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16. Abstract

For decades, Texas Department of Transportation districts have constructed auxiliary lanes to support interchange ramp operations and to resolve congestion proximate to freeway entrance and exit ramps. While auxiliary lanes are built throughout Texas, the existing roadway design manuals/guidelines do not present all of the necessary design tools and details for design engineers. The objective of this research project was to develop implementation-oriented guidelines on the use of auxiliary lanes. To fulfill this goal, the researchers (1) reviewed and synthesized national and peer states' practices, (2) conducted a survey of traffic engineers, (3) analyzed operational benefits from adding auxiliary lanes at the segment level, (4) used micro-simulation to identify scope of impacts of auxiliary lanes at the corridor level, (5) analyzed safety impacts of adding auxiliary lanes, and (6) developed guidelines and recommended best practices.

The outcomes of this study provide important recommendations and numerical tools (e.g., the look-up tables) in implementing and designing freeway auxiliary lanes for new construction or rehabilitation projects. The developed methodologies and outcomes will complement the provisions in current state roadway design manuals/guidelines.

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DESIGN AND SCOPE OF IMPACT OF AUXILIARY LANES: TECHNICAL REPORT

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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration (FHWA) or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. The researcher in charge of this project was Dr. Yi Qi.

The United States Governments and the State of Texas do not endorse products or manufacturers. Trade or manufactures' names appear herein solely because they are considered essential to the object of this report.

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- Ms. Cynthia Landez, P.E., Design Division—Project Advisor.
- Ms. Cynthia Flores, Traffic Operations Division—Project Advisor.
- Mr. Kevin Dickey, Waco District—Project Advisor.
- Mr. Richard Harper, P.E., Paris District—Project Advisor.
- Ms. Sandra Kaderka, Research and Technology Implementation Office—Contract Specialist/Budget Coordinator.

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- Mr. Carlton Allen with Transtar.
- Mr. Joshua Philips with Transtar.
- Numerous TxDOT staff that participated in web surveys.
- Numerous state and city staff who participated in web surveys.

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SUMMARY

In freeway design, an auxiliary lane typically refers to either a supplemental lane that increases merging or diverging distance for an entrance or exit ramp to offset delays caused as traffic volumes increase or an added lane between entrance and exit-ramp pairs that provides an improved weaving environment for vehicles entering and departing the freeway facilities. For decades, Texas Department of Transportation (TxDOT) districts have constructed auxiliary lanes to support interchange ramp operations and to resolve congestion proximate to freeway entrance and exit ramps. While auxiliary lanes are built throughout Texas, the existing roadway design manuals/guidelines do not present all of the necessary tools and details for design engineers. In addition, design engineers need to better understand the corridor-level impacts of auxiliary lanes, such as how auxiliary lanes preserve through-movement on the primary travel lanes of the facility while simultaneously servicing access ramps that provide traffic ingress and egress.

In this study, researchers reviewed peer states' manuals and guidelines for designing freeway auxiliary lanes. Guidance used by different states in terms of the requirements for complying with lane balance principles, factors to be considered in designing auxiliary lanes, warrants, and geometric design (e.g., width/length of auxiliary lanes/shoulders) were synthesized and compared. In addition, the researchers thoroughly reviewed journal/proceeding articles and research reports with a focus on published works regarding operational and safety impacts of auxiliary lanes.

A survey of transportation professionals at state departments of transportation (DOTs) was conducted, both within Texas and nationally, about current practices and implementations related to designing auxiliary lanes. A web-based survey was conducted from November 9, 2011, to December 15, 2011. In all, 57 unique responses were received. Of those, 26 were from within Texas and 31 were from states other than Texas. A wide range of topics associated with designing auxiliary lanes was covered in the survey, providing necessary insights into the current practices related to this project.

The researchers carefully designed and performed two sets of micro-simulation studies, aimed at investigating impacts of adding auxiliary lanes at the segment level and corridor level.

The segment-level analyses showed that:

- Density, speed, and capacity are representative operational performance measures for freeway auxiliary lanes.
- Generally, adding an auxiliary lane at weaving segments or ramp influence areas can reduce traffic density by approximately 25 percent to 40 percent.
- For weaving segments, on average, operating speed can be increased slightly (less than 8 percent) by adding an auxiliary lane where a freeway has three mainline lanes. For entrance-ramp influence areas, adding a parallel acceleration lane does not have

significant impacts on the speed. For exit-ramp influence areas, adding a parallel auxiliary/deceleration lane can slightly increase the speed by approximately 5 percent.

- For weaving segments, capacity of the segments can be significantly enhanced by adding an auxiliary lane. Over 40 percent capacity enhancement can be expected when an auxiliary lane is added where a freeway has three mainline lanes. An additional ramp lane on either the entrance ramp or the exit ramp can further enhance the capacity of the weaving segments. For isolated ramp influence areas (entrance/exit), providing a parallel auxiliary lane does not have significant impacts on the capacity of the ramp influence area. This is generally consistent with the findings in the Highway Capacity Manual (HCM, 2010).

For the corridor-level analyses, it was found that:

- Where a freeway weaving section with auxiliary lanes is followed by an entrance ramp, if the traffic volume at the entrance ramp is low to moderate, extending the weaving auxiliary lane to the entrance ramp can lead to improved traffic operation at the weaving section. On the other hand, if the traffic volume at the entrance ramp is high, extending the auxiliary lane to the entrance ramp may result in increased congestion at the downstream entrance ramp. This is a result of more vehicles traveling on the rightmost auxiliary lane, which thereafter conflict with the vehicles merging from the entrance ramp. A case-by-case evaluation is preferable to determine where the auxiliary lane should be terminated to better preserve the mobility of the corridor.
- Where a weaving auxiliary lane is followed by an exit ramp, if the traffic volume at this exit ramp is high, it can be less operationally favorable to terminate the auxiliary lane at the exit ramp. Instead, further extending it and dropping it at some point beyond the exit ramp represents a more operationally effective option.
- A double-lane exit ramp provides an easier and direct exit for diverging vehicles and usually reduces the number of lane changes required for vehicles to exit the freeway. Thus, where operational problems are caused by high exit ramp demand, a double-lane exit may be a solution to increase the ramp capacity and reduce the number of lane changes mandated for the diverging vehicles.

In addition, the researchers investigated the safety impacts of adding auxiliary lanes by analyzing the traffic conflicts derived from the traffic simulation studies. The results showed that:

- Adding auxiliary lanes can significantly reduce the frequency of traffic conflicts for both freeway weaving segments and ramp influence areas.
- Among three typical weaving segments with auxiliary lanes, Type A design (one-lane entrance and one-lane exit) generally presented the best safety performance, followed by Type B design (one-lane entrance and two-lane exit). Type C (two-lane entrance and one-

lane exit) was associated with the highest crash frequency among those three types of weaving auxiliary lane settings.

