traffic flow characteristics.

Where escape lanes are present, that is, a short extension of the exiting lane along the mainline beyond the ramp terminal, provision of overhead signing consistent with geometric design can be problematic. Because of this, the use of escape lanes should be limited to locations where extremely short auxiliary lanes precede the ramp terminal. In these cases, clarity in overhead signing is extremely important and, while the signing may not match the geometric design, consistency in application will improve driver performance. The use of “EXIT ONLY” signing upstream of an escape lane, even for very short auxiliary lanes, has the potential to improve driver performance.

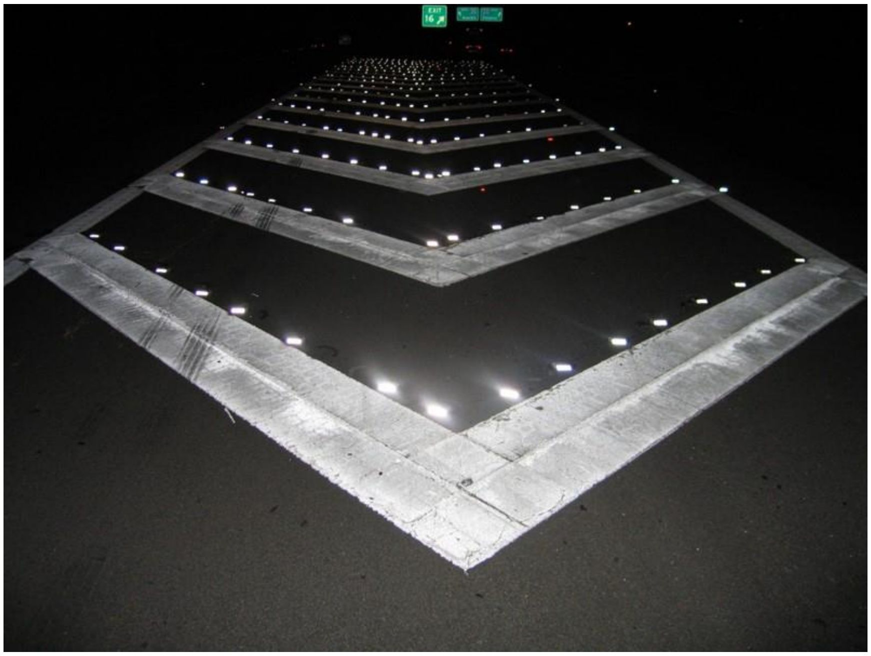
Recommendation 1-2: Construct Deceleration Lanes

In cases where multiple, subsequent exits are closely spaced, the addition of deceleration lanes provides for the placement of overhead signing and marking. The placement of exit-direction signs in areas with deceleration lanes should be consistent with all other interchanges, such that the exit-direction sign is placed adjacent to the point of departure. Aids to the guidance task in a deceleration lane include dotted extension lines across the widening taper, dotted lane lines along the length of the full width of the lane, and a solid lane line in advance of the marked gore area to provide notice that the divergence is about to begin. In addition, vertical delineation can be provided in climates where snow-covered roads hinder the visibility of the pavement markings or reduced shoulder width makes the presence of the auxiliary lane difficult to discern from the width of the roadway adjacent to the through lane.

Recommendation 1-3: Ensure Clarity With Pavement Markings

Implementing the consistency principle with pavement markings likely means using the lane drop marking or wide dotted lane line for all non-continuing lanes, even very short auxiliary lanes and lanes within cloverleaf interchanges. The broken lane line should, therefore, be used solely to separate lanes that continue on the primary marked route. In addition, lane addition tapers for non-continuing lanes (e.g., a deceleration lane) should be marked from the beginning of the taper to the full width using the dotted extension line. This prevents the large-width unmarked areas that can lead to confusion and cause erratic lane-change behaviors.

In addition, the clear marking of gore areas is especially important in areas where high-speed movements occur, particularly system interchange connections. Figure 72 illustrates the markings in a high-speed system interchange connection, where 24-inch-wide transverse lines, angled downstream on both sides of the single-direction divergence, are outlined by 8-inch-wide edgelines that are white in color until the physical nose of the gore area. RRPMs in crystal (white) outline the transverse markings and provide edgeline–appropriate spacing along the longitudinal lines.



Source: FHWA.

Figure 72. Photo. Gore area markings on a freeway in South Carolina.

Recommendation 1-4: Address Entering Lanes

Some States, such as California and Michigan, have long-established practices of constructing auxiliary lanes wherever possible, even on freeway segments outside of urban areas. Comprehensive interchange type selection, interchange design, and geometric design criteria can provide a framework for selecting appropriate entering lane terminations that are differentiated with signing, marking, and geometric design features.

In particular, entering lanes that are auxiliary to the mainline lanes should be treated in a fashion similar to exit-only lanes that are the termination of a continuing lane. All entering lanes forming an auxiliary lane that is less than 1½ mi in length should be separated from the mainline lanes with a dotted lane line. For auxiliary lane lengths exceeding 1½ mi, the use of the broken lane line is appropriate, given that it is not considerably shorter than the portion of the lane marked with the dotted lane line, which itself will generally be at least ½ mi but typically 1 mi in length, to correspond to overhead signing.

Application of the consistency principle is particularly important in the implementation of signing for the entering lanes. Consistent placement of the W4-1 Merging Traffic sign will aid road users in determining the location of the lane addition. Vertical delineation alongside the inside edges of the mainline and entering roadway provide perceptive information related to the proximity of the marked gore area.

Implementation

Each measure involves construction costs and costs associated with retrofitting existing interchanges. In cases where such retrofits reduce crash rates and reduce congestion, high benefit–cost ratios can be achieved.

Agencies exhibiting a high success rate with these implementations have established rigorous evaluation methods for system performance. These methods identify locations with upstream congestion that also exhibit higher crash rates. A systematic program of improvements with fast-tracked design and a dedicated funding source can improve the consistency of these implementations and provide immediate benefits.

All agencies can benefit from a regular program of pavement marking upgrades and the replacement of pavement markings in areas where markings are degraded because of high traffic volumes. A systematic evaluation of pavement markings in interchange areas and the implementation of a pavement marking standard that adheres to the consistency principle can lead to long-term reductions in maintenance costs and improvements in safety and operations.

TREATMENT 2—GUIDE SIGNING: SIGN LEGEND ARRANGEMENT AND PANEL CONFIGURATIONS

Treatment 2 covers the following topics:

- Confusion related to ramp terminal placement and sequence.
- Upstream non-mandatory exiting movement precedes mandatory exiting movement.
- Impacts of violation of expectations.
- Auxiliary lanes and option lanes; signing and marking for option lanes.
- Information loading, panel layout, and design and specific messaging for guide signs.
- Impacts of restricted lane exiting maneuvers.

Introduction

As part of the practices assessment, the project team discovered that State transportation departments and local agency implementations of sign panel layout and configuration principles often violated the consistency principle, were incongruous to the principles laid out in the SHS, and often sacrificed latent space on the panel that is considered helpful in grouping legends to aid in legibility and comprehension. The most notable undesirable practices are summarized in table 85.

Table 85. Practice and case summary for treatment 2.

Practice	Sample Case Description
Combining multiple, subsequent movements into a single panel	Two subsequent exits for a cloverleaf interchange are shown as separate movements on a single sign panel
Single multilane exit signed with multiple, separate sign panels	Multiple panels lack distance information to indicate that the location of the primary exiting movement for both destinations is the same
Failure to emphasize unusual configurations	Signing for two closely spaced exits lacks the legend "SECOND EXIT/1000 ft" on the sign for the second exit.
Signing omits option lanes	Signing for an exit with an option lane omits information indicating the availability of that lane or is mixed with signing that displays the lane, for example, only on the exit-direction sign
Improper legend grouping	The inconsistent placement of arrows; suppression of interline and legend-to-panel edge spacing; and inconsistent alignments of legend relative to shields, destinations, and other elements creates difficulty in identifying the purpose and general message of a guide sign from a distance, affecting legibility, comprehension, and reaction time

Design Guidelines

The MUTCD depicts signing for interchanges throughout part 2 and generally separates information for separate movements onto separate sign panels. It does not contain information concerning the use of various separator lines (e.g., those extending to the edge border, those extending within a certain distance, and those with a length determined by the length of an associated text string).

MUTCD figures 2E-11 and 2E-12 show differing treatments of option lanes with regard to, where upstream, the option lane is depicted and how the mandatory movement lane is depicted. This inconsistency has led to State transportation departments adopting various methods of signing for these configurations and omitting the option lane from signing. Positive identification of all lanes available to a destination in a consistent manner is one potential technique for improving lane use in advance of interchanges with option lanes and reducing the likelihood of sudden lane changes.

Research Findings

The simulator study research tested different signing techniques for option lanes and the separation of signing into multiple panels, even upstream of a C/D roadway with and without exclusive downstream lanes for mandatory movements. That research found that separating panels for exits with downstream, high-speed splits resulted in greater subject confidence in upstream lane selection. In addition, it found no significant difference between signing methods for option lanes, and the participant questionnaire found an association between a new type of arrow for blended arrow option lane signing and comprehension of the purpose of the sign. All signs in the simulator study were designed with appropriate legend grouping, spacing, and legend size and composition.

Principles

The following principles should be followed:

- Legend layout on sign panels adheres to principles where green space is preserved so that related elements are grouped next to any pertinent elements or groups of elements.
- If sign size is a controlling factor, due to structural limitations, uniform reductions in legend size should only be undertaken if standard spacing criteria can be applied to the selected legend size group.
- The position of arrows relative to other legends should be based on the principles of grouping legends into associated elements with orthogonal boundaries and positioning arrows relative to those groups.

Recommendations

Based on the practice evaluation and literature review, the project team proposes the following practice recommendations to address issues related to sign panel layout and configuration. The intent of these recommendations is to use sign panel arrangements to best convey the proximity of exits and their relationships to one another and to ensure that cues related to exit direction, ramp configuration, and the location of the physical gore are all incorporated into the sign design process.

Recommendation 2-1: Provide Separate Panels for Separate Movements

A key component of guide sign messaging is the use of borders and separate panels to convey to motorists, through those cues, the relative arrangement of exit ramps and continuing lanes on a freeway segment. As part of the practice evaluation, the project team evaluated signing in urban areas in several States to examine locations where single sign panels were used to convey messages for diverging lanes.

Recommendation 2-2: Place Control Cities in Designated Order

Few agencies address this specifically in their design documents. The placement of control cities, placement of arrows, and other sign legends should follow the "straight–left–right" principle for vertical arrangements and the "left-straight-right" principle for horizontal arrangements. For control cities, those to the left should be listed first and those to the right should be listed second. This is addressed in the simulator study, using the legend listing principles but applying them to a cloverleaf-style interchange, where the first movement is listed second on the sign because it is the right-hand movement.

Recommendation 2-3: Properly Align Exit Numeral Plaques

Several States continue to center-align exit numbers, some with full-width exit numeral plaques. The alignment of the exit numeral plaques and the straightforward design of the "LEFT" legend within the plaque can contribute to driver understanding of left and right exits.

The sign in figure 73 plaque demonstrates single-line application of the "LEFT" and "EXIT" with number legend layout as compared with what is presently in the MUTCD. The sign depicted on the left facilitates left-to-right reading of the exit number and has the benefit of reduced overall sign height. In addition, by using the "LEFT" inset panel on both the exit number plaque and the primary guide sign itself, additional emphasis is facilitated by means of duplication of identical elements.

Source: FHWA.

A. Single-line LEFT exit tab.

Source:Adapted from MUTCD Figure 2E-15.

B. Multi-line LEFT exit tab.

Figure 73. Graphics. Advance guide sign for left exit with "LEFT" inset panels.

Recommendation 2-4: Provide Revisions to the MUTCD on Legend Sizes

The current structure of the MUTCD groups legend sizes into categories based on the roadway cross section and roadway classification (e.g., MUTCD table 2B-1) and type of interchange (e.g., MUTCD table 2E-4). These categories, however, do not take into account the roadway design speed, mounting of signs on both sides of the roadway, or the roadway cross section beyond two lanes. In not explicitly addressing sign sizes based on the factors that influence legibility distance, the tables in the MUTCD do not provide explicit information to practitioners for use in designing signs that fall outside of what is accommodated in the tables.

In practice, signing on conventional roads, including primary highways, often fails to provide legends of sufficient size for the design speed. In addition, in urban areas, placement of regulatory and warning signs on both sides of the roadway improves visibility for road users and sign sizes can often be reduced. One potential solution to the right-sized selection of sign sizes and legend elements is the use of a two-step process for selecting legend sizes. The first step is to use the posted speed limit (or 85th-percentile speed) in conjunction with the cross section to determine the size class that will meet those requirements. A sample size-class table, currently blank pending future research, is included as figure 74.

		CROSS SECTION AND PROPOSED SIGNING					
		1 LANE SIGN ON ONE SIDE	**2 LANES SIGN ON ONE SIDE**	**2 LANES SIGNS ON TWO SIDES**	**3 LANES SIGN ON ONE SIDE**	**3 LANES SIGNS ON TWO SIDES**	**OVERHEAD SIGN**
POSTED SPEED LIMIT	**20**						
	25						
	30						
	35						
	40						
	45						
	50						
	55						
	60						
	65						
	70						
	75						
	80						
	85						
	90						

Source: FHWA.

Figure 74. Graphic. Sample size class selection table.

Once a size class has been determined by selecting the size from the appropriate intersecting row and column in the size class selection table, that size class is carried over to the legend and element size table (see figure 75). By reading down the column for the appropriate size class, the practitioner can readily determine legend sizes for various elements of signs for all size classes.

SIZE CLASS	3	4	5	6	7	8	9	10	11	12	Text Examples
Mixed-Case Uppercase Text	4	6	8	10 ⅔	13 ⅓	13 ⅓	16	16	20	20	
Mixed-Case Lowercase Text	3	4.5	6	8	10	10	12	12	15	15	
PRIMARY GUIDE SIGNING											
EXIT Placard											
PANEL HEIGHT			24	24	30	30	30	30	30	30	
"EXIT"			6	8	10	10	10	10	10	10	
Numerals/Letters			10	12	15	15	15	15	15	15	
Route Designations											
Word	4	6	6	10	12	12	12	12	12	15	"BYPASS", "BUSINESS"
Numeral	5	8	8	12	15	15	15	15	15	18	"U.S. 23"
Road Name (w/shields)	4	6	6	8	10 ⅔	10 ⅔	13 ⅓	13 ⅓	16	16	"Cumberland Rd"
Road Designation (w/shields)	4	6	6	8	10	10	12	12	15	15	"TOLLWAY", "EXPRESS"
Cardinal Direction											
Initial Capital	5	5	6	10	12	12	15	15	15	18	
Remaining Capitals	4	4	5	8	10	10	12	12	12	15	
Directional Supplement											
Word	3	4	5	6	8	8	10	10	12	15	"TO", "NEXT EXIT"
Distances											
Numeral (guide signs)			6	8	12	12	15	15	15	18	
Fraction Height (1.5 x Frac Num)			6	9	12	12	15	15	15	18	
Fraction Numeral			4	6	8	8	10	10	10	12	
Unit (Word)			4	6	8	8	10	10	10	12	"MILES", "FEET"
Action Messages											
Initial Impact Word	6	6	7	8	10	10	12	12	15	18	"LEFT"
Preceding Distance Messages			6	8	12	12	15	15	15	18	LEFT ½
Message Body			5	6	8	8	10	10	12	12	"LANE", "NEXT RIGHT"
EXIT ONLY Panel											
PANEL HEIGHT				30	36	36	36	36			
"EXIT ONLY"				8	10	10	12	12			
SUPPLEMENTAL GUIDE SIGNING											
Place Name (mixed-case)					10 ⅔	10 ⅔	13 ⅓				
Word "EXIT"					8	8	10				
Exit Number/Letter					12	12	15				
Action Message					8	8	10				

Source: FHWA.

Figure 75. Graphic. Excerpt from sample legend and element size table.

The use of size classes and one single table for guide sign design (and, as it is developed, regulatory and warning sign size selection) will aid agencies in uniformly applying sign design principles on low-speed roadways and high-speed, multilane, limited-access highways.

Recommendation 2-5: Clarify Requirements for Larger Initial Capital Letters

While cardinal directions should include larger initial capital letters, the use of larger initial capitals for action messages and legends (e.g., "TO" and "BYPASS") has also been observed. The MUTCD should explicitly clarify that the legend height is uniform for these words to improve consistency in practice.

Recommendation 2-6: Include Option Lane Signing Conforming to Consistency Principle in MUTCD

The participant questionnaire from the simulator study included questions about various advance guide signs for option lanes. While all signs were found to perform consistently in the simulator, the participant questionnaire revealed that subjects reported a better understanding of the sign design used in alternatives C1 and C2 as compared to the sign design from alternative C4.

Statistical analysis on question 3-4 revealed that 67 percent of respondents indicated that the sign design from alternative C2 “provides clearer direction” to the destinations than the sign design in alternative C4.

The advance guide sign in figure 76, using the method from alternative C2 of the simulator study, indicates the downstream configuration of the lanes addressed by the sign. The left lane and right lane both serve the destination via exit 301, as indicated by the arrowheads. Unlike the conventional practice of using down arrows over the lanes, which was also found to be suitable for option lane signing in the simulator study, the null-terminated two-headed arrow method provides the benefit of indicating that the lanes continue straight before exiting. In addition, the null-terminated two-headed arrow, in lacking an arrowhead pointing up, has the potential to avoid confusion of the blended arrow signing of alternative C4, where arrowheads point right and straight into the same legend, the legend pertaining to the destination served by the exit.