Based on the major findings of the study, guidelines were developed regarding the conditions under which freeway auxiliary lanes should be considered and the methods for assessing their impacts. A set of look-up tables was developed to assess the operational and safety impacts of freeway auxiliary lanes under various geometric conditions (e.g., length of auxiliary lanes, number of ramp lanes, and connectivity of lanes) and traffic conditions (e.g., traffic volume on freeway mainlines and traffic volume on ramps). These tables can be used to preliminarily project changes in density, speed, capacity, and traffic conflict frequency in a freeway section after installing auxiliary lanes. The tables can allow users to perform a preliminary analysis without having to use the complicated HCM procedures or traffic simulation.

Finally, the following guidelines regarding the geometric design of auxiliary lanes were also provided:

- General principles for lane arrangement where auxiliary lanes are used.
- Length of parallel acceleration/deceleration auxiliary lanes at merge/diverge area.
- Design of auxiliary lanes at two-lane ramps.
- Width of auxiliary lanes and shoulders.

The findings from this research along with the developed guidelines can be used in implementing and designing freeway auxiliary lanes for new construction or retrofit projects. The developed methodologies and outcomes will complement the provisions in current state roadway design manuals/guidelines.

CHAPTER 1: INTRODUCTION

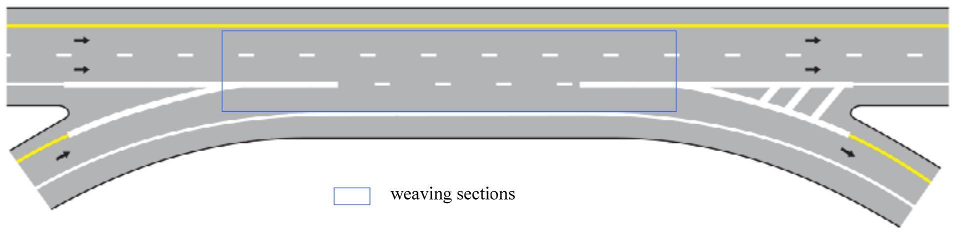
1.1 BACKGROUND

The publication *A Policy on Geometric Design of Highways and Streets* (also known as the American Association of State Highway and Transportation Officials [AASHTO] Green Book, 2004) defines an auxiliary lane as the portion of the roadway adjoining the traveled way for speed change, turning, turning storage, weaving, truck climbing, and other purposes supplementary to through-traffic movement. In freeway design, an auxiliary lane typically refers to the supplemental lanes that either increase merging or diverging distance for an entrance or exit ramp, usually to offset delays caused as traffic volumes increase, or added lanes between entrance- and exit-ramp pairs that provide an improved weaving environment (rather than a forced or direct merge or diverge) for vehicles entering and departing the freeway facility.

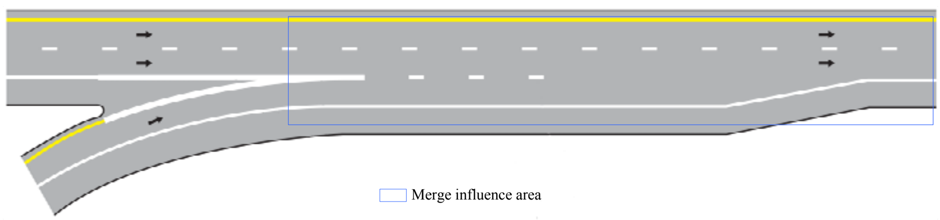
For decades, TxDOT districts have constructed auxiliary lanes to support interchange ramp operations and to resolve congestion proximate to freeway entrance and exit ramps. While auxiliary lanes are built throughout Texas, the TxDOT Roadway Design Manual (2009) does not present all of the necessary design tools and details for design engineers. In addition, design engineers need to better understand the corridor-level impacts of auxiliary lanes, such as how auxiliary lanes preserve through-movement on the primary travel lanes of the facility while simultaneously servicing access ramps that provide traffic ingress and egress. Therefore, it is necessary that broader understanding be gained regarding the design and impacts of auxiliary lanes, and their role in access-controlled facility functions and operations.

Auxiliary lanes are the added lanes that are commonly provided:

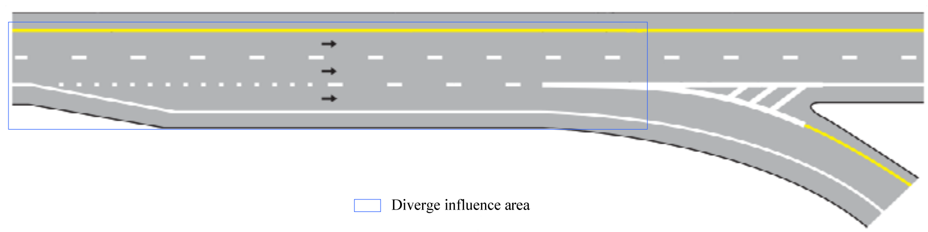
- At weaving segments between paired entrance and exit ramps as a “continuous auxiliary lane” (see Figure 1-1[a]).
- At isolated merge influence areas as a “parallel acceleration lane” (see Figure 1-1[b]).
- At isolated diverge influence areas as a “parallel deceleration lane” (see Figure 1-1[c]).



(a) Continuous auxiliary lane at paired entrance and exit ramps



(b) Auxiliary lane as parallel acceleration lane



(c) Auxiliary lane as parallel deceleration lane

Figure 1-1. Continuous Auxiliary Lane and Isolated Ramp Auxiliary Lane.

(Source: Texas Manual of Uniform Traffic Control Devices [MUTCD], 2006)

The lengths of weaving segments and merge and diverge influence areas are generally defined based on theoretical gores, as presented in Figure 1-1. The merge and diverge influence areas are normally defined at a length of 1,500 ft (450 m) in the HCM (2000, 2010).

1.2 RESEARCH GOALS AND OBJECTIVES

The goal of this project was to develop guidelines for the design of freeway auxiliary lanes and to provide methods for assessing the impacts of such design solutions. To this end, the research had the following specific objectives:

- Define the conditions under which auxiliary lanes shall be used in design and rehabilitation projects.
- Analyze the operational and safety impacts of auxiliary lanes at both the segment level and corridor level.
- Suggest performance measures that can effectively characterize the broad scope impacts of auxiliary lanes.
- Recommend best practices for the design and use of auxiliary lanes.
- Develop implementation-oriented guidelines on the design and use of auxiliary lanes.

1.3 OUTLINE OF THIS REPORT

This report covers all the tasks conducted during the span of the research project. In Chapter 2, existing literature and national/state guidelines are reviewed and synthesized. In Chapter 3, a survey of traffic engineers is presented, and the survey responses are analyzed to identify the current practices. In Chapter 4, simulation studies that investigate the impacts of various types of auxiliary lanes are presented. Operational benefits from adding auxiliary lanes at the segment level are estimated. In Chapter 5, simulation studies that identify the scope of impacts of auxiliary lanes at the corridor level are presented. VISSIM simulation results are presented to show the effects of auxiliary lanes on the freeway operations at a corridor level. In Chapter 6, findings on safety impacts of auxiliary lanes are presented. In Chapter 7, the developed guidelines for auxiliary lanes are discussed, followed by Chapter 8 summarizing the key findings and recommendations based on the outcomes of this research.