Source: FHWA.
A. Advance guide sign.

Source: FHWA.
B. Exit-direction sign.

Figure 76. Graphics. Option lane signing using the discrete arrow method with a null-terminated two-headed arrow in place of down arrow over option lane.

The design of the null-terminated two-headed arrow was inspired by similar designs on guide signs for roundabouts, where the circulating lane is terminated without an arrow, because no information about the destination of the circulating lane is provided on the guide sign.

Implementation

Implementation costs vary for different groups of signing changes. MnDOT conducted a statewide sign modification in the mid-2000s to move all center-aligned exit plaques to the side of the sign corresponding with the exiting movement. The provision of separate signs for separate movements is difficult to estimate, as costs for structures can vary widely case-by-case, depending on the existing structure type, while the calculation of costs for fabrication and installation of sign panels (assuming a typical size of 12 ft 6 inches by 15 ft 0 inches) is relatively straightforward.

TREATMENT 3—GUIDE SIGNING: SIGN PLACEMENT AND USE OF ARROWS AND DISTANCES

Treatment 3 covers the following topics:

- Traffic volume and density impacts.
- Confusion related to ramp terminal placement and sequence.
- Upstream non-mandatory exiting movement precedes mandatory exiting movement.
- Impacts of violation of expectations.
- Auxiliary lanes and option lanes; signing and marking for option lanes.
- Information loading, panel layout, and design and specific messaging for guide signs.
- Pavement markings.
- Impacts of restricted lane exiting maneuvers.

Introduction

In conducting the practices evaluation and literature review, the project team identified practices related to sign panel legend selection and placement of the signs themselves that can contribute to driver-expectancy violations. Some of these are related to existing policy, and others are violations of existing practice literature likely borne of designer inexperience and insufficient familiarity with HFs guidelines. The notable undesirable practices are summarized in table 86.

Table 86. Practice and case summary for treatment 3.

Practice	Sample Case Description
Placement of exit-direction sign in accordance with MUTCD figures 2E-38 and 2E-39	An agency places exit-direction signs at the beginning of the ramp taper, while another agency places the exit-direction signs more consistently at the beginning of the exiting movement itself. In inclement weather and reduced visibility conditions, this can lead to driver-expectancy issues related to the point of departure.
Use of angled type A and type B arrows to indicate a lane change as opposed to indicating an exiting movement	An agency uses angled type A and type B arrows on overhead signing to indicate a lane change. In low-visibility conditions where pavement markings are obscured, this could lead to erratic behavior. Down arrows or word messages would eliminate confusing these arrows with arrows used at the point of departure.

Practice	Sample Case Description
Lack of distance information on signs	Without “closing distances” on guide signing, motorists may be unsure of the point of departure, particularly where APL (combination arrow) signs are used.
Multiple identical signs in advance of the exit gore	Because a bridge blocks the view of a downstream overhead sign, an agency installs an additional upstream sign on the bridge without providing type C arrows or a distance to the exit in conjunction with either down arrows or type C arrows.

Design Guidelines

In cases where geometric design and other factors influence the placement of signs, designers often make choices that do not consider the overall use of sign panel separation, arrows, and other cues.

In figure 77, the overcrossing roadway obscures the view of the exit-direction sign in the gore area, while the upstream location of another sign is too far in advance for placement of an exit-direction sign. The design of the first sign does not include a distance, reference to the auxiliary lane, or an arrow consistent with this application. The second sign indicates dual exit-only lanes, which is not the case in this interchange, where only one lane is mandatory movement and the second lane is an auxiliary lane. No specific language in the MUTCD addresses these types of cases.

Source: FHWA.

Figure 77. Photo. Use of multiple signs approaching a single departure point.

Research Findings

The simulator study found that regardless of signing alternative used, participants were generally able to successfully navigate complex interchanges as long as good signing practices and consistent implementations were followed.

Recommendations

Based on the practice evaluation and literature review, the project team is proposing the following practice recommendations to address issues related to the interaction of sign placement locations and the arrows and distance information displayed on sign panels. The intent of these recommendations is to use sign panel legends and placement of signs to best convey the proximity of exits and their relationships to one another and to ensure cues related to exit direction, ramp configuration, and the location of the physical gore.

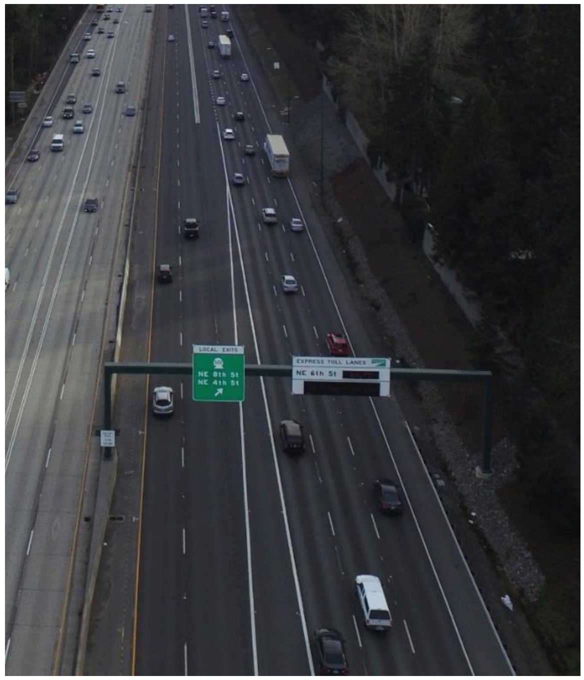
Recommendation 3-1: Provide Distances to the Departure Point on All Primary Guide Signing

Numerous States, particularly those implementing large APL signs, omit advance distances on some guide signs, especially exit-only and diagrammatic signs, where distances are especially important. Addressed in part 5, this is an issue of compliance with the MUTCD and is related to agency perceptions on the excessive size of the blended arrow signing.

Recommendation 3-2: Use Arrows Appropriate for the Sign Location and Geometry

Addressing the use of downward-pointing and upward-pointing arrows is essential to ensuring that arrows use can be applied consistently in practice. In addition, application of the consistency principle indicates that the use of upward-pointing arrows should be restricted to only those locations where geometric design includes an exit ramp or angled departure from the lane and should not be used in conjunction with lane changes.

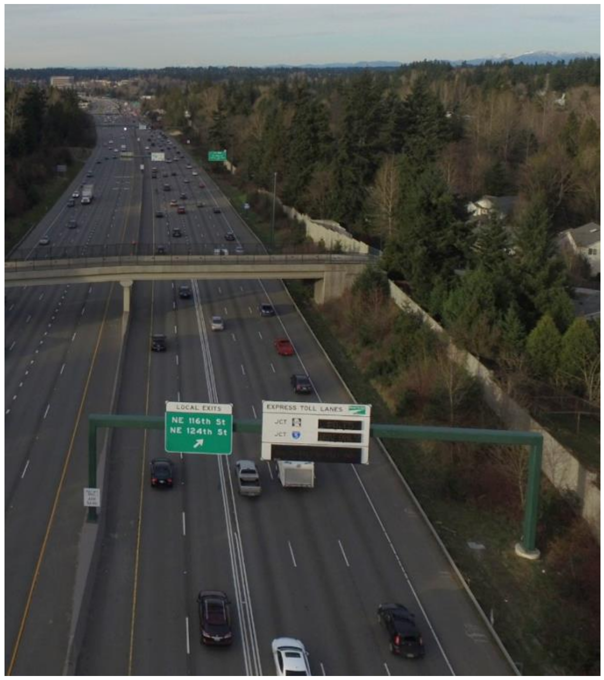
In figure 78, access to the general-purpose lanes of a freeway is provided from the managed lanes by an exiting maneuver that involves a tapered lane addition. On the sign, the angled-up arrow is placed roughly in alignment with the beginning of the exiting movement taper; this use is consistent with using angled-up arrows for departing movements only, as the downstream double-white line provides a legal separation similar to a median or barrier. To the driver, this looks similar to a conventional exit, and the driver's maneuver into the lane formed by the taper is unimpeded by any adjacent traffic. The use of the angled type A arrow is appropriate here, then, because the setting matches many other settings where angled type A arrows are applied.



Source: FHWA.

Figure 78. Photo. Use of a tapered lane addition to enter the general-purpose lanes of a freeway from the managed lanes.

In contrast, the configuration of the freeway in figure 79 does not include the addition of a lane or an exit-type maneuver. Rather, the access point for the general-purpose lanes is parallel lanes and lane changes, not an exiting maneuver, and motorists are required to access the general-purpose lanes from the managed lane. An angled-up arrow, typically reserved for geometry with an exiting movement, is used to indicate a lane-change movement far ahead of the break in the double-white lines, which prohibit these movements. The use of the angled type A arrow in this case is misleading, because road users who previously saw its use associated with a non-lane-change maneuver may make errant maneuvers, particularly in inclement weather where pavement markings are obscured. This broadening application of the angled type A arrow is incongruous with the consistency principle and violates road-user expectancy of the specific meaning of the arrow; namely, that there is an exit available proximate to the exit-direction sign.



Source: FHWA.

Figure 79. Photo. Use of misleading signing and parallel lanes and lane changes to access the general-purpose lanes of a freeway from the managed lanes.

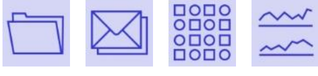
The use of down arrows should be similarly restricted to those locations where there is not an immediate exit from the lane to which the down arrow applies. In Colorado, for example, down arrows are used on “EXIT ONLY” panels in advance of the exit and also at the departure point. When distances are omitted, this practice leads to broadening use of the down arrow, such that it is no longer restricted to upstream locations where a continuing lane is present, whether or not that lane is marked as “EXIT ONLY.”

Table 87 provides recommendations on the use of arrows such that use of arrow type and orientation is consistent with geometric design and accommodates legend grouping.

Table 87. Recommended uses of currently approved guide sign arrows.

Arrow Type	Arrow Use	Information from Angle
	A down arrow always indicates a lane that continues on along the mainline, even if that lane terminates downstream in a service interchange. The exception to this use is that down arrows may be used on more than one sign at a junction if the additional movements are considered primary movements, such as at a major split of two marked routes of equal importance along a freeway corridor.	The degree of the angle of installation of a down arrow, when not 0 degrees off the vertical, indicates the curvature of the mainline movement or primary movement(s) within an interchange, used only on signs placed at the departure point. Angled down arrows are only applied in conjunction with overhead exit-direction signs.
	Type A and type B arrows are typically restricted to use on exit-direction signs at service interchanges. Type A arrows are used to the side of text at angles up to 45 degrees off the vertical when two or more lines of text are adjacent. Type A arrows pointing left or right are used underneath text, and an upward angled type A arrow may be used under all text on a ground-mounted guide sign. Type A arrows never point down into a lane from an overhead sign.	The upward angle of a type A arrow is indicative of the severity of the exiting movement. Type A arrows generally are slanted 30 degrees off the vertical for primary guide signing and exit gore signing, with 45-degree angles appropriate for ramps with a greater curvature.
	Type A and type B arrows are typically restricted to use on exit-direction signs at service interchanges. Type B arrows are used to the side of text when pointing left or right and adjacent to a single line of text when pointing up or angled. Type B arrows may be used under all text on an overhead guide sign or between the legend text “EXIT,” “LEFT,” or “RIGHT” and “ONLY.” Type B arrows never point down into a lane from an overhead sign.	The upward angle of a type B arrow is indicative of the severity of the exiting movement. A type B arrow may point down into a lane from a ground-mounted sign immediately adjacent to the lane to which the arrow applies.
	Type C arrows are used on guide signs that are placed in advance of but in close proximity to the departure point and typically used only where no sign is present at the departure point. Except in cases where no sign is provided at the departure point and the sign with the type C arrow is installed where the departure point is visible, a distance to the departure point should be provided.	The upward angle of a type C arrow indicates the severity of the exiting movement. Type C arrows generally are slanted 30 degrees off the vertical for primary guide signing and exit gore signing, with 45-degree angles appropriate for ramps with a greater curvature.

Recommendation 3-3: Provide One Arrow Shaft Over Each Lane



The MUTCD specifically prohibits the use of multiple arrows pointing into one lane or associated with a single lane. Continuing instances of this practice can be addressed with information on the use of various traffic signing arrows.

Recommendation 3-4: Accommodate Angled Down Arrows

Additional MUTCD language prohibits the use of angled down arrows. This research observed numerous instances where angled down arrows are used to effectively convey a change in alignment of the primary route or exiting movement for a high-speed movement. Specific language on the use of angled down arrows will limit their use in this way while explicitly prohibiting the use of more than one arrow over a single lane.

Recommendation 3-5: Place Exit-Direction Signs Adjacent to the Departure Point

Addressed in chapter 5 of this report, the placement of exit-direction signs is critical information to the guidance task. MUTCD figures should be revised so that exit-direction sign placement is consistently illustrated as being adjacent to the point of departure, near the gore area. When this placement cannot be provided, the use of a 45-degree type C arrow should be considered for any exit-direction sign placed in advance of the point of departure.

Implementation

The implementation of these measures is not expected to considerably increase the cost of signing for interchanges. Marginal height increases (18 to 24 inches) on some signs will be offset by significant reductions in sign heights because of the altered arrow designs of recommendation 2-6, even as continued use of the down arrows on the conventional practice is made.

TREATMENT 4—DELINEATION FOR EXITING LANES AND SPECIAL USE LANES

Treatment 4 covers the following topics:

- Traffic volume and density impacts.
- Confusion related to ramp terminal placement and sequence.
- Impacts of violation of expectations.
- Auxiliary lanes and option lanes; signing and marking for option lanes.
- Pavement markings.
- Impacts of restricted lane exiting maneuvers.

Introduction

In conducting the practices evaluation and literature review, the project team identified practices related to delineation that can contribute to driver-expectancy violations. Many agencies neglect to use dotted lane lines (in lieu of broken lane lines) in advance of mandatory exiting movements. Other agencies do not differentiate between the dotted lane line and the dotted extension line, either in width or pattern, leading to confusion concerning the presence of a full-width lane and the applicability of that lane. The most notable undesirable practices are summarized in table 88.

Table 88. Practice and case summary for treatment 4.

Practice	Sample Case Description
Failure to use dotted lane line for all mandatory exiting movement lanes	An agency occasionally uses dotted lane lines in advance of exit-only movements on the freeway but never uses them in cloverleaf ramp configurations.
Omitting markings at critical points	In a busy urban area, a long deceleration lane is provided with a full lane width but no pavement markings are provided between the continuing lanes and the deceleration lane, leading to confusion about the purpose and termination of the lane.
Sporadic use of dotted extension lines	A ramp located on a left-hand curve includes the addition of an exiting lane on the left following a tunnel. Because no white dotted extension lines are provided in the transition area, traffic veers into and then out of the lane.
Multiple identical signs in advance of the exit gore	Because a bridge blocks the view of a downstream overhead sign, an agency installs an additional upstream sign on the bridge without providing type C arrows or a distance to the exit in conjunction with either down arrows or type C arrows.

Design Guidelines

Few States require the use of dotted extension lines along the lane addition tapers leading into restricted use or mandatory movement lanes. In Illinois and Virginia, dotted extension markings are used in lane addition tapers for left turn and right turn lanes on arterial routes. In North Carolina, dotted extension lines are used for all lane addition and lane-reduction tapers.

States typically avoid the use of dotted extension markings along the lane addition tapers where a continuing general-purpose lane is being added because motorist movement into that lane is typically not discouraged. In figure 80, the lane addition taper (marked with a broken red line) is not delineated with dotted extension lines, leading to veering behavior by westbound motorists leaving the tunnel and approaching the apex of the short crest vertical curve.

Source: FHWA.

Figure 80. Photo. The use of a lane addition taper (marked with a broken red line) not delineated with dotted extension lines.

Research Findings

The simulator study used dotted lane lines along all exit-only lanes. For clarity and to avoid additional effects, no word or symbol markings are used.

Recommendations

Based on the practice evaluation and literature review, the project team proposes the following practice recommendations to address issues related to the interaction of sign placement locations and the arrows and distance information displayed on sign panels. The intent of these recommendations is to use sign panel legends and placement of signs to best convey the proximity of exits and their relationships to one another and to ensure cues related to exit direction, ramp configuration, and the location of the physical gore.

Recommendation 4-1: Provide Differentiated Markings

Differentiated markings should be provided for continuing lanes, mandatory movement lanes, and areas of transition (lane-reduction tapers and lane addition tapers for exit-only lanes). For full-width lane areas, solid, broken, or dotted lane lines are used. For transition areas (lane addition and lane-reduction tapers), the dotted extension line provides a visual cue about the taper while also providing a boundary for vehicles intending to remain in the adjacent lane.

Recommendation 4-2: Provide Lane Use Arrows for All Exiting Lanes

Several States provide lane use arrows and, for all single-headed arrows, the word “ONLY” in the exiting lanes along approaches to movements with multiple exiting lanes. This practice, when combined with the use of dotted lane lines, provides additional aids to recognition of the change in lane state and destination, even when overhead signing is not visible.

Recommendation 4-3: Provide Solid Line Markings Upstream and Downstream of Decision Points

Solid lines discourage lane changes in critical areas, where drivers are navigating an exit ramp, also emphasizing the presence of multiple exiting lanes in areas where auxiliary lanes occur. Wide solid lane lines should be considered where operations exhibit excessive lane changes in these areas.