1.4 REFERENCES

A Policy on Geometric Design of Highways and Streets. American Association of State Highway and Transportation Officials. Washington, D.C., 2004.

Highway Capacity Manual. TRB, National Research Council, Washington, D.C., 2000.

Highway Capacity Manual. TRB, National Research Council, Washington, D.C., 2010.

Roadway Design Manual. Texas Department of Transportation, 2009.

Texas Manual of Uniform Traffic Control Devices, Part 3: Markings. Texas Department of Transportation, Austin, TX, 2006.

CHAPTER 2: LITERATURE REVIEW

This chapter is organized as follows. First, peer state DOTs' design standards were reviewed to develop a context on related practices. The existing research regarding safety impacts of auxiliary lanes was reviewed and summarized. Then, studies on merge, diverge, weaving behavior, and ramp design were reviewed to provide a basis for the modeling efforts in this project. The researchers also explored the available studies on operational impacts of auxiliary lanes. Finally, methods that can be used for assessing ramp influence and weaving areas were summarized and compared.

2.1 METHOD FOR LITERATURE REVIEW

The literature review focused primarily on related practice and research. It began with a search for any resources that had the potential for further review. An online search was conducted using traffic resource websites and search engines to gather available electronic resources. This was followed by searching DOT design standards available at DOT online libraries and by exploring existing resources at the Texas Southern University (TSU) library. Relevant publications, reports, presentations, and manuals were located by various search methods including, but not limited to, the following sources of information:

- TxDOT and peer DOT online libraries.
- EBSCO Scholarly Content Host (with books and full-text journals available through TSU).
- MetaPress Scholarly Content Host (with books and full-text journals available through TSU).
- Online Transportation Research Information Service (TRIS).
- Research and Innovative Technology Administration (RITA) National Transportation Library.
- Google Scholar search engine.

2.2 GUIDELINES IN AASHTO GREEN BOOK AND TEXAS

2.2.1 Guidelines in the AASHTO Green Book

A Policy on Geometric Design of Highways and Streets (AASHTO Green Book, 2004) is a guidebook that contains the latest design practices in universal use as the standard for highway geometric design and has been updated to reflect the latest research. Many state DOTs' design manuals follow the standards and provisions in the AASHTO Green Book. This section summarizes the guidelines associated with the design and use of freeway auxiliary lanes as detailed in the AASHTO Green Book.

To determine the number and arrangement of lanes on freeway mainlines and ramps, two principles are being used by transportation professionals in practice. They are (1) consistency of basic number of lanes, and (2) principles of lane balance.

2.2.1.1 Consistency of Basic Number of Lanes

Basic number of lanes is the minimum number of traffic lanes designated and maintained over a significant length of a freeway. The basic number of lanes is often determined based on the traffic demand on freeway mainlines. The basic number of lanes should be consistent for a substantial length of freeway, irrespective of changes in traffic volume and lane balance needs.

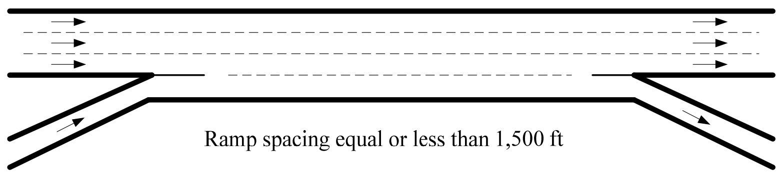
2.2.1.2 Principles of Lane Balance

To realize efficient traffic operation through and beyond an interchange, the AASHTO Green Book recommends that there be a balance in the number of lanes on the freeway and ramps. Based on the lane balance principles, the number of lanes beyond the merging point of the entrance should not be less than the sum of traffic lanes on the merging roadways. At the exit, the number of lanes on the freeway should be equal to the number of lanes beyond the exit plus the number of lanes on the exit minus one.

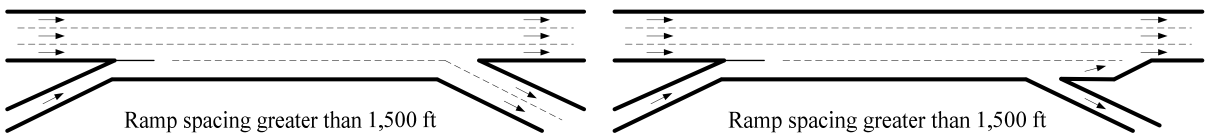
For auxiliary lanes between two successive interchanges, two conditions are possible:

- Condition 1: For auxiliary lanes less than 1,500 ft in length (e.g., between closely spaced interchanges or between the loop ramp entrance and the loop ramp exit of a cloverleaf interchange), lane balance principles permit the termination of the auxiliary lane with a one-lane exit ramp as shown in Figure 2-1(a).
- Condition 2: For auxiliary lanes greater than 1,500 ft in length, lane balance principles state that the number of approach lanes on the freeway must be equal to the number of lanes on the freeway beyond the exit plus the number of lanes on the exit, minus one, as shown in Figures 2-1(b) and 2-1(c).

Under Condition 2, the auxiliary lane may be terminated by one of two methods. The first method, shown in Figure 2-1(b), drops the auxiliary lane with a two-lane exit. In this configuration, traffic in the auxiliary lane must exit. Traffic in the basic lane to the left of the auxiliary lane may exit or may proceed along the mainline. The second method, shown in Figure 2-1(c), provides a one-lane exit ramp but carries the auxiliary lane through the exit before it is tapered into the through roadway. This design provides a recovery lane for drivers who inadvertently remain in the discontinued lane.



(a) Auxiliary lane terminated with one-lane exit ramp



(b) Auxiliary lane terminated with two-lane exit ramp (c) Auxiliary lane terminated with downstream taper

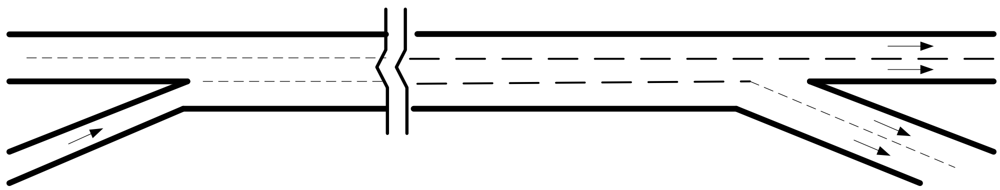
Figure 2-1. Illustration for Lane Balance Principles.

(Source: AASHTO Green Book, 2011)

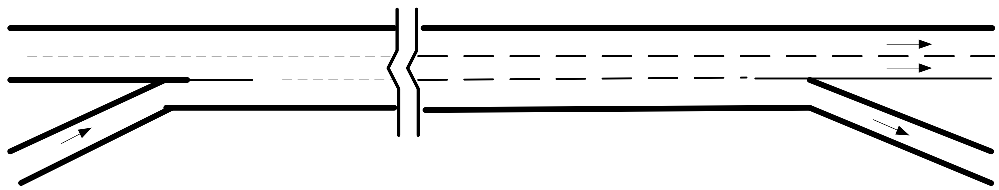
The lane balance principles have been used extensively to help designers determine the number of lanes on freeway entrance and exit ramps.

2.2.1.3 Alternative Methods to Drop Auxiliary Lanes

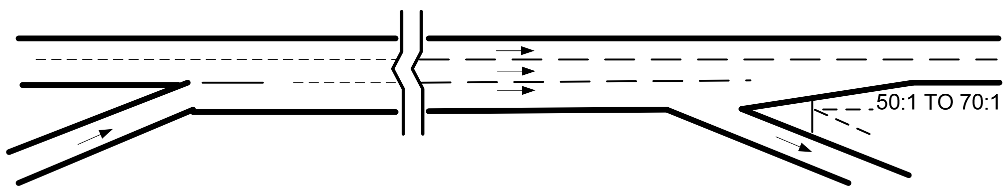
Auxiliary lanes are normally used to balance the traffic load and maintain a uniform level of service on the highway. They help drivers get positioned correctly when the drivers are diverging at exits and merging at entrances. Thus, the concept is very much related to signing and route continuity. Careful consideration should be given to the design treatment of an auxiliary lane because it may have the potential for trapping a driver at its termination point or the point where it is continued onto a ramp or turning roadway. Figure 2-2 shows some alternative methods to drop auxiliary lanes.



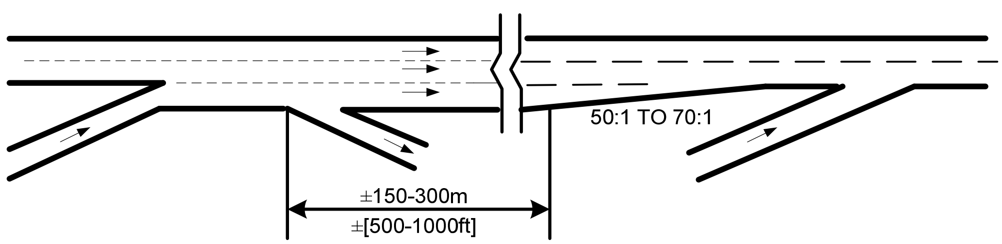
(a) Auxiliary lane dropped on exit ramp



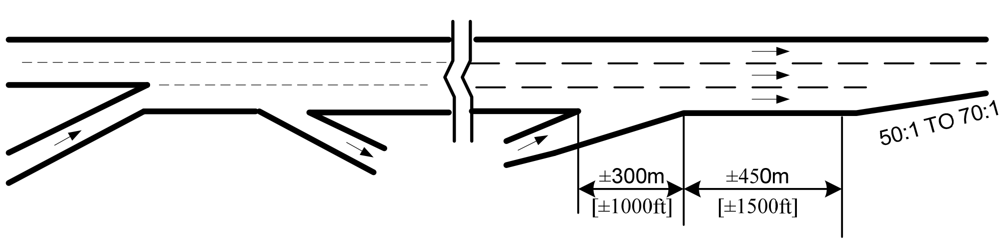
(b) Auxiliary lane between cloverleaf loops or closely spaced interchanges dropped on single exit lane



(c) Auxiliary lane dropped at physical nose



(d) Auxiliary lane dropped within an interchange



(e) Auxiliary lane dropped beyond an interchange

Figure 2-2. Alternative Methods to Drop Auxiliary Lanes.

(Source: AASHTO Green Book, 2004)

2.2.1.4 Quantitative Suggestions

If local experience with single-exit design indicates problems with turbulence in the traffic flow caused by vehicles attempting to recover and proceed on the through lanes, the recovery lane should be extended 500 to 1,000 ft (150 to 300 m) before being tapered into the through lanes. Within large interchanges, this distance should be increased to 1,500 ft (450 m). When an auxiliary lane is carried through one or more interchanges, it may be dropped as indicated above, or it may be merged into the through roadway approximately 2,500 ft (750 m) beyond the influence of the last interchange.

2.2.1.5 Qualitative Suggestions

Operational efficiency may be improved by using a continuous auxiliary lane between the entrance and exit terminals where (1) interchanges are closed spaced, (2) the distance between the end of the taper on the entrance terminal taper and the beginning of the taper on the exit terminal taper is short, and/or (3) local frontage roads do not exist.

An auxiliary lane may be introduced as a single exclusive lane or in conjunction with a two-lane entrance. The termination of the auxiliary lane may be accomplished by several methods. The auxiliary lane may be dropped in a two-lane exit, as illustrated in Figure 2-2(b).

When interchanges are widely spaced, it might not be practical or necessary to extend the auxiliary lane from one interchange to the next. In such cases, the auxiliary lane originating at a two-lane entrance should be carried along the freeway for an effective distance beyond the merging point. An auxiliary lane introduced for a two-lane exit should be carried along the freeway for an effective distance in advance of the exit and extended onto the ramp.

Generally, parallel designs are preferred. While tapered designs are acceptable, some agencies are concerned about the inside merge on the tapered entrance ramps. It is not precisely known what the effective length of the introduced auxiliary lane should be under these circumstances. Experience indicates that minimum distances of about 2,500 ft (750 m) produce the desired operational effects and enable development of the full capacity of two-lane entrances and exits.

2.2.1.6 Shoulder and Lane Width

Where auxiliary lanes are provided along freeway main lanes, the adjacent shoulder should desirably be 8 ft-12 ft (2.4 to 3.6 m) in width, with a minimum 6 ft (1.8 m) wide shoulder considered.

2.2.2 Available Design Guidelines in Texas

The TxDOT Roadway Design Manual, Freeway Signing Handbook, and Texas MUTCD basically represent the available official guidelines on the use of auxiliary lanes for Texas practitioners.

2.2.2.1 TxDOT Roadway Design Manual (2009)

In the TxDOT Roadway Design Manual, provisions regarding auxiliary lanes include:

- The minimum acceptable distance between ramps with/without an auxiliary lane (Section 2.6.1).
- Length of taper and parallel acceleration/deceleration lanes at merge/diverge areas (Guideline 5 in Chapter 7).
- Length of taper and parallel acceleration/deceleration lanes at two-lane entrance/exit ramps (Guideline 6 in Chapter 7).

2.2.2.2 TxDOT Freeway Signing Handbook (2008)

For situations in which an auxiliary lane is present, the design and placement of guide signs is suggested for various lane arrangements. The sign design and placement of guides depends on the auxiliary lane length and exit-ramp lane arrangement (lane-drop exit ramp or diverge exit ramp; single or multi lanes). Five scenarios are illustrated in the manual, and examples of guide signs are presented.