Implementation

The implementation of these measures is not expected to considerably increase the cost of signing for interchanges.

TREATMENT 5—LANE-REDUCTION METHODS, SIGNING, AND DELINEATION

Treatment 5 covers the following topics:

- Traffic volume and density impacts.
- Confusion related to ramp terminal placement and sequence.
- Impacts of violation of expectations.
- Pavement markings.

Introduction

In conducting the practices evaluation and literature review, the project team identified practices related to sign panel legend selection and placement of the signs themselves that can contribute to driver-expectancy violations. Some of these are related to existing policy, and others are violations of existing practice literature likely borne of designer inexperience and insufficient familiarity with HFs guidelines. The notable undesirable practices are summarized in table 89.

Table 89. Practice and case summary for treatment 5.

Practice	Sample Case Description
Using a mixture of W9-1 "RIGHT LANE ENDS," W9-2 "LANE ENDS MERGE LEFT," and W4-2 symbol signs in advance of lane reductions	Numerous agencies mix the use of the W9-1, W9-2, and W4-2 signs at the advance placement distance, leading to confusion about the location of the beginning of lane-reduction taper relative to the placement of the warning sign. One partner agency uses the W9-1 sign exclusively in advance.
Omitting dotted extension lines along lane-reduction taper	A lane-reduction taper occurring in a curve causes vehicles to drift into the adjacent lane in a wide area of unmarked pavement. A dotted extension line along the lane-reduction taper would assist in delineating the thru lane and clearly visually indicating the reduction in lane width.
Failure to use lane-reduction arrows	A vertical curve and ambiguous lane-reduction signing causes a crash problem and recurring congestion in advance of a lane reduction on a freeway segment. An entrance ramp terminating in a long acceleration lane is delineated from the mainline lanes with a dotted line marking, leading drivers to assume the lane is an auxiliary lane, as no lane-reduction arrows or lane-reduction signing is provided.
Multiple identical signs in advance of the exit gore	Because a bridge blocks the view of a downstream overhead sign, an agency installs an additional upstream sign on the bridge without providing type C arrows or a distance to the exit in conjunction with either down arrows or type C arrows.

Design Guidelines

Washington State, Florida, and Minnesota (project partners in the working group) have strong pavement marking standards development and integration into the design process. Each State differentiates between dotted lane lines and dotted extensions. All three States use lane-reduction arrows in conjunction with a physical reduction in the number of lanes, with Washington State using arrows along in a progressive fashion.

Part 3 of the MUTCD specifically differentiates between the dotted line and dotted extension markings in both the pattern and width. Dotted extension markings are also not required by a standard statement to be placed in the 1:3 ratio, and some States, including Minnesota and Washington State, have numerous installations using a 1:4 ratio to further differentiate the lane lines (e.g., solid lane divider line markings, dotted line markings, and broken line markings) from the guide lines.

Research Findings

In addition to researching the effectiveness of guide signs relative to lane choice, the simulator study also included several lane reductions. These lane reductions were treated in various ways to judge participant reaction to warning signs with a participant survey. The participant survey found that the majority of participants, including those who did not observe the sign in figure 81, interpreted the meaning of the sign to be that the lane was ending up ahead, in close proximity to the sign.

Source: FHWA.

Figure 81. Graphic. Proposed W4-3X sign for multilane entrances.

The W4-3X warning sign is a design that was developed for locations where tapered multilane entrances exist. While these are becoming less common, there are nearly 20 such instances in northeastern Illinois on roadway systems managed by 2 authorities, and other locations in urban areas where space constraints preclude the construction of multilane entrance ramps of the parallel type. This sign was not evaluated in the field because of construction conflicts at the evaluation site, but it is recommended for further study to replace the six designs observed in use in the United States. Future comprehension testing subsequent to a synthesis of signs is recommended.

Recommendations

Based on the practice evaluation and literature review, the project team is proposing further evaluations that specifically address warning sign placement and lane additions, in addition to pavement markings for entering and exiting lanes. The practice and research recommendations here are intended to apply the consistency principle in the placement of markings that convey the proximity of exits, the downstream duration and function of entering lanes, and their relationships to one another. In addition, these recommendations are predicated on the principle that warning signs should be sequenced so that they can function independently, as part of a system, and with or without associated markings, for all lane reductions. This enables practitioners to use just a single sign near the beginning of the lane-reduction taper, even if upstream signing cannot be provided.

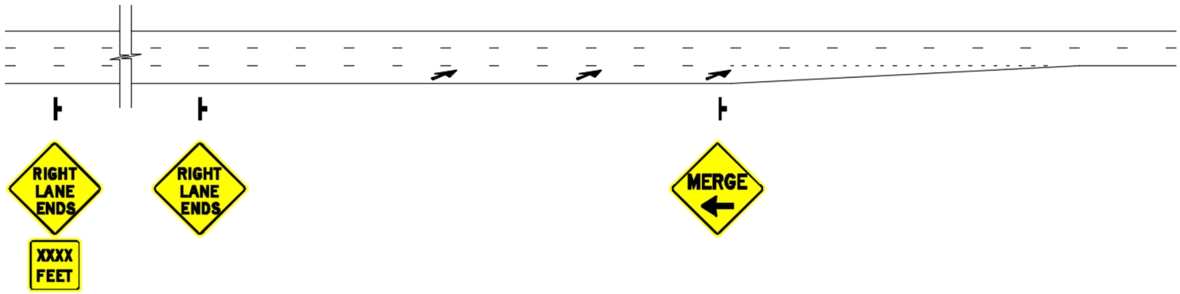
Recommendation 5-1: Provide Sign to Indicate Beginning of Lane-Reduction Tapers

A sign that warns about the location for the lane-reduction taper would help provide an enhanced warning in addition to pavement markings. Several potential signs could be used, and it is recommended that a consistent method be chosen. Figure 82 shows a MnDOT-designed sign, referred to here as the merge point sign (provisionally assigned MUTCD code W9-2A), that has been in use in work zones in Minnesota since the 1960s and, within the last decade, implemented in permanent installations as a means of clearly identifying the beginning of the lane-reduction taper. The high recognition score of the sign’s purpose, from the simulator study and an application that conforms to the consistency principle, indicates that this sign would be a useful addition to lane-reduction warning sign implementations. It is intended to be placed only adjacent to the outside lane to which it applies.

Source: FHWA.

Figure 82. Graphic. MnDOT-designed W9-2A(L).

The sign is intended to supplement the upstream primary warning sign, the W4-2 pavement width transition symbol (see figure 83). The W9-2A sign is a replacement for the word message W9-2 sign and should be used opposite the W9-1L or R; the W9-2A simplifies the message for the motorist by providing a clear needful action.

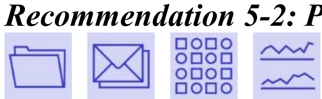


Source: FHWA.

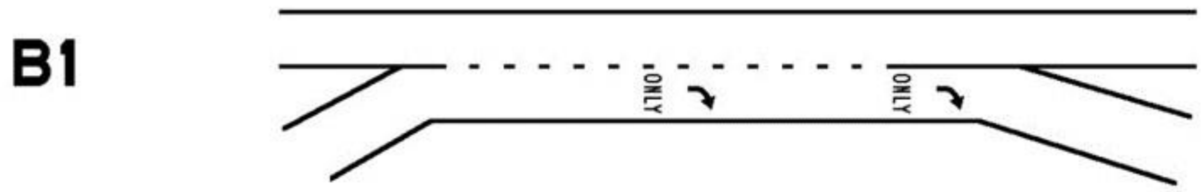
Figure 83. Graphic. Schematic of proposed lane-reduction signing.

Placement of the merge point sign, in contrast to the W9-2 and W4-2 signs, is uniformly located for all lane reductions. Such a consistent placement location, close to or adjacent to the beginning of the lane-reduction taper, aids motorists in identifying the taper in any situation where the sign is used. In situations where advance warning signs (e.g., the W9-1 sign) cannot be provided (e.g., short acceleration lanes associated with entrance ramps of the parallel design), the W9-2A sign can always be used in the location proximate to the beginning of the lane-reduction taper. With this consistent application, road users will always be able to identify their proximity to the lane-reduction taper and plan lane change and speed change maneuvers accordingly. Because lane-reduction tapers are based on speed, the placement of the sign relative to the beginning of the taper needs not vary on roadways with different speed limits and design speeds.

Recommendation 5-2: Provide Differentiated Pavement Markings

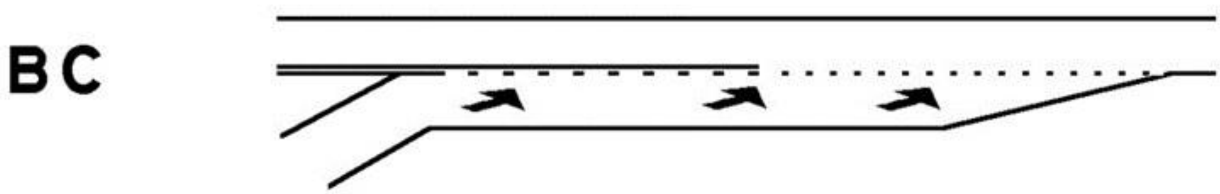


Provide differentiated markings for lane reductions that are dissimilar from the markings used for auxiliary lanes. For example, the use of the dotted lane line adjacent to a solid line would provide a pattern significantly different from the standard dotted line markings that separate auxiliary lanes from continuing lanes. The contrast between the entering lane forming an auxiliary exit-only lane and the entering lane forming an acceleration lane is illustrated in figure 84. Depiction BC illustrates the use of the solid line adjacent to the continuing lane, indicating that free access to the acceleration lane is not intended, as it is with the auxiliary exit-only lane in depiction B1.



A. An entering lane forming an exit-only lane.

Source: FHWA.



B. An entering lane forming an acceleration lane.

Source: FHWA.

Figure 84. Graphic. Comparison of markings for auxiliary exit-only lanes and acceleration lanes.

Use of such a pattern on short- to medium-length acceleration lanes, with the solid line on the side of the continuing lanes, will indicate that the continuing lane traffic is not to cross over into the acceleration lane. In cases where acceleration lanes are marked with the dotted line, road users may mistake the lane as an auxiliary lane that continues to the next interchange and move into the acceleration lane.

Recommendation 5-3: Provide Lane-Reduction Arrows for All Lane Reductions

Washington State, California, Florida, Minnesota, and several other States provide lane-reduction arrows in advance of physical reductions in the number of lanes. The lane-reduction arrow orientation sets the long axis of the arrow along the longitudinal center of the lane. Lane-reduction arrows are never used in auxiliary lanes terminating as exit-only lanes, where lane use markings are appropriate.

Recommendation 5-4: Improve Maintenance Practices

In most urban interchanges, high traffic volumes and the large fraction of lane changes typically lead to accelerated degradation of pavement markings. Several agencies provide for an “at-risk markings” biennial pavement marking renewal program, particularly in climates where snow removal is performed and ice control products are used. Targeted, limited renewal of solid lane lines, dotted lane lines, gore markings near the leading edge, and lane-reduction arrows ensures that TCD effectiveness is not reduced. This is particularly important in the spring, following winter snow removal, when wet roads further impede visibility.

Implementation

The cost of retrofitting existing markings can be incorporated into existing maintenance activities; new construction will not incur significant additional costs. The cost of additional markings (e.g., word and symbol legends) is a marginal addition to new contracts and would be an addition to regular maintenance activities.

TREATMENT 6—TCDS EDUCATION AND DESIGN REVIEW WORKSHOPS

Treatment 6 covers the following topics:

- Traffic volume and density impacts.
- Confusion related to ramp terminal placement and sequence.
- Upstream non-mandatory exiting movement that precedes mandatory exiting movement.
- Impacts of violation of expectations.
- System design characteristics.
- Impacts of ramp arrangements.
- Auxiliary lanes and option lanes; signing and marking for option lanes.
- Information loading, panel layout, and design and specific messaging for guide signs.
- Pavement markings.
- Impacts of restricted lane exiting maneuvers.

Introduction

In conducting the practices evaluation and literature review, the project team identified practices related to sign panel legend selection and placement of the signs themselves that can contribute to driver-expectancy violations. Some of these are related to existing policy, and others are violations of existing practice literature likely as a result of designer inexperience and insufficient familiarity with HFs guidelines. Some example practices that result in inconsistent design are summarized in table 90.

Table 90. Practice and case summary for treatment 6.

Practice	Sample Case Description
Signing plans are developed in preliminary planning stages subsequent to detailed geometric design	Large-scale projects without up-front attention to complex signing often require adjustments to geometric design after a traffic engineering and operations review, usually because the necessary signing cannot be provided in the longitudinal distances provided along additional lanes.
Use of overhead structures or structures of sufficient size is curtailed because of insufficient project budgets	A project subjected to value engineering is modified and overhead sign structures for exit-only lanes are removed. On another project, shortened cantilever structures prevent appropriate sign layout and legend spacing.
Different consulting firms design various segments of a large project	One consulting firm is experienced with signing and fabrication drawings while another produces drawings that are complicit in fabrication errors. This leads to inconsistent quality in signing along a roadway segment.

Design Guidelines

Addressing these issues may require changes to internal policy and procedures and may require modifications to specifications and special provisions for some types of contracts. In many cases, further guidance documents may be useful to encourage consistent practices.

Recommendations

While practitioners should determine appropriate policy and practice recommendations concerning the design, approval, fabrication, and installation of signs, it is important to do the following:

- Involve traffic operations personnel in conceptual design process, including application of the *NCHRP Report 600 Human Factors Guidelines for Road Systems*.(52)

- Provide for high-level review of signing plans by specially trained personnel responsible for policy, standards, and sign design and fabrication.

- Require central office or region/district office freeway signing design unit approval for all guide signs.

- Require that inspection of fabricated signs, pavement markings, and other TCDs on construction contracts be handled by specially qualified inspectors trained in traffic engineering principles and specifications.

- Encourage efforts to provide resources and training for sign design and HFs in freeway signing, aiding the development of staff and consulting contractors, to ensure that policies and practices are implemented consistently with conformance to the intent of regulations and publications.

Implementation

The implementation of these measures is not expected to considerably increase the cost of signing for interchanges when incorporated early in the design process.

APPENDIX A. CANDIDATE SITE INFORMATION SHEETS (SUPPLEMENT TO CHAPTER 4)

INTRODUCTION

This appendix provides information on 13 candidate locations for data collection in this project. Each page shows which of the attributes of interchange complexity are present at the location (i.e., written in black lettering), and which were not (i.e., written in gray lettering). In addition, an aerial view as well as a brief narrative describing each location is provided.

LOCATION 1: I-880 AT SR 237 IN MILPITAS, CA

Shown in figure 85, this interchange comprises a major direction change for a corridor of high-occupancy vehicle and tolling (HO/T) lanes developed by the Santa Clara Valley Transportation Authority. The function of this corridor is to serve a major movement between I-880 and the SR 237 freeway.

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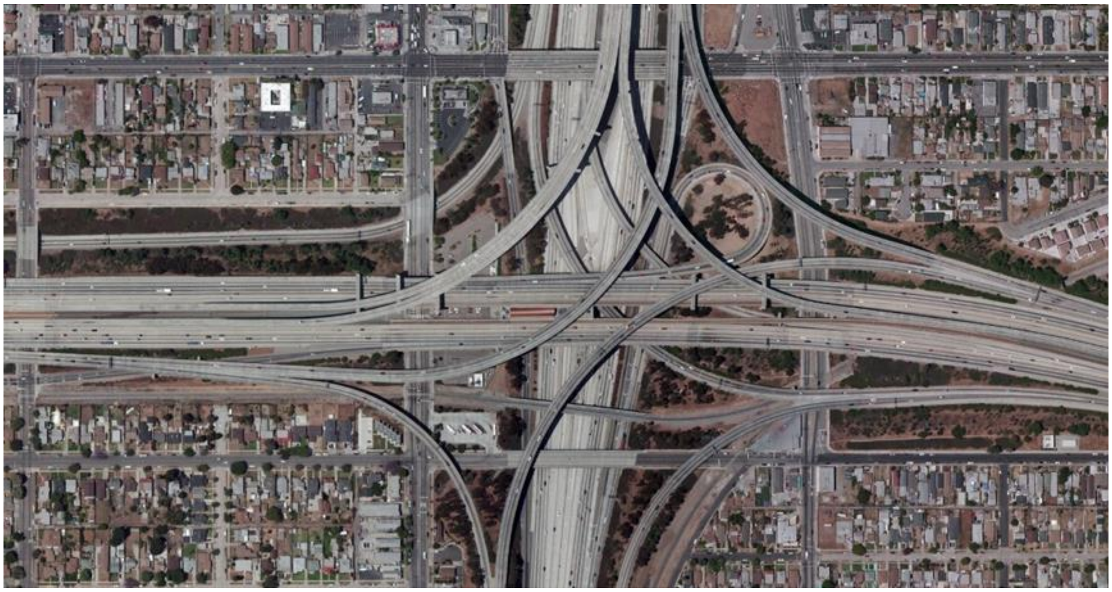
Figure 85. Photo. Aerial view of location 1.[53]

One key feature of this interchange is the movement from SR 237 to I-880 northbound. Both the HO/T and general-purpose lanes occupy the same carriageway until a split within the interchange, essentially allowing for all northbound movements to serve as one continuous roadway with what appears to be an HO/T bypass lane.