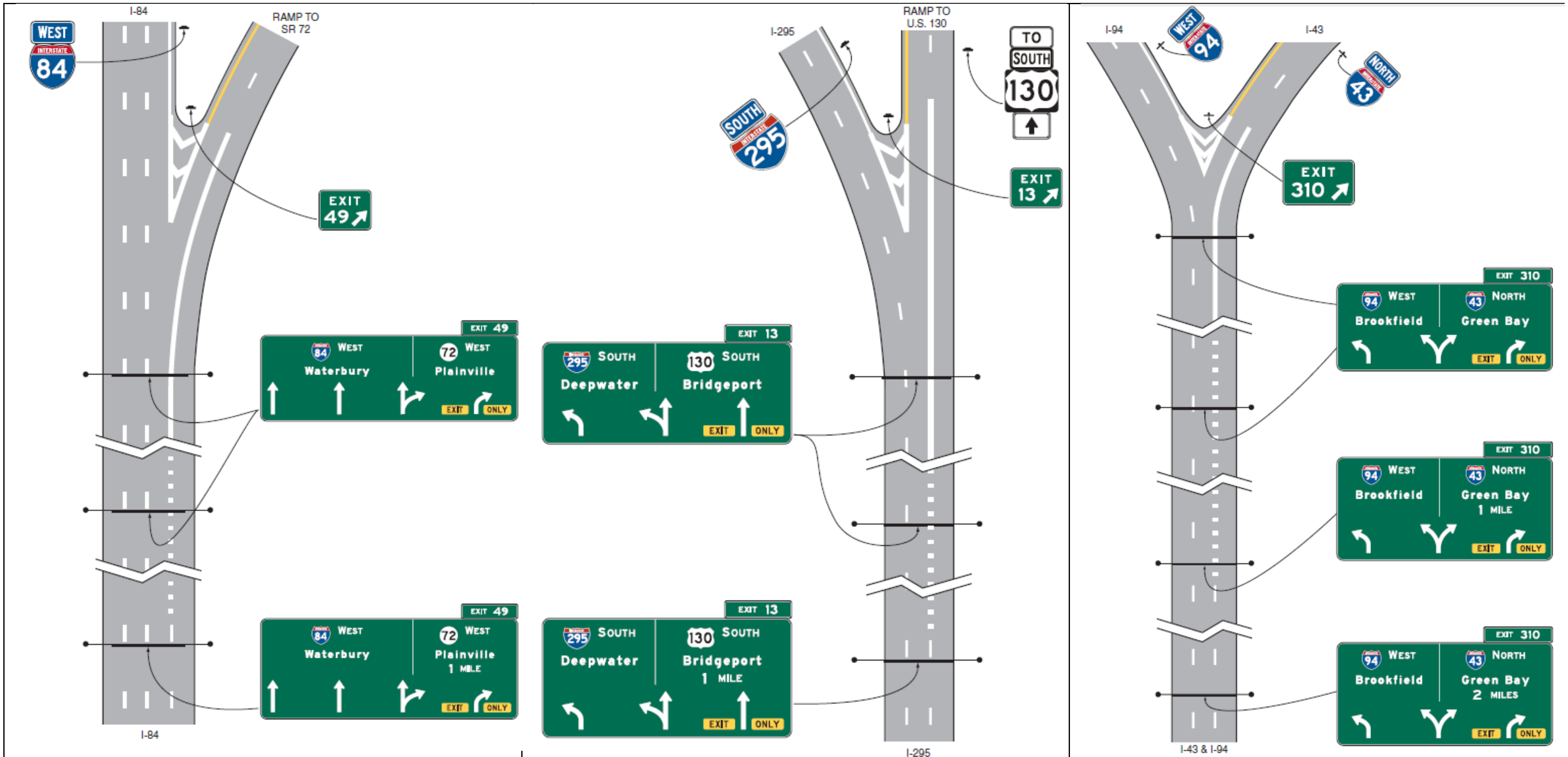
2.2.2.3 Texas MUTCD (2006)

Some provisions related to the design of pavement marking are provided for entrance and exit ramps in the Texas MUTCD, which covers lane-drop markings, broken-lane line markings for the full length of parallel acceleration and deceleration lanes, channelizing lines, optional diagonal approach markings for neutral areas, gore points, and optional dotted extensions of lane lines.

2.2.3 Available Design Guidelines in the MUTCD (2009)

2.2.3.1 Sign Design and Placement of Guides

Section 2E.20 to Section 2E.24 of the MUTCD (2009) describe the placement of overhead arrow-per-lane guide signs and diagrammatic guide signs for different scenarios, which includes the one-lane exit and two-lane exit, as shown in Figure 2-3 and Figure 2-4. In addition, the MUTCD also provides guidance and options.

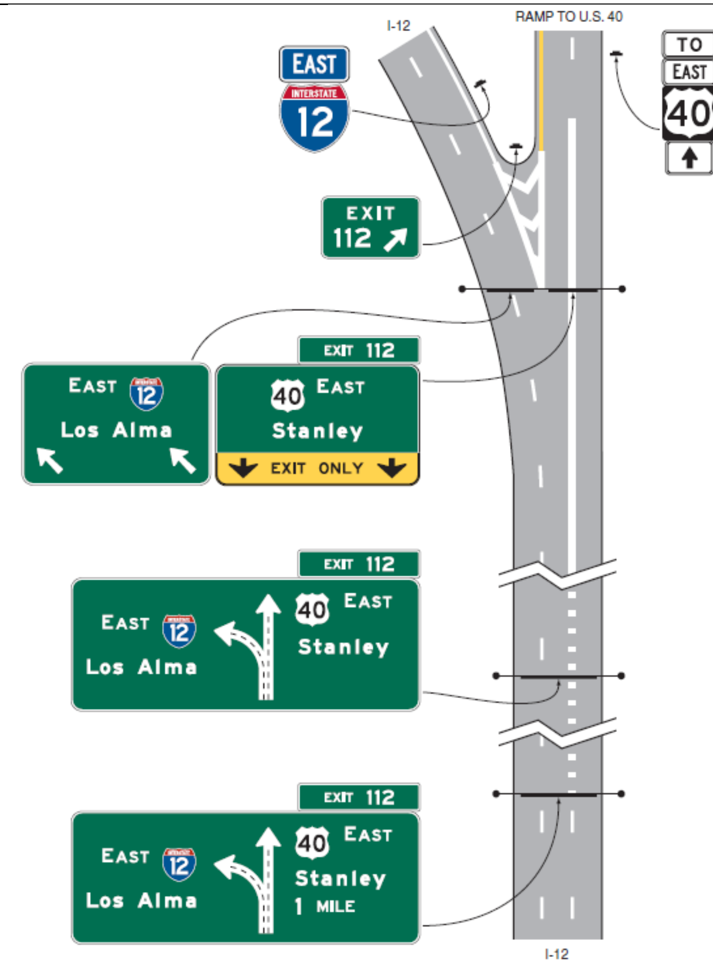


For a Two-Lane Exit to the Right with an Option Lane	For a Two-Lane Exit to the Right with an Option Lane (Through Lanes Curve to the Left)	For a Split with an Option Lane

Figure 2-3. Overhead Arrow-per-Lane Guide Signs.

For a Multi-Lane with an Option Lane

For a Two-Lane Exit to the Right with an Option Lane



For a Two-Lane Exit to the Right with an Option Lane (Through Lanes Curve to the Left)

Figure 2-4. Diagrammatic Guide Sign.

2.2.3.2 Design of Pavement Markings

Provisions are provided in Section 3B.04 of the MUTCD 2009 for designing pavement markings. The Texas MUTCD 2006 edition also follows most of the standards. In addition, the MUTCD provides guidance and options for pavement markings, as shown in Figures 2-5, 2-6, and 2-7.

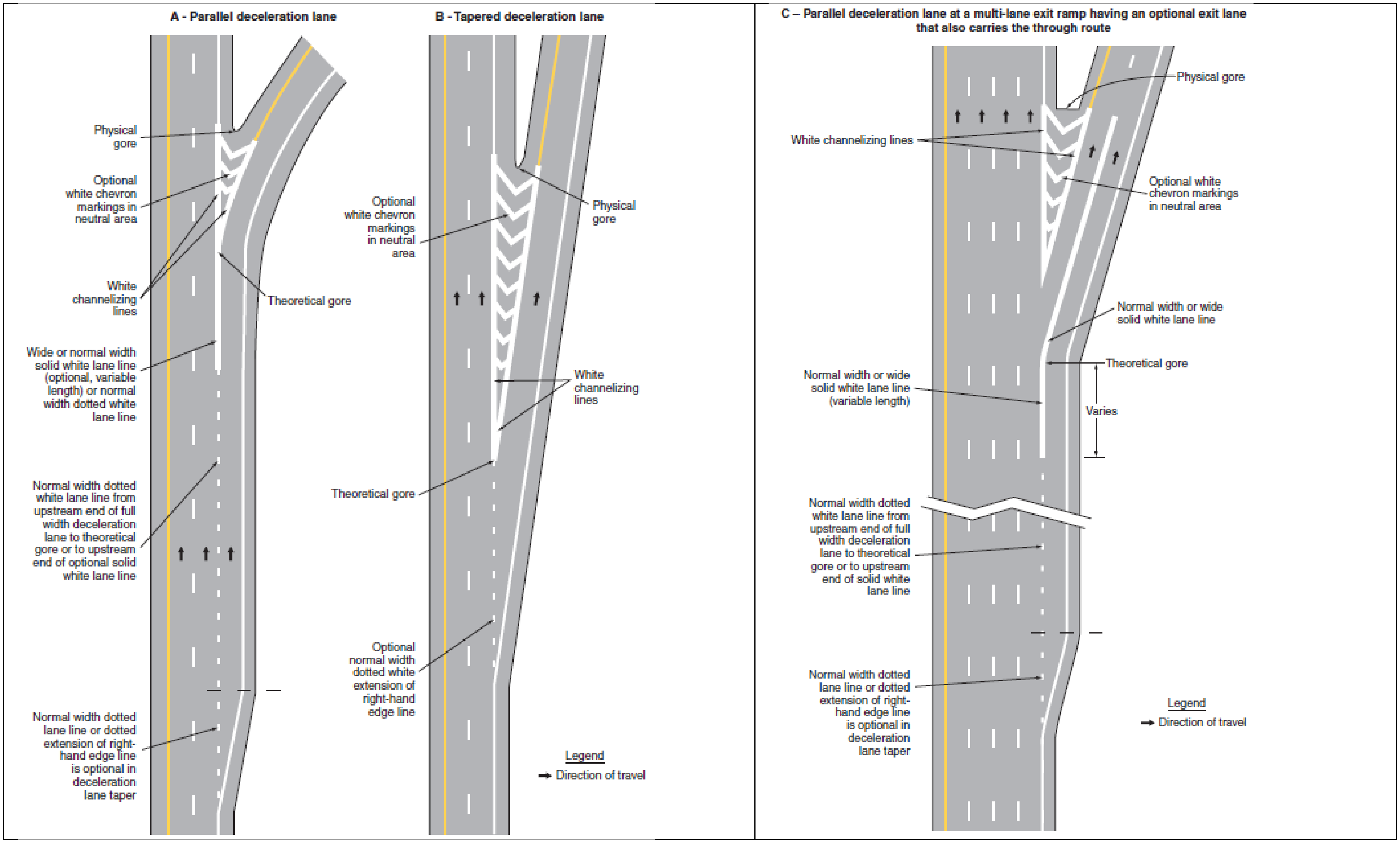


Figure 2-5. Example of Dotted Line and Channelizing Line Application for Exit Ramp Markings.