LOCATION 2: I-110 AT I-105 IN LOS ANGELES, CA

Shown in figure 86, this interchange is a modified four-level interchange with one loop ramp and direct HO/T connections from I-105 to the north side of the interchange. There are no HO/T direct connections from I-105 to I-110 southbound or from I-110 northbound to I-105.



©Esri.

Figure 86. Photo. Aerial view of location 2.(54)

All approaches feature some combination of option lanes, auxiliary lanes, and access to service interchanges within the interchange influence area. Notable also is that the HO/T exits are not out of sequence on southbound I-110, as the first exit is for westbound I-105 and the second exit is for eastbound I-105, consistent with right-hand and left-hand conventions.

LOCATION 3: I-5 AT CALIFORNIA ROUTES 22 AND 57 FREEWAYS IN SANTA ANA, CA

Shown in figure 87, this interchange is a five-way junction with access to numerous heavily traveled arterial routes from the 22 Freeway. In general, exits conform to the first exit for right-hand movements sequencing method, with the exception of the 57 Freeway connection to I-5, which is also served by heavy-occupancy vehicle direct-connection ramps for movements in the same cardinal direction only.

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Figure 87. Photo. Aerial view of location 3.[55]

This interchange features a redundant bypass lane for southbound I-5 traffic, intended for vehicles bound for the service interchange to the south. There is also a slip ramp from the entrance ramp from the 22 Freeway serving this short C/D roadway.

LOCATION 4: I-75 AT I-285 NORTHWEST JUNCTION IN ATLANTA, GA

Shown in figure 88, the interchange is a modified cloverleaf interchange with direct-connection ramps for the primary movements. In its present configuration, the interchange features several braided connections to adjacent service interchanges, and access is provided to and from interchanges from all directions of all freeways, an unusual approach. The interchange is a modification of the original interchange, which featured left exits from the I-285 mainline, similar to the interchange of I-285 and I-20 east of Atlanta. It is slated for modifications related to the I-75/575 HO/T lane program, expected to include direct-connection ramps from the outside lanes of I-285 to the inside lanes of I-75.

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Figure 88. Photo. Aerial view of location 4.[56]

LOCATION 5: I-75 AT I-85 NORTH JUNCTION IN ATLANTA, GA

Shown in figure 89 this interchange is the major split of I-75 and I-85 north of downtown Atlanta. Interestingly, despite that I-85 traffic is headed northwest and I-75 traffic is headed northeast, the interchange places the movements in the left and right lanes, respectively. Recently, this interchange, which does not include option lanes, received new guide signing—APL. Previous approaches to signing in this interchange have included angled down arrows, clearly indicating major movement curvature and direction. The interchange also uses non-colored pavement markings for the major movement route numbers.

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Figure 89. Photo. Aerial view of location 5.[57]

LOCATION 6: I-85 AT I-285 SOUTHWEST JUNCTION IN COLLEGE PARK, GA

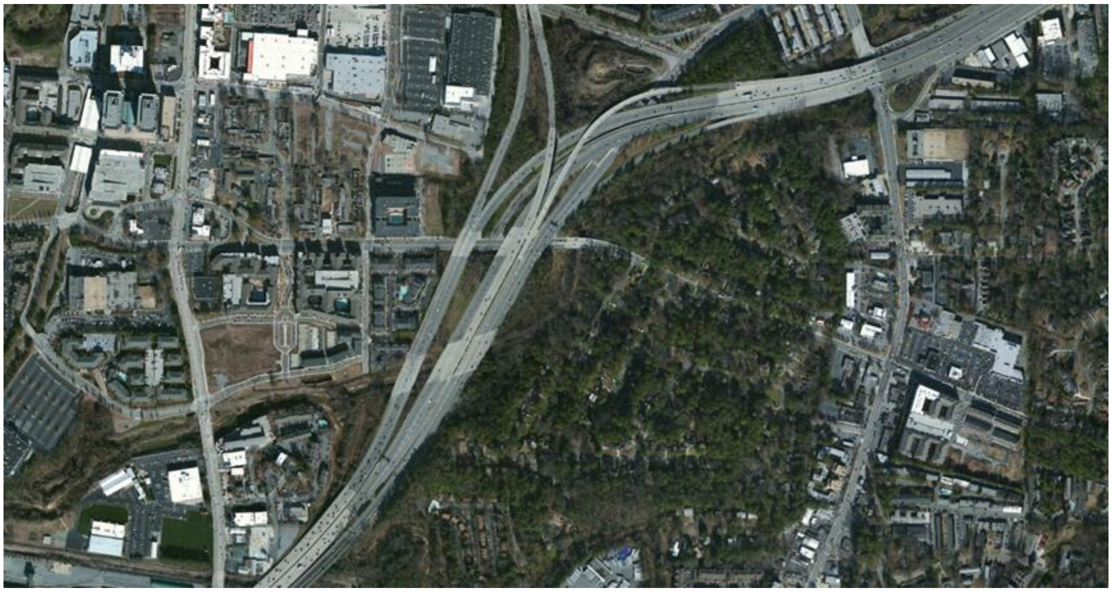
Shown in figure 90, this interchange provides complete separation of mainline traffic for I-285 and I-85, while facilitating all connections between the two routes, serving three intersecting freeway corridors. The quad-carriageway design, similar to I-88 at I-355 in west suburban Chicago, IL, also provides full access to an embedded service interchange.

Figure 90. Photo. Aerial view of location 6.(58)

The interchange uses a somewhat conventional loop-ramp design, similar to the eastern end of Study Interchange 10, to serve movements outside of the I-85 mainline and I-285 route continuity movements.

LOCATION 7: I-85 AT GEORGIA ROUTE 400 TOLL ROAD IN ATLANTA, GA

Shown in figure 91, this interchange features a type of C/D roadway in the form of a parallel multilane facility, Georgia SR 13, with this collector being largely inaccessible from I-85. The guide signing in this interchange has been recently replaced with APL signing. The northbound lanes feature a four-lane to three-lane/two-lane split, and gore area markings indicate pavement marking changes from a previous configuration. Two heavy-occupancy vehicle-only ramps serve a local facility within the interchange area, with access to and from the northeast only. This segment of I-85 features HO/T lanes.



©Esri.

Figure 91. Photo. Aerial view of location 7.[(59)]

LOCATION 8: I-85 AT I-285 NORTHEAST JUNCTION IN ATLANTA, GA

Shown in figure 92, this interchange typifies four-level interchange design with high-volume connections between the intersecting freeways, including option lanes on the mainline access to the ramps and on the ramps at the splits for the two directions of I-285.

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Figure 92. Photo. Aerial view of location 8.[(60)]

LOCATION 9: I-35W AT MINNESOTA CROSSTOWN FREEWAY/TH 62 IN MINNEAPOLIS, MN

Shown in figure 93, this interchange did not employ C/D roadways in its previous configuration. The present interchange fully separates through movements for both intersecting routes. Most notable in this interchange is the consistent use of dotted lane line markings (drop line markings, which, in Minnesota, are distinguished as a 3-ft line with a 12-ft space), particularly on the ramps serving southbound I-35W traffic to both TH 62 and adjacent local streets. Despite its extremely constrained size, the interchange sacrifices little in the way of readily discernible geometry.

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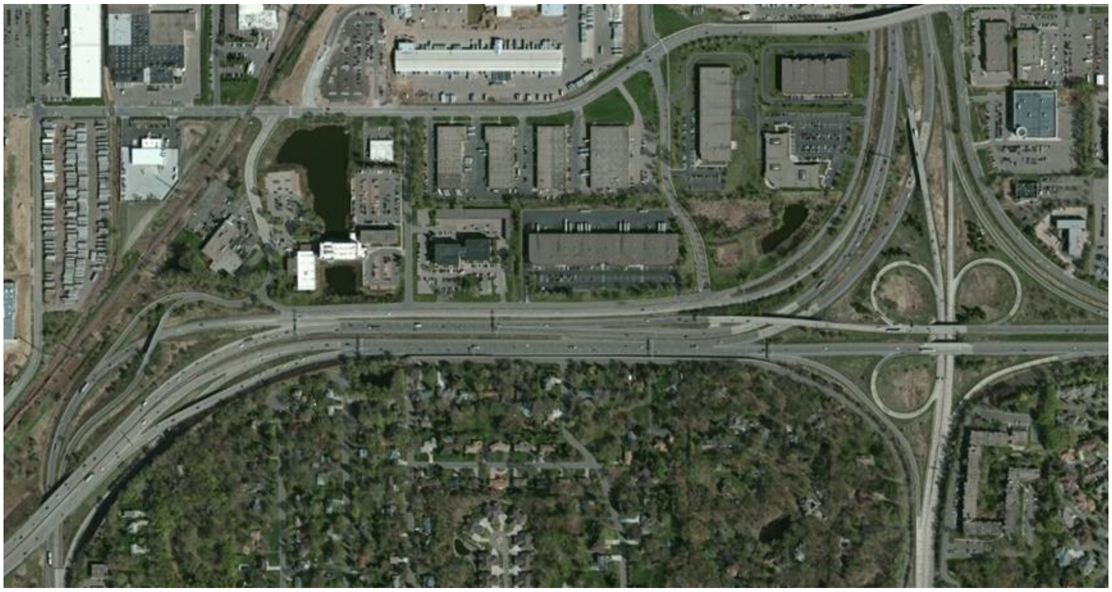
Figure 93. Photo. Aerial view of location 9.(61)

LOCATION 10: I-35W AT HIGHWAYS 36 AND 280 IN MINNEAPOLIS, MN

Shown in figure 94, this interchange provides access to Highway 280 from I-35W southbound in two locations because of the unseparated entrance lane from westbound Highway 36 to southbound I-35W. A similar braided geometry occurs in the northbound direction, effectively providing two carriageways for I-35W northbound through traffic.

In the southbound direction, I-35W is signed for an advisory speed of 50 mi/h using inset panels on the primary guide signing.



©Esri.

Figure 94. Photo. Aerial view of location 10.[(62)]

LOCATION 11: I-394 AT HIGHWAY 100 IN GOLDEN VALLEY, MN

Shown in figure 95, this interchange serves the I-394 HO/T lanes barrier-separated section with ramps to and from downtown Minneapolis. The interchange features two direct-access ramps, serving both northbound and southbound directions of Highway 100 and, in the westbound direction of I-394, access to a local roadway.

West of this location, the HO/T lanes become congruent with the general-purpose lanes, as opposed to the barrier-separated reversible facility that exists to the east of here.

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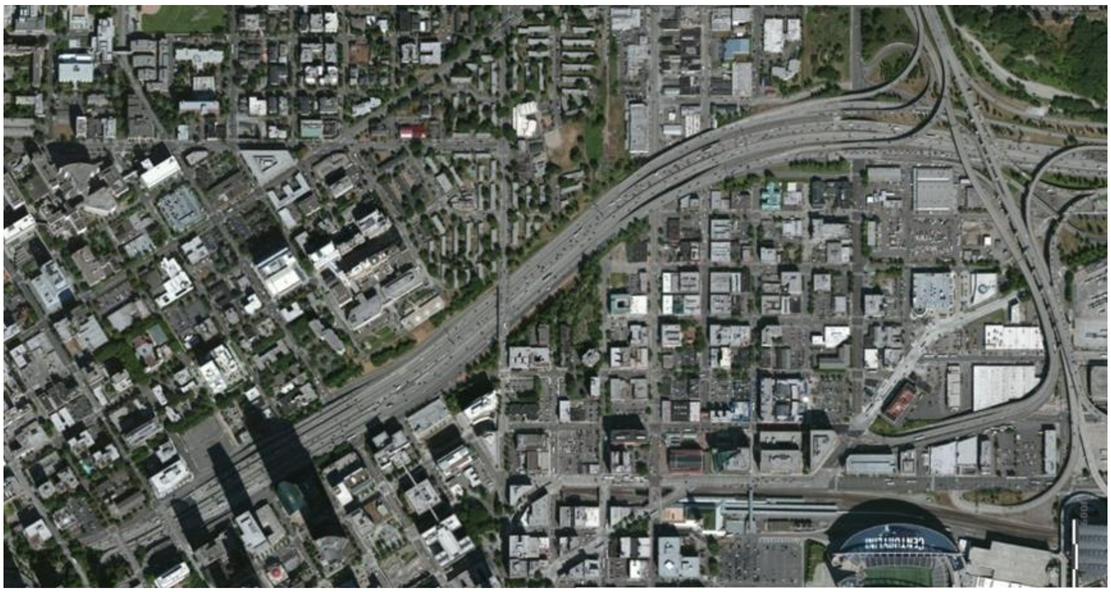
Figure 95. Photo. Aerial view of location 11.[(63)]

LOCATION 12: I-5 AT I-90 AND SEATTLE DOWNTOWN EXITS IN SEATTLE, WA

Shown in figure 96, this interchange is of mid-1960s vintage, with I-90 access in the southbound direction being moved. Improvements here are planned and include northbound freeway-to-freeway ramp metering, a reconfiguration of the northbound mainline lanes to permit two entering lanes from the C/D roadway, and other changes to local access. Adding to the complexity is the entrance to the express lanes facility, which is not restricted access. During the morning peak period, this entrance is closed, and the left lane through traffic must merge into a mandatory movement for a left exit to a service interchange.



©Esri.

Figure 96. Photo. Aerial view of location 12.[(64)]

LOCATION 13: I-5 AT I-405 AND ROUTE 518 IN TUKWILA, WA

Shown in figure 97, this junction is characterized by three distinct treatments of the upstream exit to a service interchange with downstream exit only (including option lane) within the system interchange. While the guide signing uses the type A, type B, and down arrow methodology, signing of option lanes is inconsistent within the interchange, and issues with sign structure maintenance have resulted in the elimination of signing and downsizing of some signs, particularly those closer to the decision points. A southbound left exit for a major movement is a compound exit, with a heavy-occupancy vehicle lane adjacent to the general-purpose exiting lane.

Figure 97. Photo. Aerial view of location 13.[65]

APPENDIX B. DIAGRAMS OF LAYOUTS WITH SIGNING ALTERNATIVES (SUPPLEMENT TO CHAPTER 6)

INTRODUCTION

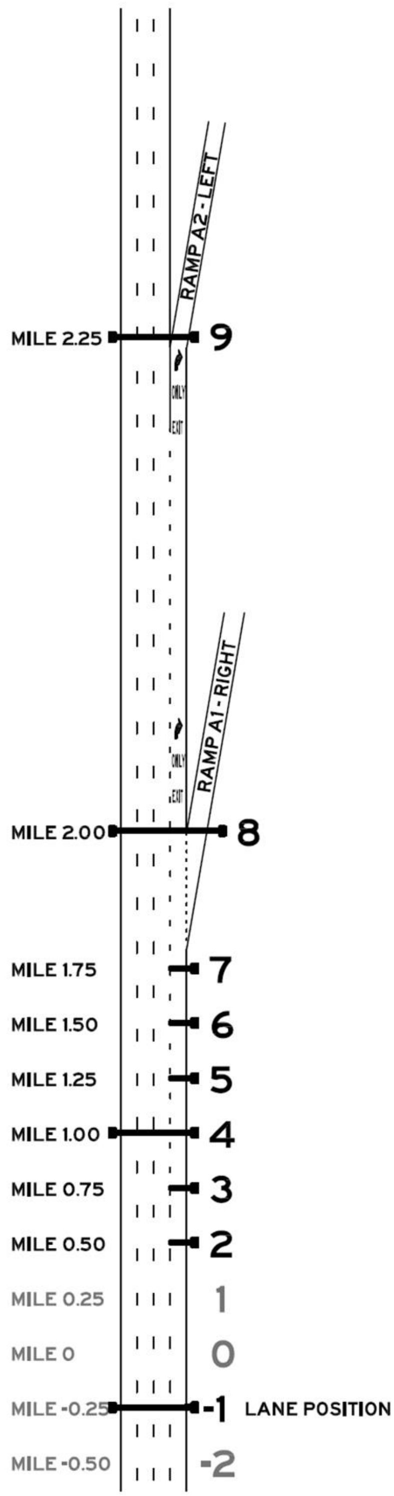
This appendix provides a complete catalog of the signing alternatives (e.g., A, C, L, and E) used for testing in the simulator, in conjunction with diagrams of the geometric layouts associated with each. Each signing alternative was designed to accommodate the three possible destinations for each of the alternatives in a given layout. These movements are considered THRU (T), LEFT (L), and RIGHT (R). Participants were told that their task was to follow the signs toward Greenville; Greenville was always the destination to which they were instructed to drive. For example, a participant might be trying to navigate to Greenville on Route 28 without being told a cardinal direction for Route 28. Using the information provided on overhead guide signs, the participant would either continue THRU to Greenville or exit the interchange to the RIGHT or the LEFT toward Greenville based on the experimental scenario. As there is no LEFT movement in Layout A, a Destination of “L” for this layout represents the second RIGHT movement.

Additional information on this project’s research design can be found in chapter 6.

SCENARIOS FOR

LAYOUT A

LAYOUT A
ALTERNATIVE A1, SCENARIO A1-L



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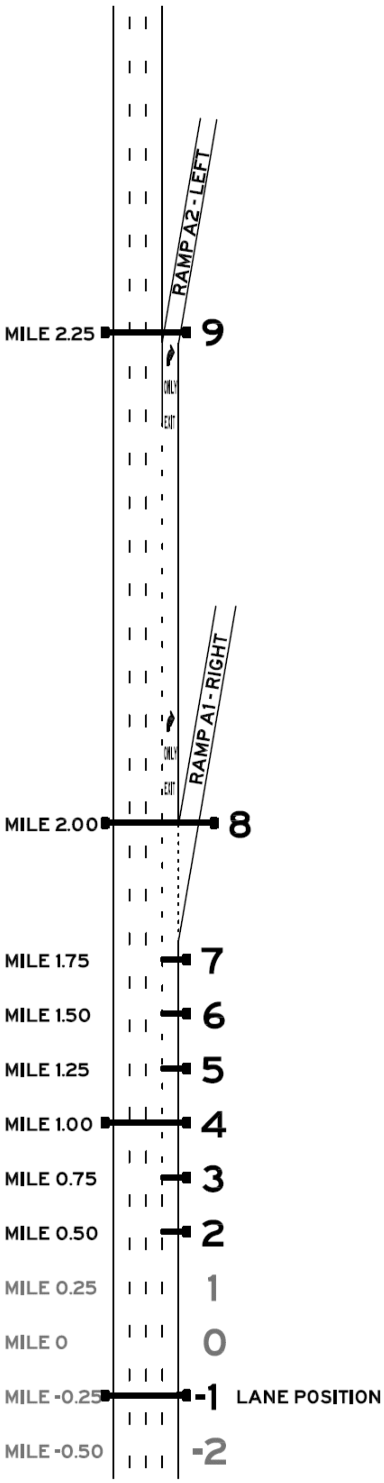
LAYOUT A
ALTERNATIVE A1, SCENARIO A1-R



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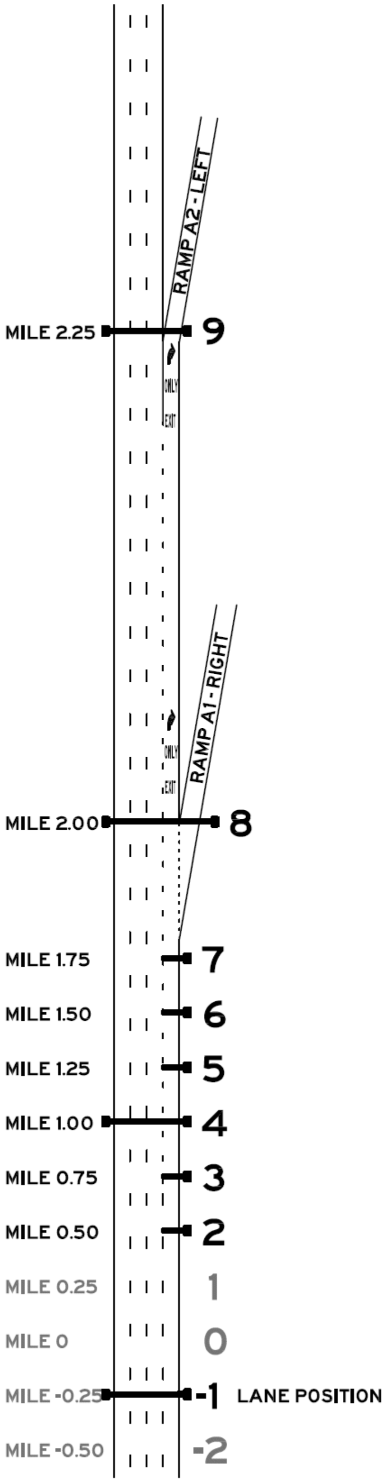
LAYOUT A
ALTERNATIVE A1, SCENARIO A1-T



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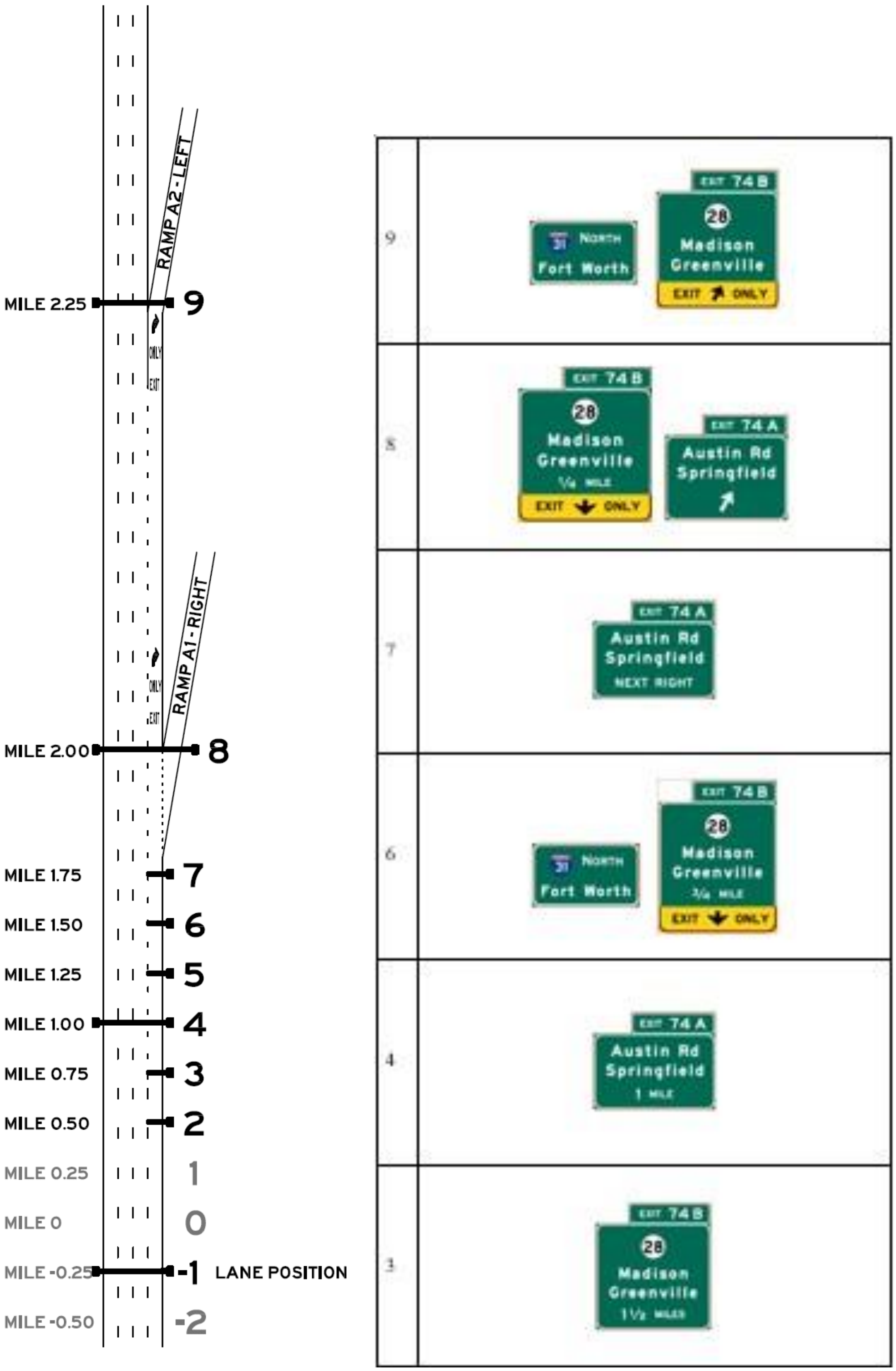
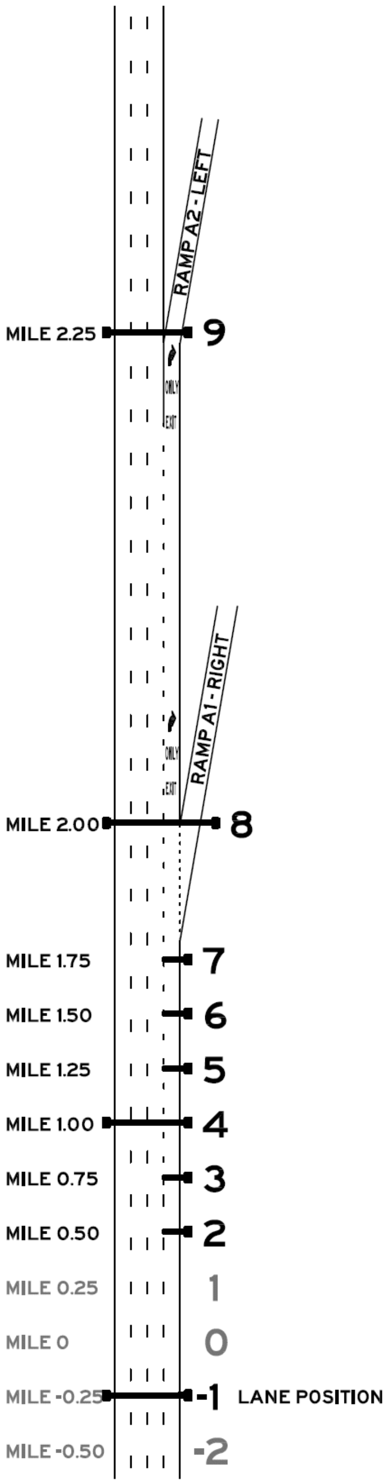
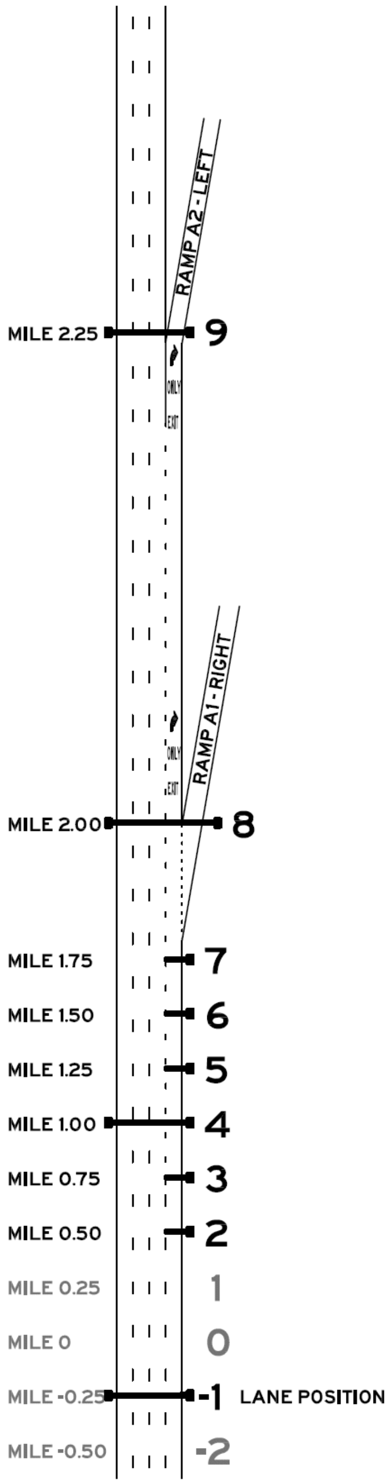
LAYOUT A
ALTERNATIVE A2, SCENARIO A2-L



LAYOUT A
ALTERNATIVE A2, SCENARIO A2-R



LAYOUT A
ALTERNATIVE A2, SCENARIO A2-T



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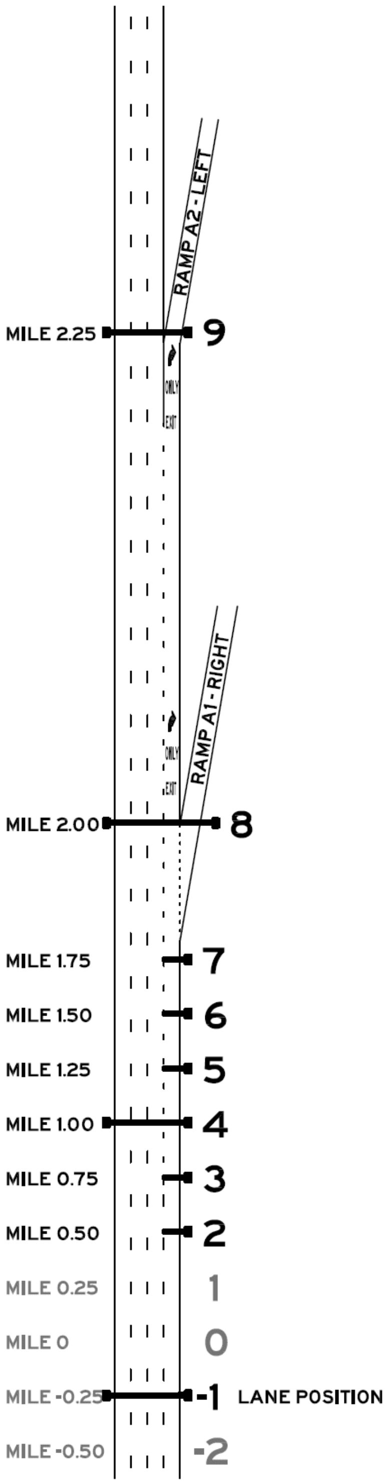
ALTERNATIVE A3, SCENARIO A3-L



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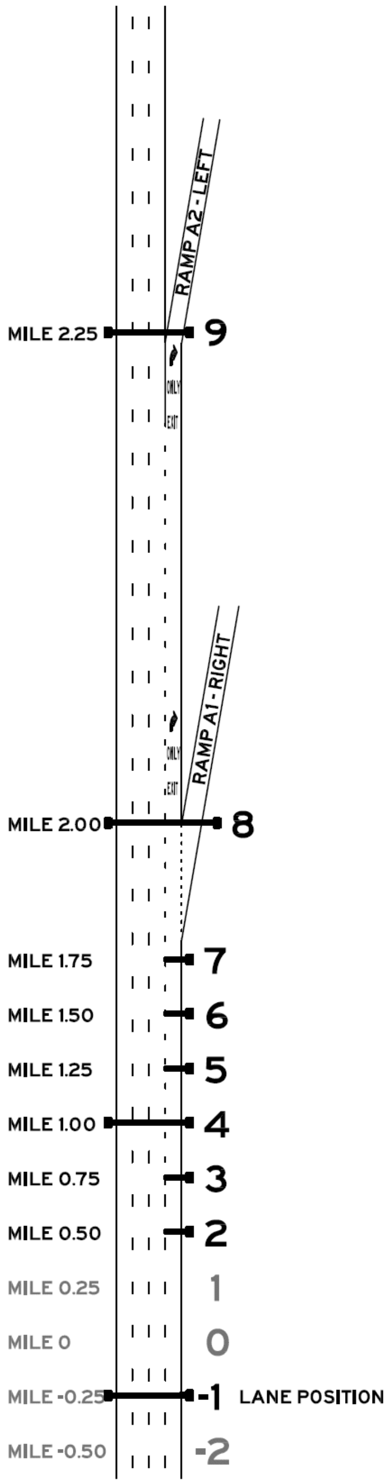
LAYOUT A
ALTERNATIVE A3, SCENARIO A3-R



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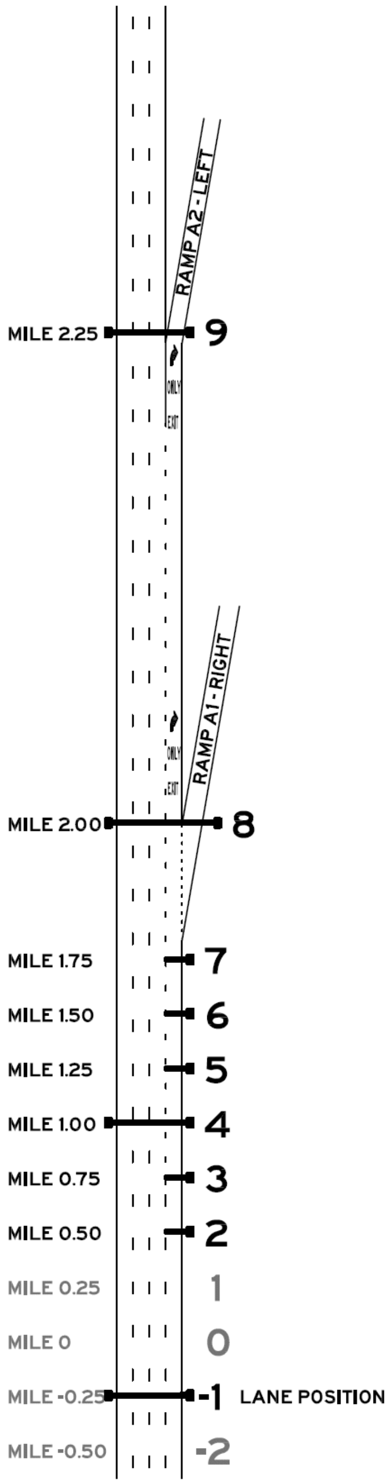
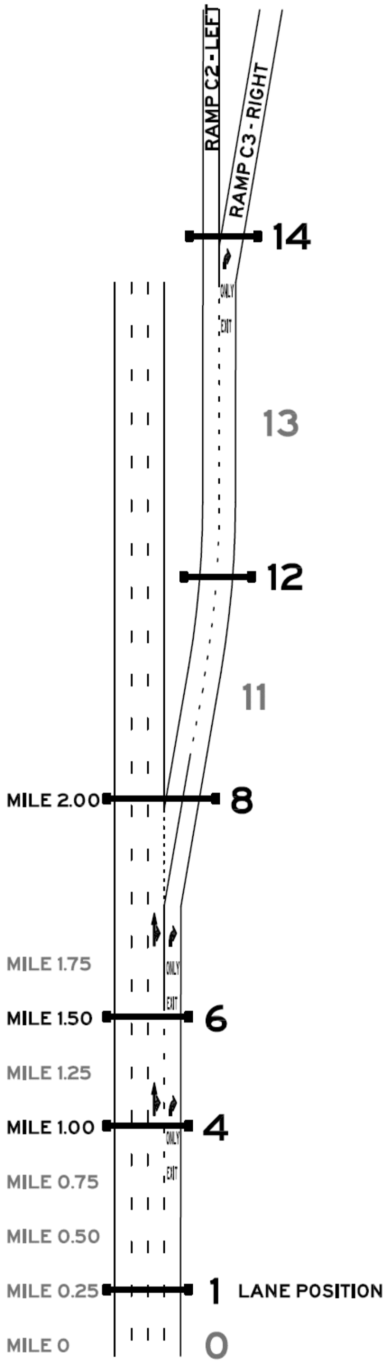
ALTERNATIVE A3, SCENARIO A3-T