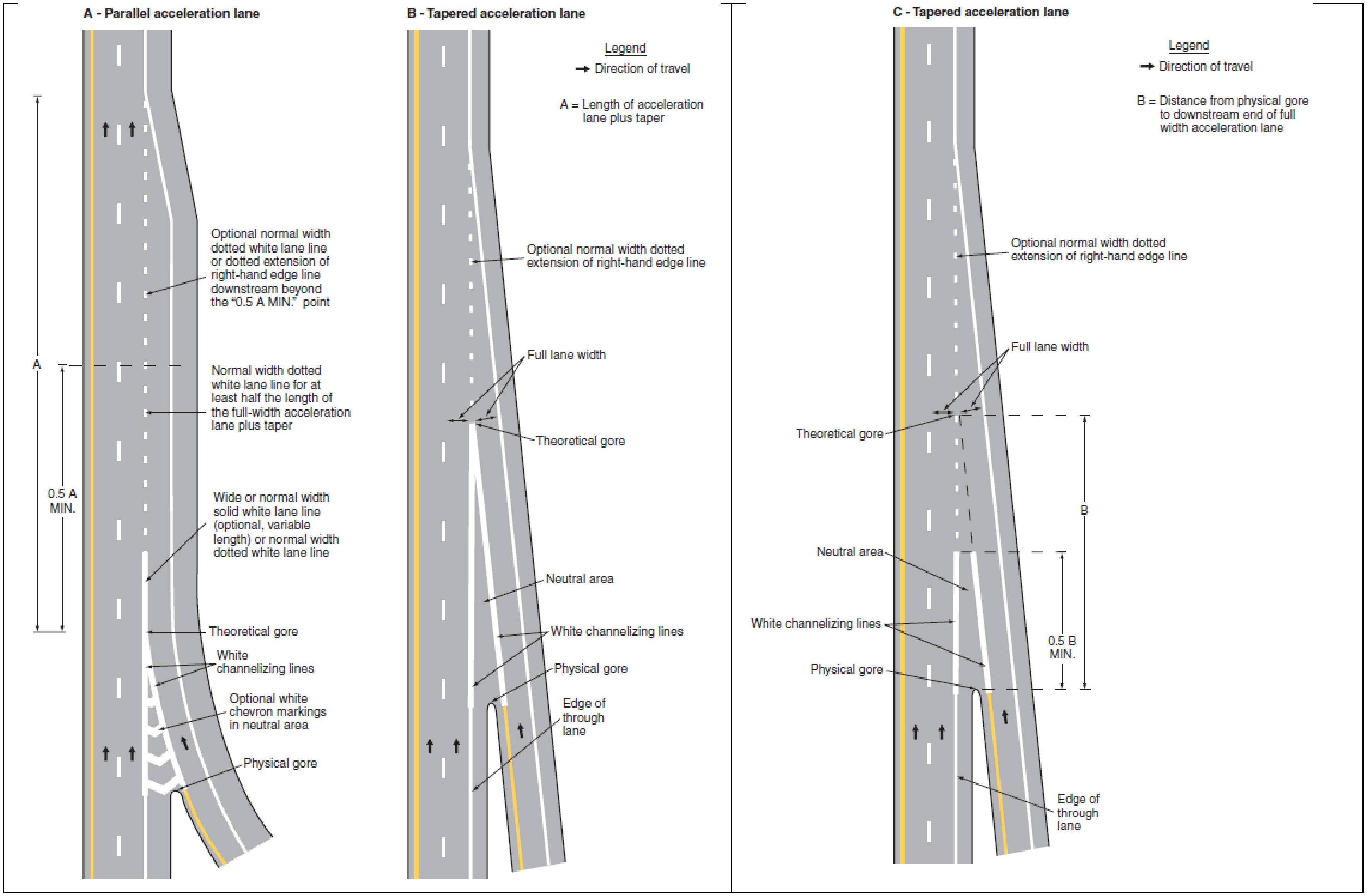


Figure 2-6. Example of Dotted Line and Channelizing Line Application for Entrance-Ramp Markings.

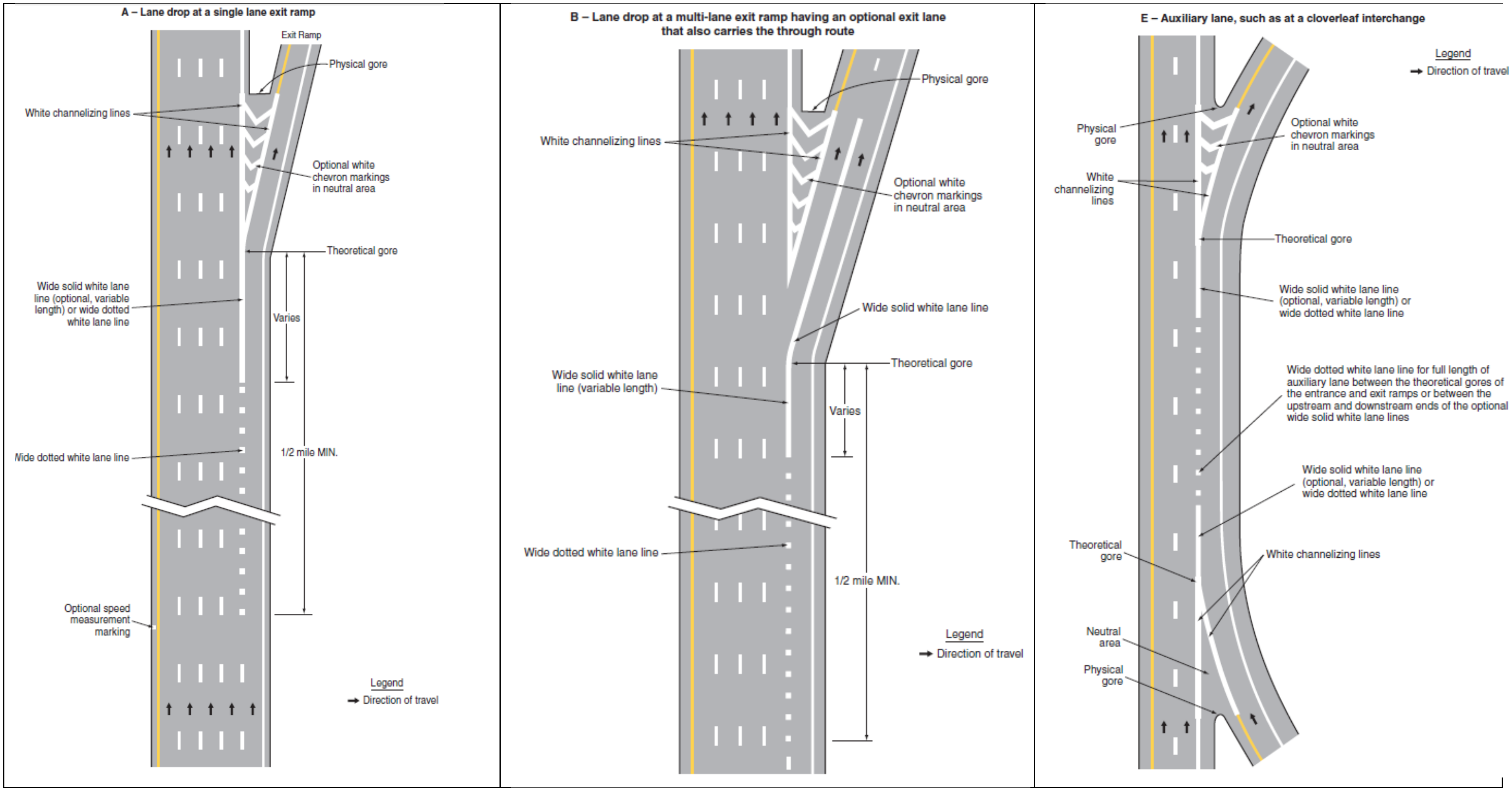


Figure 2-7. Examples of Applications of Freeway and Expressway Lane-Drop Markings.

2.3 PEER STATE DOTS' DESIGN STANDARDS

2.3.1 Overview of Existing Guidelines in Peer State DOTs

Guidelines of peer state DOTs on design of auxiliary lanes can be valuable resources for developing guidelines for Texas engineers. The researchers reviewed approximately 50 states' highway design manuals or guidelines. Table 2-1 lists the existing, available design guidelines associated with freeway auxiliary lanes. Each of these guidelines covers one or several of the following aspects: definition of auxiliary lanes, whether the design of freeways should explicitly comply with lane balance rules, what factors should be considered in designing auxiliary lanes, quantitative warrants, and length/width for auxiliary lanes and shoulders.

Table 2-1. Available DOT Standards Regarding Design of Freeway Auxiliary Lanes.

	Explicitly comply with lane balance principles	Factors to be considered in designing auxiliary lanes	Quantitative warrants	Geometric design (e.g., width/length of auxiliary lanes/shoulders)	Sources
Arizona		√			ADOT Roadway Design Guidelines (2007)
California		√	√		CDOT Highway Design Manual (2001)
Illinois	√	√	√		IDOT Bureau of Design and Environment Manual (2010)
Indiana	√	√			INDOT The Indiana Design Manual (2011)
Kentucky		√			KYTC Highway Design Manual (2006)
Maine				√	Maine Highway Design Manual (2004)
Massachusetts	√			√	MassDOT Project Development & Design Guide (2006)
Minnesota	√		√		MNDOT Roadway Design Manual (2001)
Montana	√	√	√		MDT Road Design Manual (2007)
New Mexico		√			NMDOT State Access Management Manual (2001)
Nevada	√			√	NDOT Roadway Design Guide (2010)
Ohio	√		√		ODOT Location and Design Manual (2011)
Oregon				√	ODOT Highway Design Manual (2003)
Utah	√			√	UDOT Roadway Design Manual of Instruction (2007)
Washington	√			√	WSDOT Design Manual (2011)
Wisconsin	√		√		WisDOT Facilities Development Manual (2006)

Note: "√" means that relevant guidelines were available; the highlighted states were also identified to have related guidelines by local respondents who participated in the survey described in Chapter 2 of this project.