SCENARIOS FOR

LAYOUT C

LAYOUT C
ALTERNATIVE C1, SCENARIO C1-L



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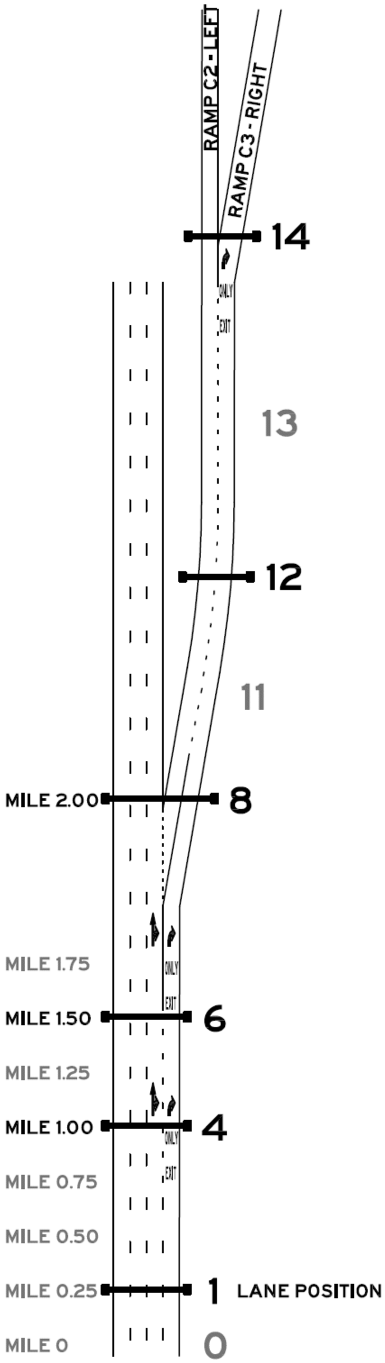
LAYOUT C
ALTERNATIVE C1, SCENARIO C1-R



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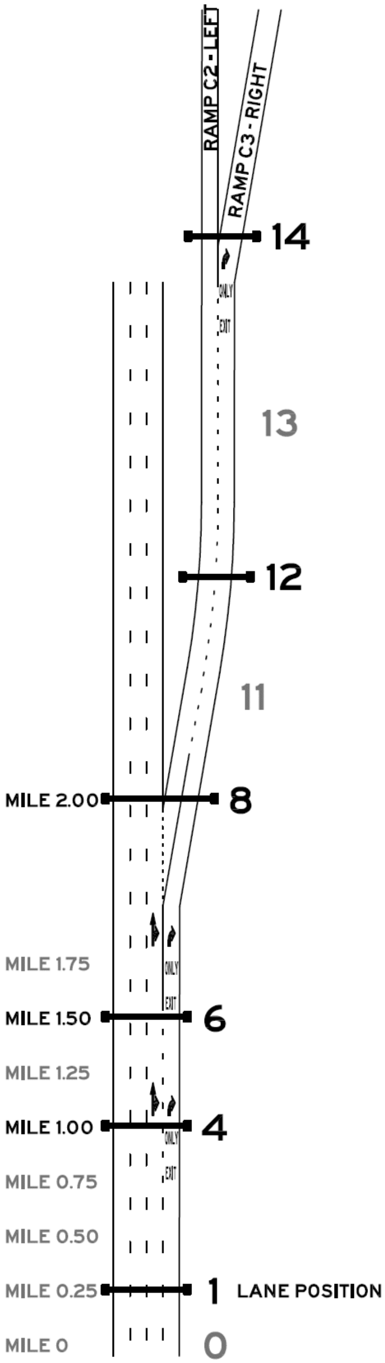

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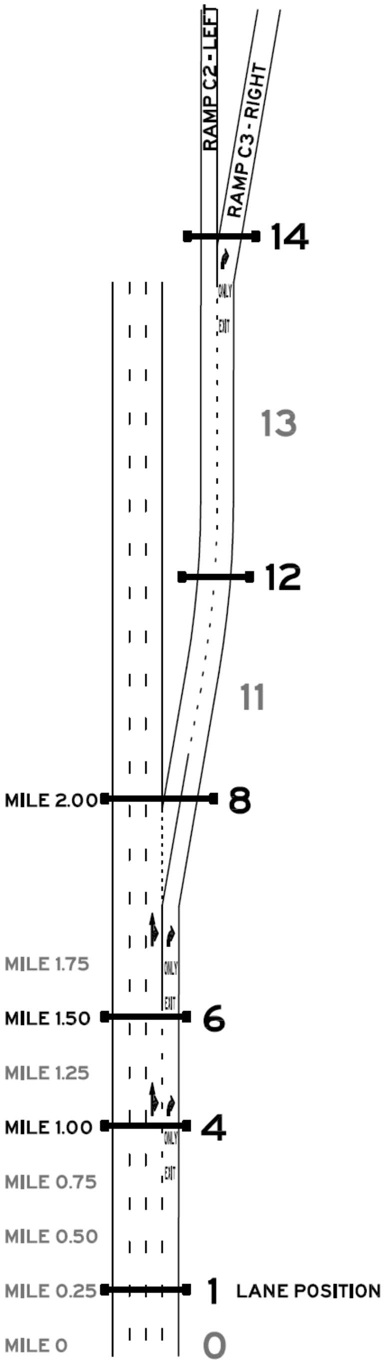

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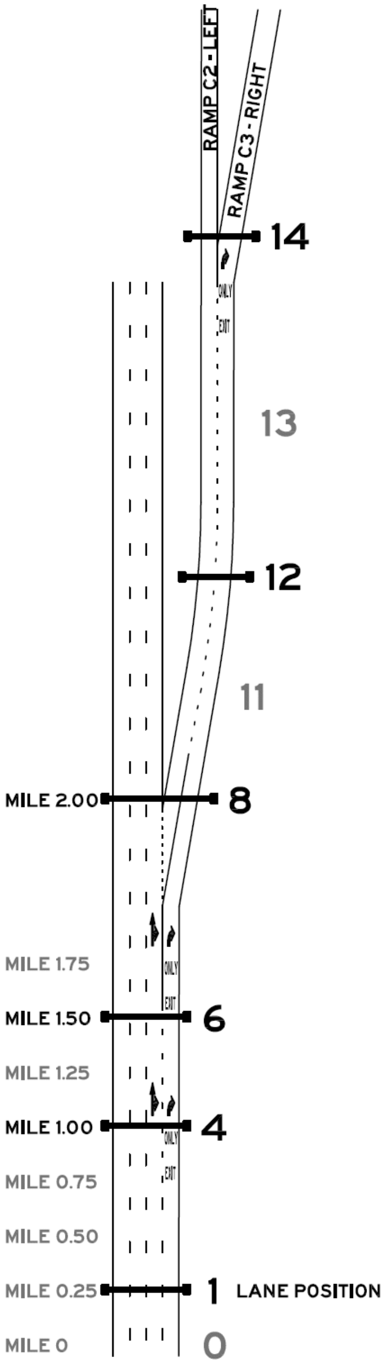

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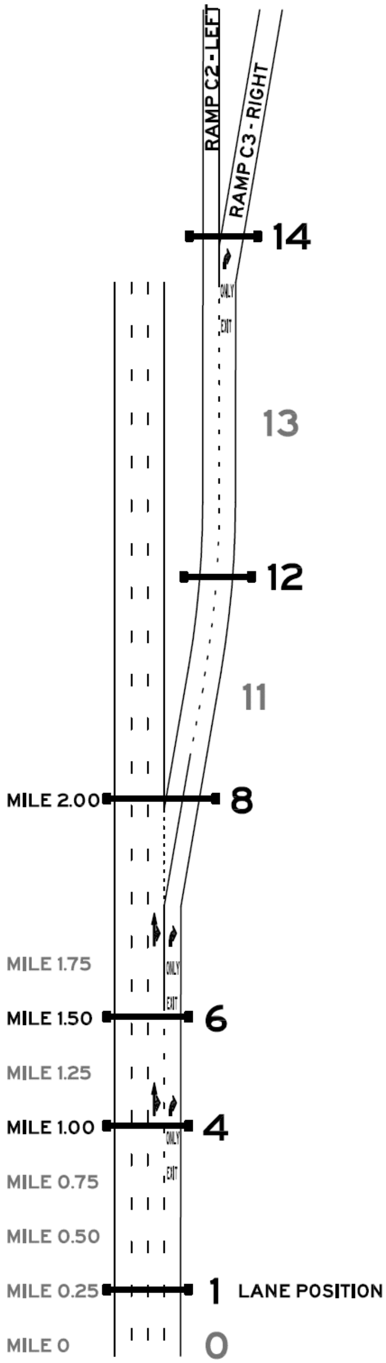

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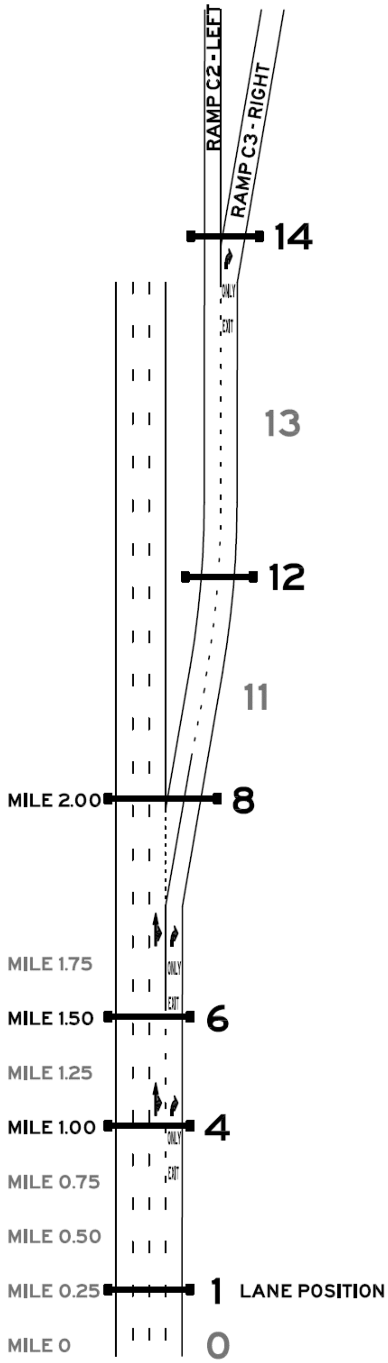
ALTERNATIVE C3, SCENARIO C3-L



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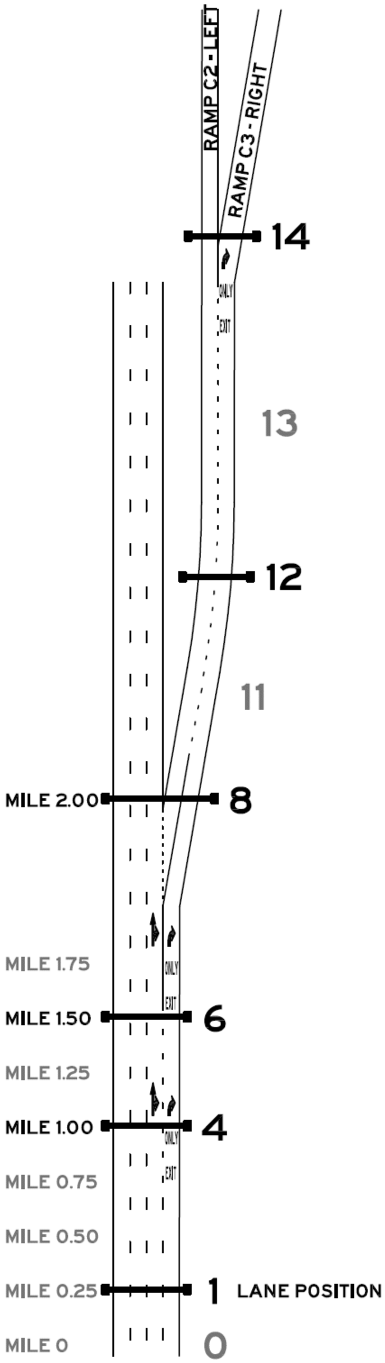

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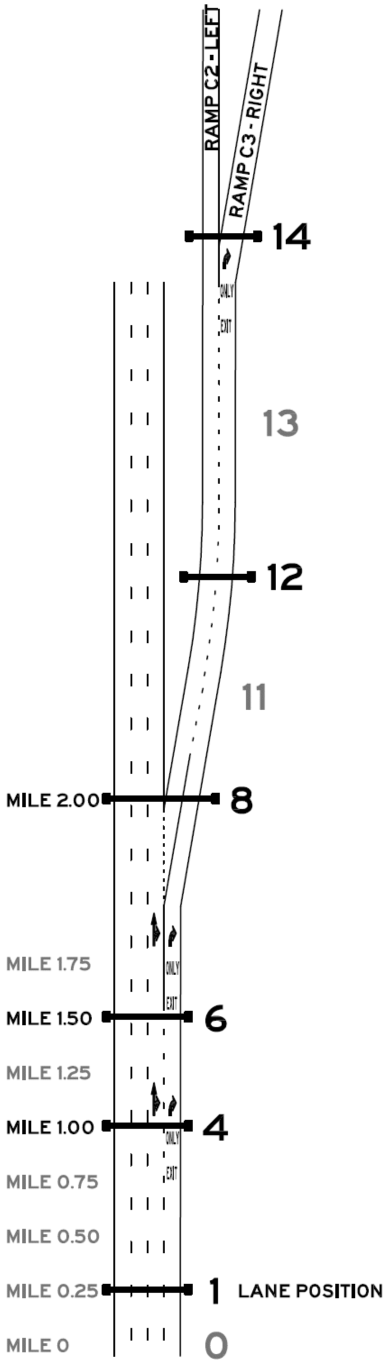

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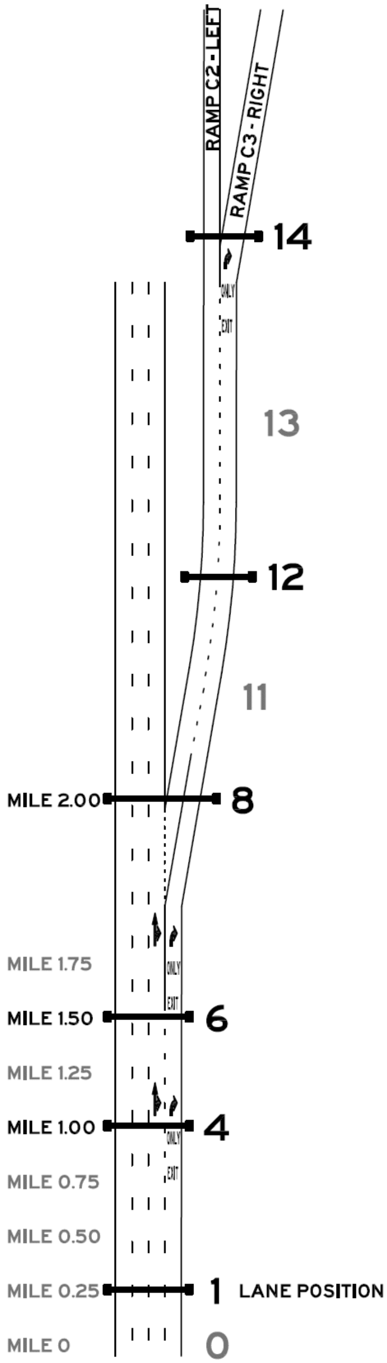
ALTERNATIVE C4, SCENARIO C4-L



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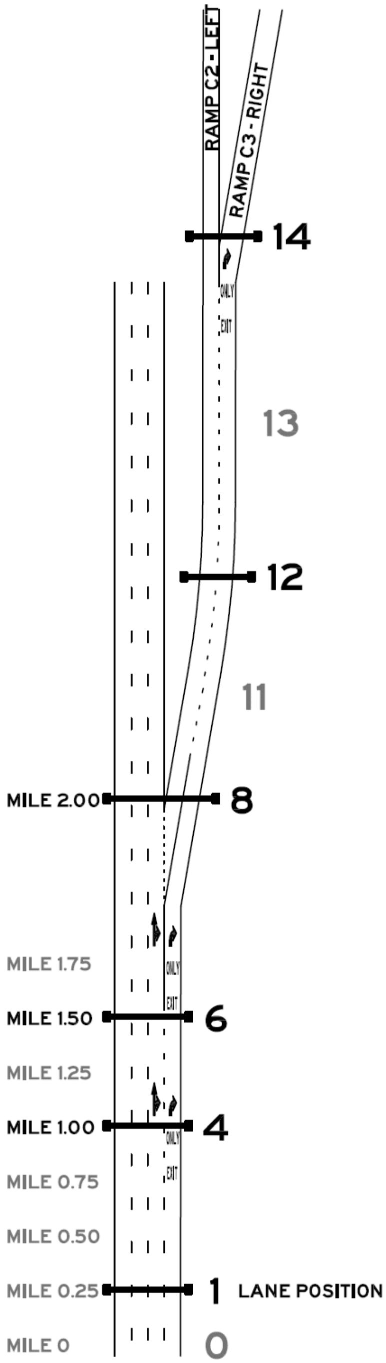
ALTERNATIVE C4, SCENARIO C4-R



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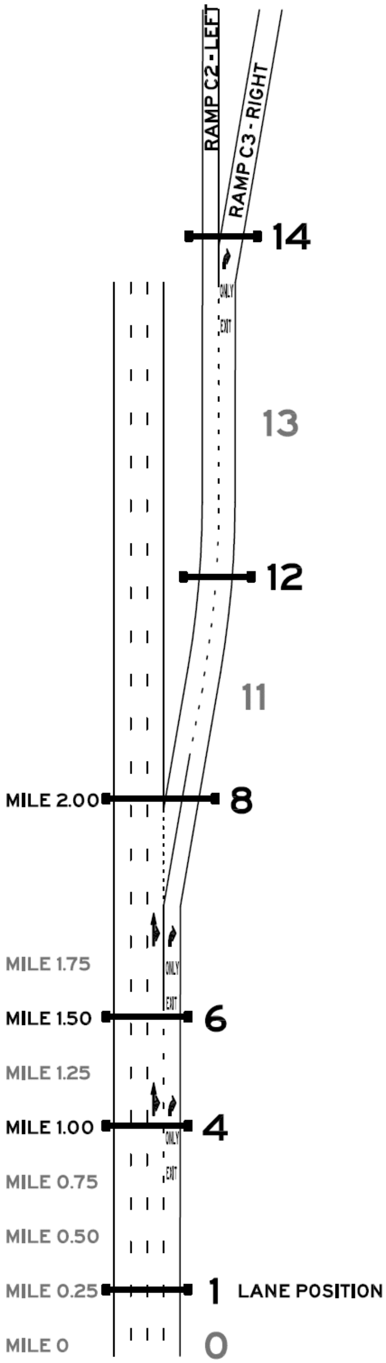

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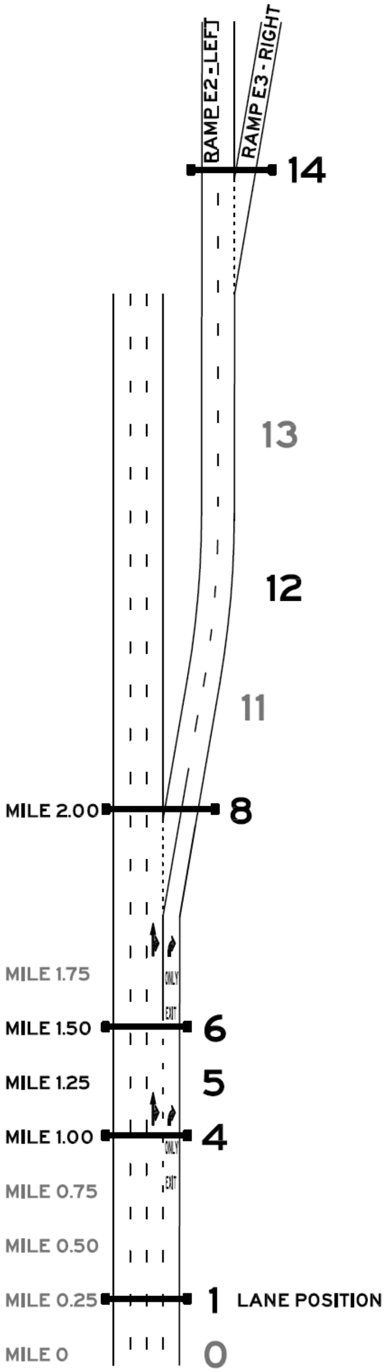
SCENARIOS FOR

LAYOUT E

LAYOUT E
ALTERNATIVE E1, SCENARIO E1-L



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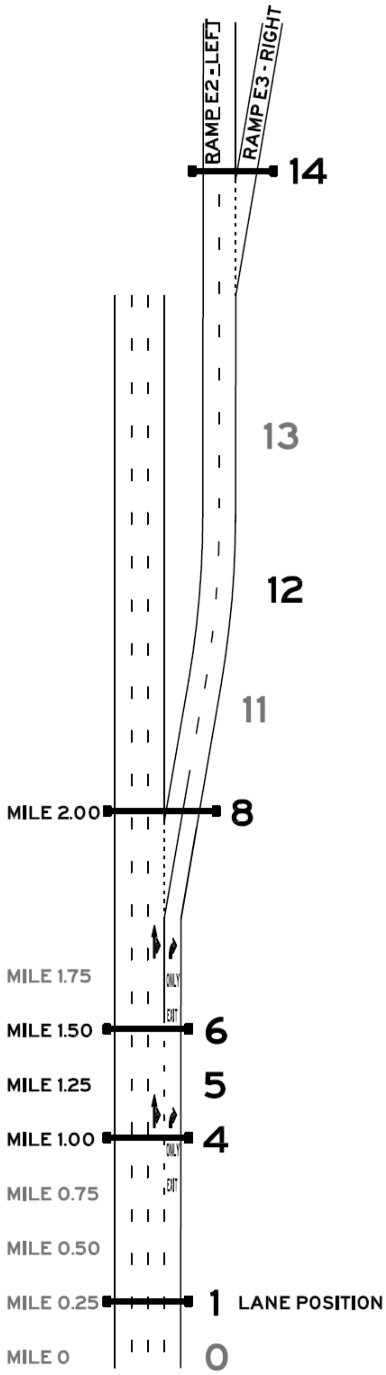

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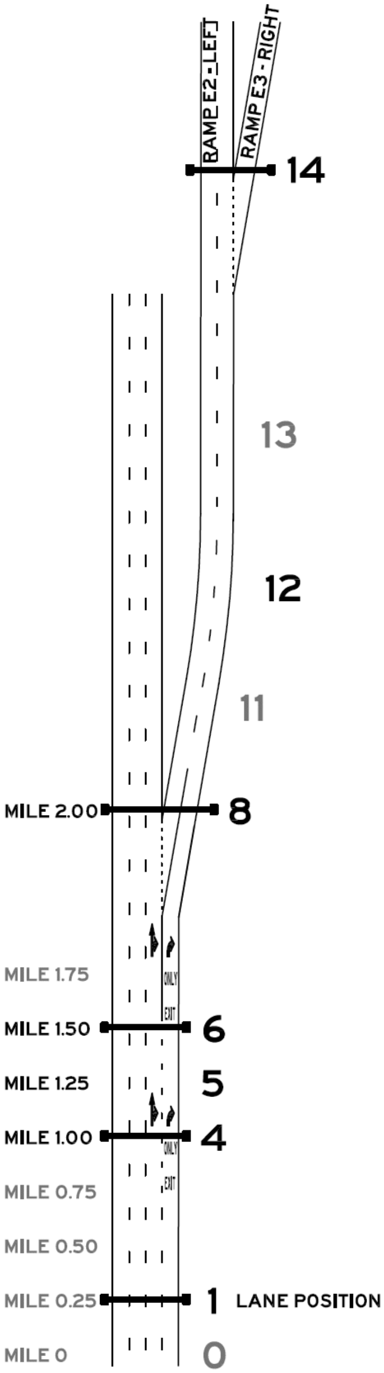
LAYOUT E
ALTERNATIVE E1, SCENARIO E1-T



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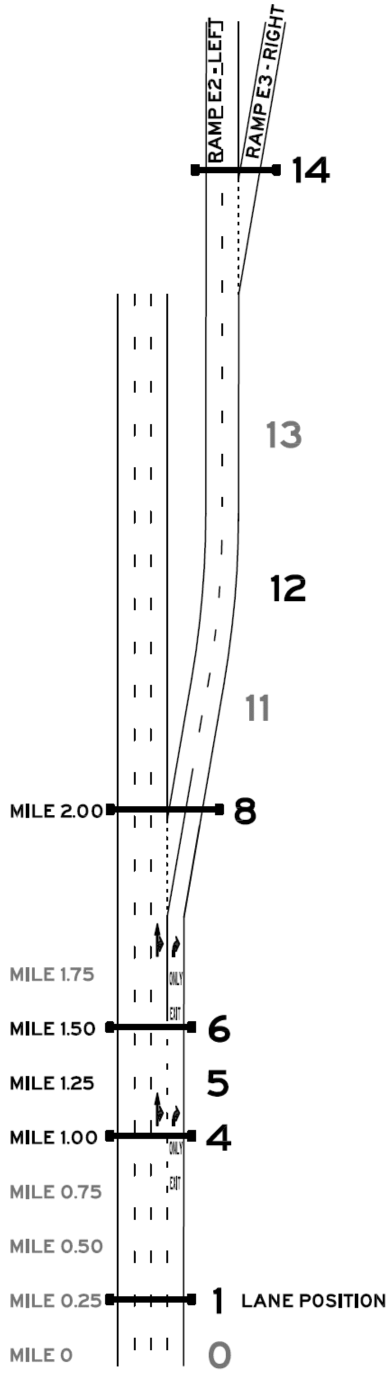

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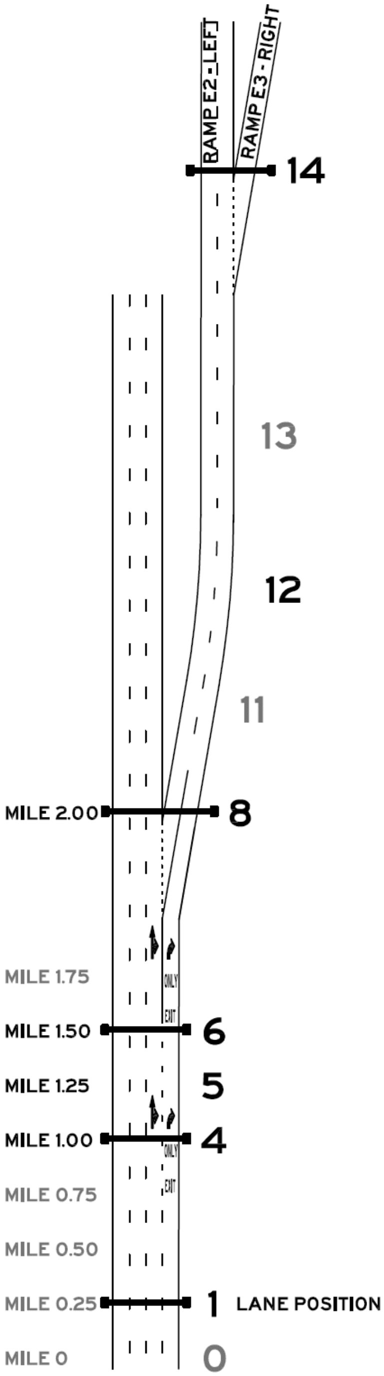
LAYOUT E
ALTERNATIVE E2, SCENARIO E2-R



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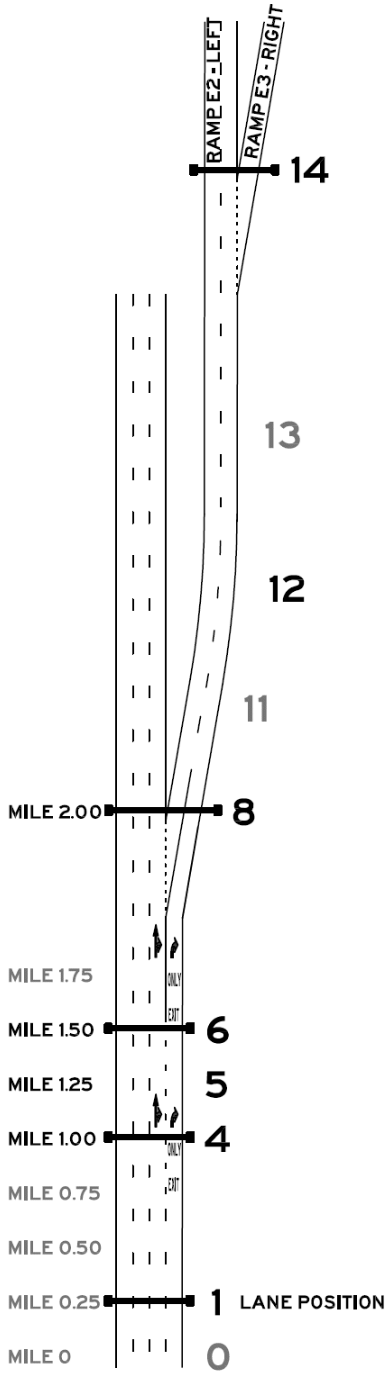

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LAYOUT E
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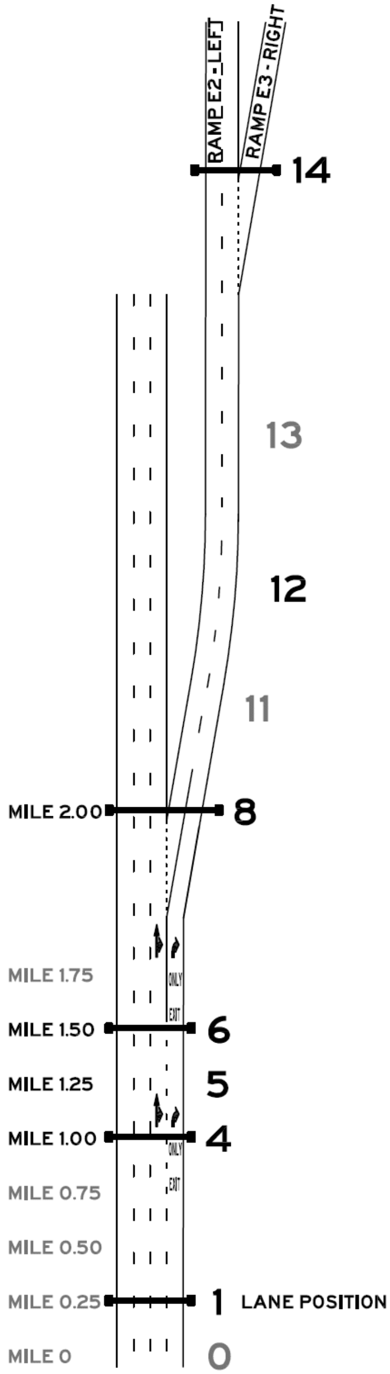

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LAYOUT E
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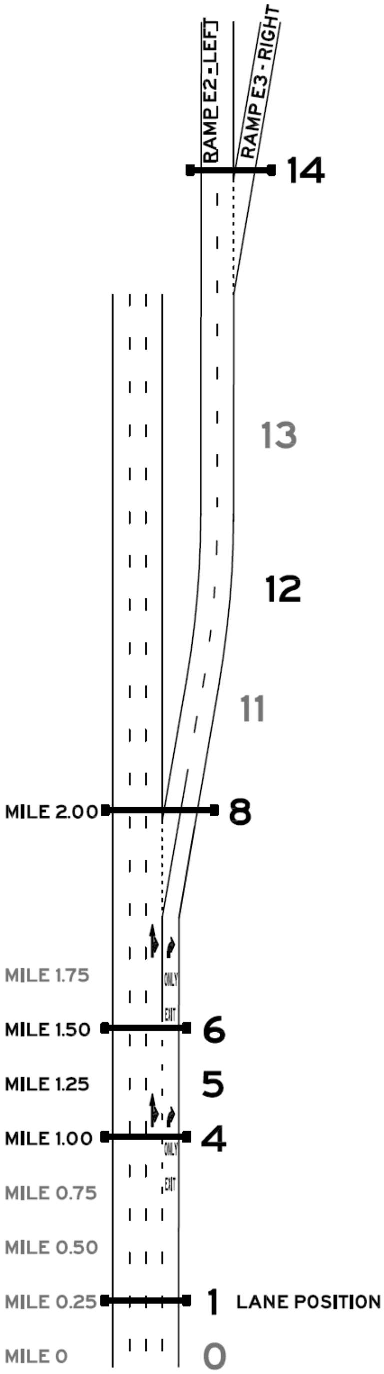
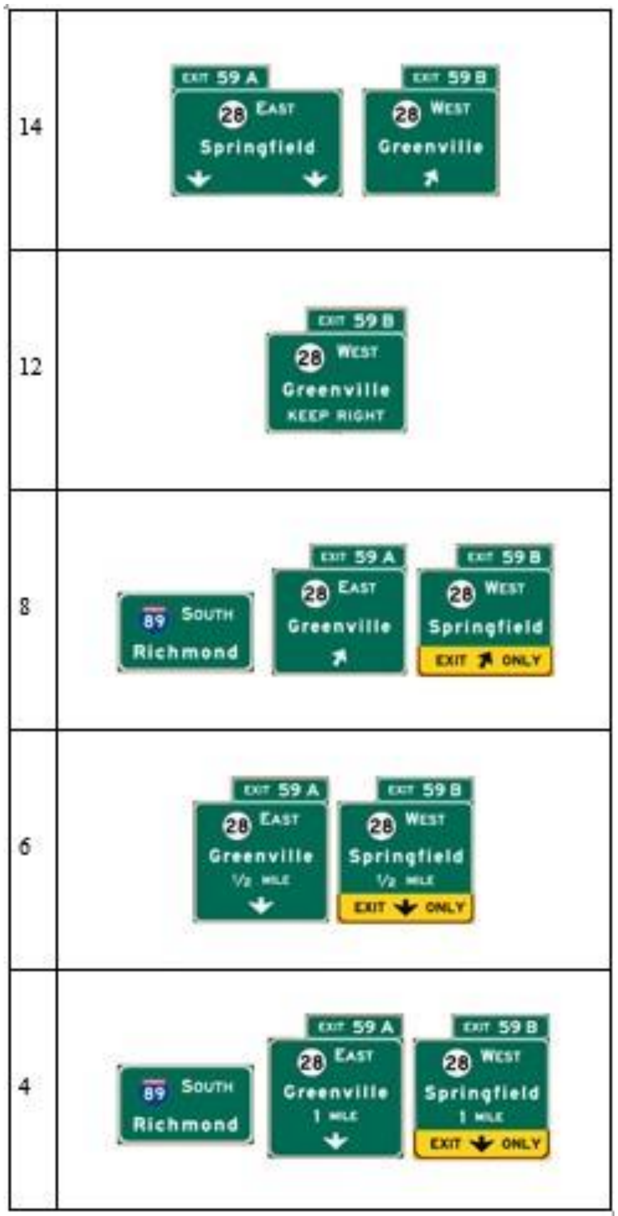
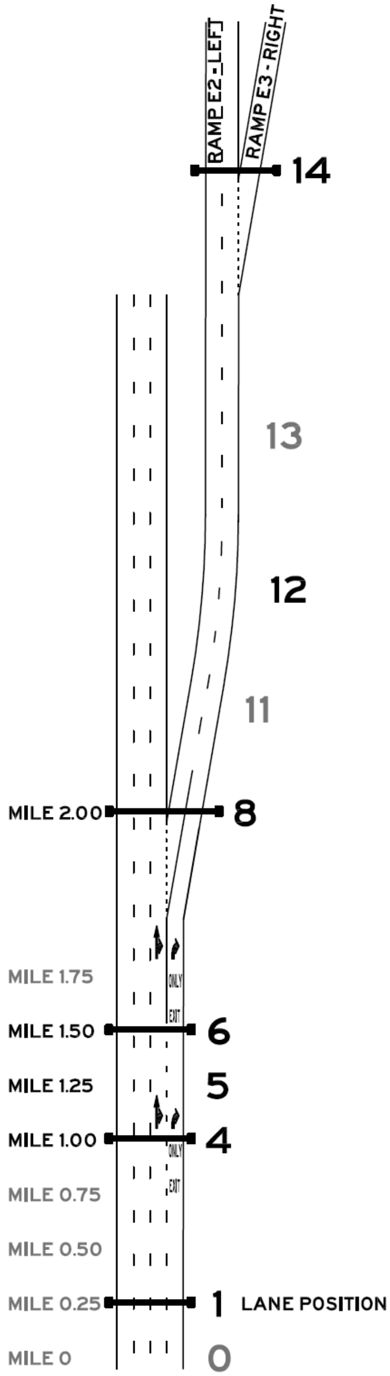




LAYOUT E
ALTERNATIVE E3, SCENARIO E3-T



14	
12	
8	
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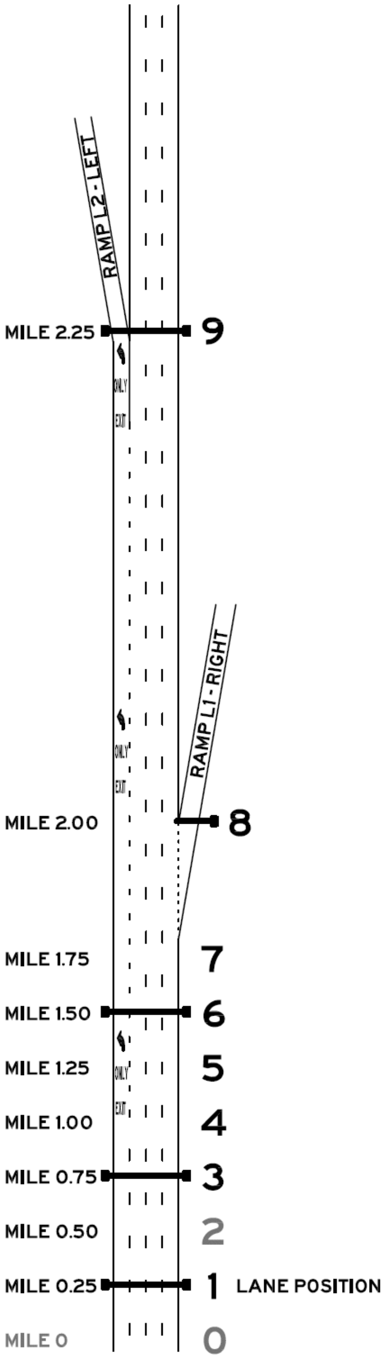
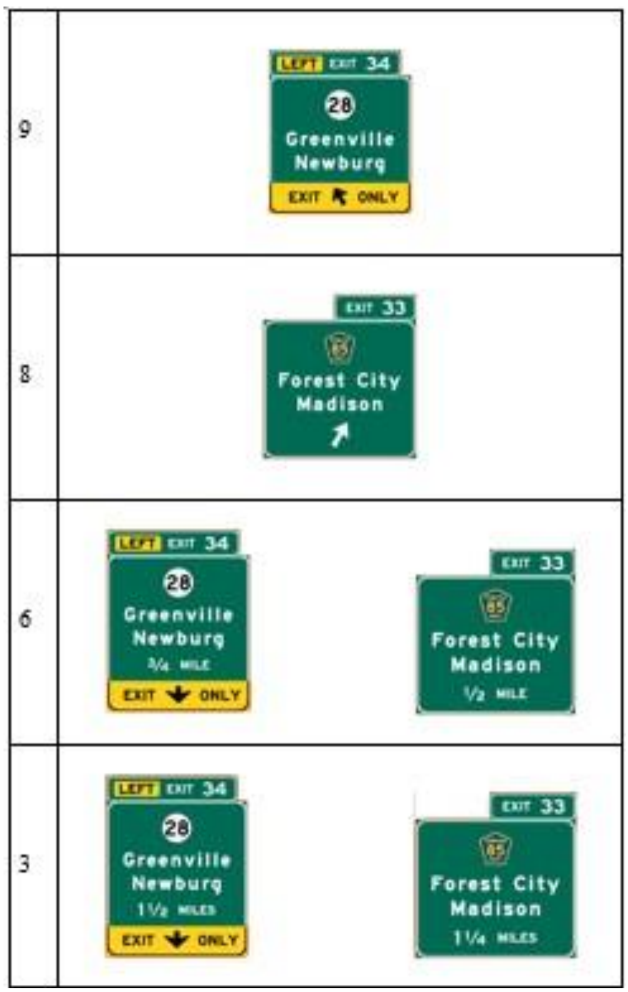
SCENARIOS FOR

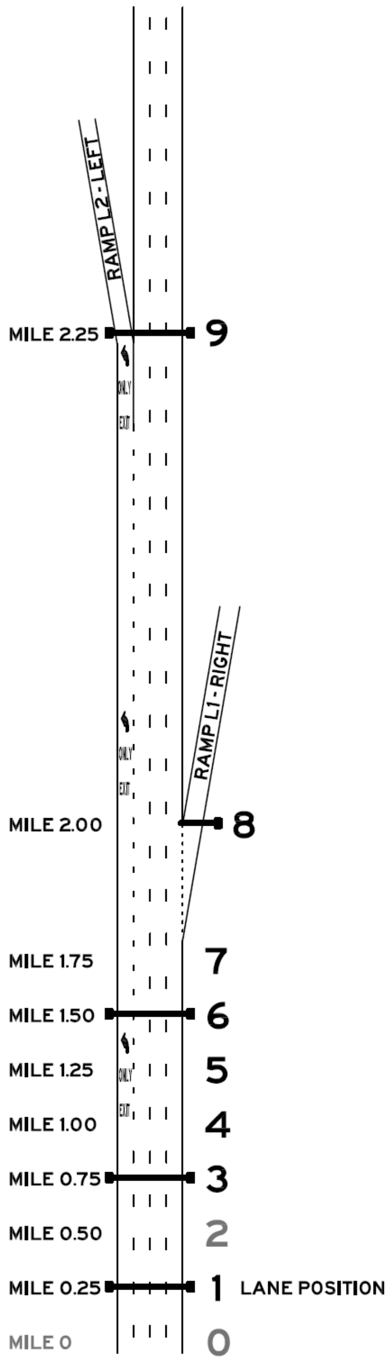
LAYOUT L

LAYOUT L
ALTERNATIVE L1, SCENARIO L1-L

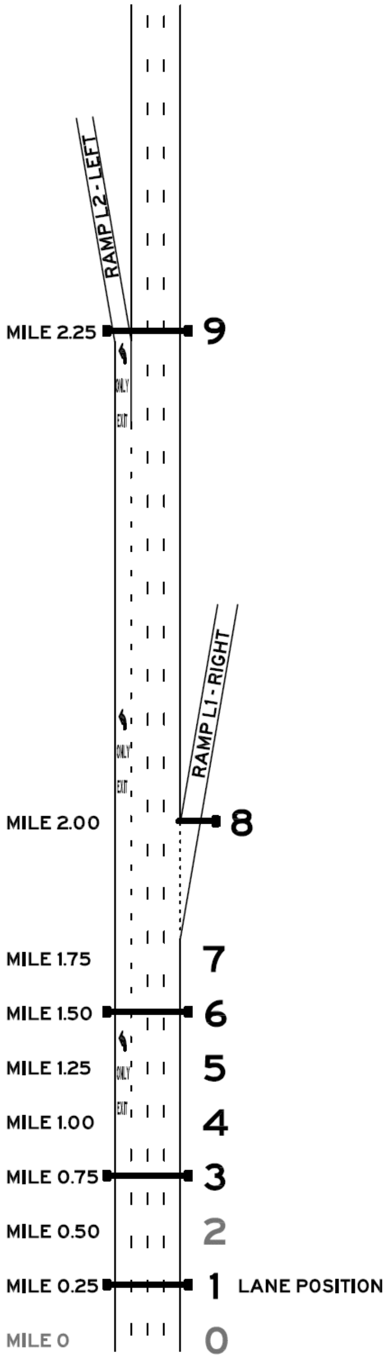




LAYOUT L
ALTERNATIVE L2, SCENARIO L2-L



LAYOUT L
ALTERNATIVE L2, SCENARIO L2-T



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APPENDIX C. INSTRUCTIONS TO PARTICIPANTS (SUPPLEMENT TO CHAPTER 6)

INSTRUCTIONS

Practice Drive

First, we'll do a brief practice drive, about 3-min long, so that you can get a feel for the simulator. During this drive, there won't be any roadway signs; I'll just ask you to do some accelerating and lane changing so that you get a feel for the simulator and how it handles.

The sign that you see here is what we call the "starting lane" sign. *(Experimenter to point to Starting Lane sign at beginning of practice drive, before participant begins driving).* This sign will be shown periodically throughout the two main drives. As you can see, the sign has an arrow above each lane, and an asterisk above one of the lanes. In the main drives, we'll ask that whenever you see one of these signs that you get into the lane with the asterisk above it. Once you are in that lane, you will proceed with the driving task, but I'll explain that in a bit more detail before those drives. *(Experimenter to show participants the Starting Lane sign in practice drive so they know what to look for in the main drives [i.e. so they are not seeing the sign for the first time in the main drive]).*

At first, driving in a simulator feels a little different than driving in your own car, but do your best to drive as you normally would on the real road. The steering wheel is a bit touchy; you don't need to move it much for the vehicle to react. Don't worry if it takes a while for you to get used to driving in the simulator, that's why we are doing this practice!

So, if you're ready, please go ahead and put the car into drive, and begin slowly accelerating to 65 mi/hr.

(Once the participant has accelerated to around 65 mi/hr AND is able to keep the vehicle steady in the lane, ask them to make a lane change. Have the participant make a few lane changes to the left and the right, and have them take the exit to the right. Once they have taken the exit, ask them to come to a gradual stop and place the car into park. At this point, if they really struggled to control the vehicle, start another practice drive. If you felt they had a good handle on it, then ask them if they would like to do another practice drive or if they would like to proceed to the main drives.)

Experimental Drives

Now that you are familiar with the simulator, you will do the first of the two main drives. Each will last about 20 min, with a break in between. Your task for both drives is to follow the signs to continue toward Greenville. So, Greenville will always be the destination that you want to drive toward. During this drive, please do your best to maintain the posted speed limit, drive as you normally would, and determine what to do to reach your destination most efficiently.

You will see the Starting Lane signs (that I showed you earlier) throughout each of the drives. Whenever you see one and can tell which lane the asterisk is over, please go ahead and get into that lane. Once you are in the appropriate Starting Lane, you can make any lane changes that you need to make to reach your destination. We would, however, like you to avoid making any unnecessary lane changes throughout the drives. In other words, only make the lane changes that you need to make to complete the task of driving toward Greenville. For example, if the Starting Lane is the left lane, and you don't typically drive in the left lane, don't make a lane change just to get into another lane out of habit. However, if you see something that makes you think that you need to change lanes to get to Greenville, go ahead and do that. In other words, try to make the fewest number of lane changes necessary to reach your destination.

Also, if we feel that you've done your best to follow these instructions, you'll earn an additional 10-dollar bonus.

Do you have any questions?

APPENDIX D. PARTICIPANT QUESTIONNAIRE (SUPPLEMENT TO CHAPTER 6)

PART 1 General Questions

1-1 How often do you drive on the freeway or toll roads?

- ○ Daily
- ○ Once a week or so
- ○ Once a month or so
- ○ Almost never

1-2 What do you find most challenging about driving on the freeway or toll roads?

- ○ Merging into traffic
- ○ Knowing just where the exit is
- ○ Lanes that can go straight or exit
- ○ Aggressive driving
- ○ People who block lanes and don't move over
- ○ Difficulty reading signs at night
- ○ HOV lanes and special toll lanes
- ○ ____

1-3 Characterize your style of driving on the freeway or toll road.

- ○ Cautious, I like to drive a bit slower
- ○ Cautious, generally driving with traffic
- ○ Confident, generally driving with traffic
- ○ Confident, generally exceeding the speed of other traffic

1-3 In your opinion, considering how you usually drive and irrespective of laws concerning the left lane, what is the purpose of the left lane on the freeway or toll road?

YOU MAY CHOOSE MORE THAN ONE ANSWER

- ○ I can drive in it at any time
- ○ I can use it to pass other people
- ○ I shouldn't have to move over, even if I'm going slower
- ○ If I'm doing the speed limit, I should move over to let faster traffic pass
- ○ If I'm doing faster than the speed limit, I don't need to move over to let faster traffic pass
- ○ I stay out of it unless I'm going to pass someone
- ○ When I'm in the left lane, I drive faster than the prevailing speed of traffic
- ○ Sometimes I use the left lane to avoid conflicts with people getting on the freeway and exiting the freeway

PART 2 Lane Reduction Signs

Look at the sign in the image below. This sign was used in the driving simulator study.

2-1 Did you notice this sign as you were driving the simulator today?

- ○ Yes
- ○ No

2-2 What does it mean?

- ○ The right lane is ending up ahead
- ○ The right lane is ending here
- ○ No lane is ending, but people should move over
- ○ The left lane is ending
- ○ ____

2-3 Where did you see it was placed?

- ○ A long distance ahead of where the lane ends, as the only sign
- ○ A long distance ahead of where the lane begins to end, as a second sign
- ○ Near the beginning of the taper, the point where the lane starts to get narrower before it goes away
- ○ Cannot recall

2-4 Which of the following signs could be replaced with the sign above?

DRAW A BOX AROUND YOUR CHOICE

A

B

3-1 Considering Sign A only, what happens to the left lane (the lane underneath the white arrow, not the lane underneath the black arrow) in ½ a mile?

- ○ It must exit to the right
- ○ It can exit to the right, but people in that lane can go straight to an unknown destination
- ○ It can exit to the right, but people in that lane can go straight into a dead-end road

3-2 Considering Sign B only, what happens to the left lane (the lane underneath the white arrow, not the lane underneath the black arrow) in ½ a mile?

- ○ It is a through lane
- ○ It is an exiting lane, but not an exit-only
- ○ It is an exit-only lane

3-3 Looking at the signs above, which one do you find most clearly indicates that the second lane from the right could be used for the next ½ mile by both exiting traffic and through traffic?

- ○ SIGN A
- ○ SIGN B

CONTINUED ON NEXT PAGE

A

C

3-4 Looking at the signs above, which one provides clearer direction to Route 28 and Greenville?

- ○ SIGN A
- ○ SIGN B

3-5 Considering Sign C only, could a driver in the lane underneath the left-hand side of the sign go straight to get to Route 28 and Greenville? Choose the answer that most closely agrees with your thinking.

- ○ Yes, by following the up arrow
- ○ Yes, both arrow heads point to Greenville
- ○ No, because the left arrow head doesn't point at anything
- ○ No, because only the right-hand lane exits
- ○ There is not enough information to determine this

3-6 Considering Sign A only, could a driver in the lane underneath the left-hand side of the sign go straight to get to Route 28 and Greenville? Choose the answer that most closely agrees with your thinking.

- ○ Yes, because there is a straight potion to the arrow
- ○ No, because the arrow head points up and to the right
- ○ No, because there is no arrow head on the straight-up portion of the left-hand arrow; it exists, but does not point to anything
- ○ No, because only the right lane exits

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