Note that California, Kentucky, Maine, Massachusetts, Minnesota, New Mexico, Ohio, Utah, Vermont Wisconsin, and Washington explicitly follow the guidelines provided by AASHTO in their highway design manuals.

2.3.2 Compliance with Lane Balance Principles

As mentioned before, an auxiliary lane may be provided to comply with the lane balance principles to meet capacity needs or to accommodate speed changes and weaving of entering and leaving traffic. Guidelines by Illinois, Indiana, Massachusetts, Minnesota, Montana, Nevada, Ohio, Utah, and Washington explicitly mention that the principles of lane balance should be followed.

2.3.3 Factors Considered in Designing Auxiliary Lanes

2.3.3.1 Arizona Department of Transportation (ADOT) Roadway Design Guidelines (2007)

Within the metropolitan areas and all other urban/suburban areas throughout the state, mainline auxiliary lanes should be provided on controlled-access highways between ramp entrances and exits of nominal 1 mile interchanges. When the distance between interchanges is greater than 1.5 miles, or when collector, distributor roads are used, the operational effectiveness of such auxiliary lanes should be confirmed by a traffic analysis before being incorporated in the interchange design. The design configuration of the ramps and the auxiliary lane should be based upon a complete operational analysis including traffic volumes, weaving lengths, acceleration/deceleration requirements, and operational speeds.

2.3.3.2 California Department of Transportation (CDOT) Highway Design Manual (2001)

The grade, volumes, and speeds should be analyzed to determine the need for auxiliary lanes. An auxiliary lane would allow entrance-ramp traffic to accelerate to a higher speed before merging with mainline traffic, or simply provide more opportunity to merge.

2.3.3.3 Illinois Department of Transportation (IDOT) Bureau of Design and Environment Manual (2010), Indiana Department of Transportation (INDOT) Indiana Design Manual (2011), and Montana Department of Transportation (MDT) Road Design Manual (2007)

The selected design will depend upon traffic volumes for the exiting, entering, and through movements within the interchange.

2.3.3.4 New Mexico Department of Transportation (NMDOT) State Access Management Manual

Speed is a major consideration in New Mexico. Speed-change lanes on grade-separated highway facilities are referred to as acceleration lanes, deceleration lanes, or auxiliary lanes. At a minimum, speed-change lanes should enable a driver to make the necessary transition between the speed on a ramp roadway and the speed of operation on the mainline highway in a safe and comfortable manner.

2.3.4 Quantitative Warrants

2.3.4.1 ADOT Roadway Design Guidelines (2007)

Within the metropolitan areas (e.g., Phoenix and Tucson) and all other urban/suburban areas throughout the state, mainline auxiliary lanes should be provided on controlled-access highways between ramp entrances and exits of nominal 1 mile interchanges.

2.3.4.2 CDOT Highway Design Manual (2001)

Auxiliary lanes should be provided in all cases when the weaving distance is less than 600 m (2000 ft).

2.3.4.3 IDOT Bureau of Design and Environment Manual (2010), Ohio Department of Transportation (ODOT) Location and Design Manual (2011), and Minnesota Department of Transportation (MNDOT) Roadway Design Manual (2001)

Where interchanges are closely spaced, the designer should provide an auxiliary lane where the distance between the taper end of the entrance terminal and beginning taper of the exit taper is less than 1500 ft (450 m).

2.3.4.4 MDOT Road Design Manual (2007)

An auxiliary lane should be provided where the distance between the end of the entrance terminal and the beginning of an exit terminal is less 1600 ft (450 m).

2.3.5 Width of Auxiliary Lanes and Shoulders

2.3.5.1 Massachusetts Department of Transportation (MassDOT) Project Development & Design Guide (2006) and Utah Department of Transportation (UDOT) Roadway Design Manual of Instruction (2007)

Same as AASHTO Green Book.

2.3.5.2 Nevada Department of Transportation (NDOT) Roadway Design Guide (2010)

Where auxiliary lanes are provided along freeway main lanes, the adjacent shoulder should be 8 to 12 ft in width; the preferred width of 12 ft should be considered unless otherwise justified.

2.3.5.3 Oregon Department of Transportation (ODOT) Highway Design Manual (2003)

Auxiliary lane width shall be 12 ft, and auxiliary lane shoulder width shall be 10 ft.

2.3.6 Summary

Collectively, several state DOTs provide, in their roadway design manuals, very general guidelines regarding freeway auxiliary lanes, which are basically consistent with the provisions in the AASHTO Green Book (2004). These guidelines identify the factors to be considered in the design of auxiliary lanes, which include:

- Grade.
- Volume.
- Speed.

In addition, quantitative warrants for auxiliary lanes have been provided by some states manuals and are mainly based on:

- Interchange spacing.
- Space between upstream enter ramp and downstream exit ramp.
- Existence of frontage roads.

Furthermore, the width of auxiliary lanes is suggested to be 12 ft, while a shoulder of 8 to 12 ft is preferred.

These existing guidelines provided valuable resources for this study.

2.4 SAFETY IMPACTS OF FREEWAY AUXILIARY LANES

2.4.1 Liu et al. (2010)

Three types of freeway and ramp arrangements with closely spaced entrance and exit ramps were compared. As shown in Figure 2-8, they are Type A—freeway segment without auxiliary lane between paired entrance and exit ramps; Type B—freeway segment with a continuous auxiliary lane that connects entrance and exit ramps and is dropped in a two-lane exit; and Type C—freeway segment with a continuous auxiliary lane that connects entrance and exit ramps and is dropped in a one-lane exit.

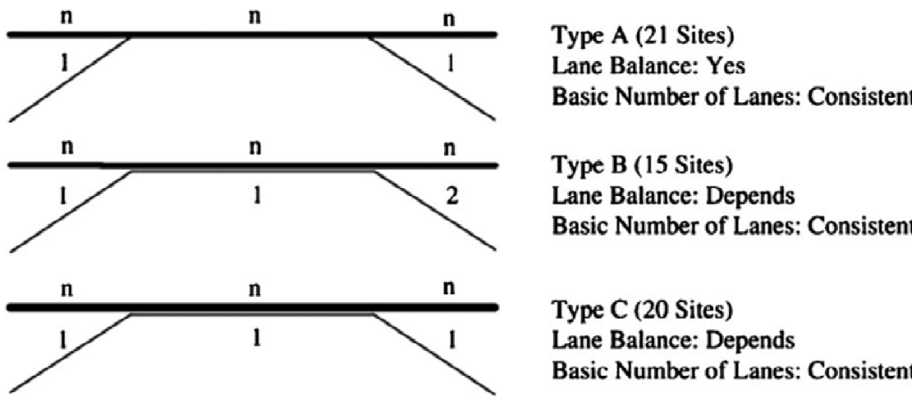


Figure 2-8. Types of Freeway and Ramp Arrangements Evaluated in Liu et al. (2010).

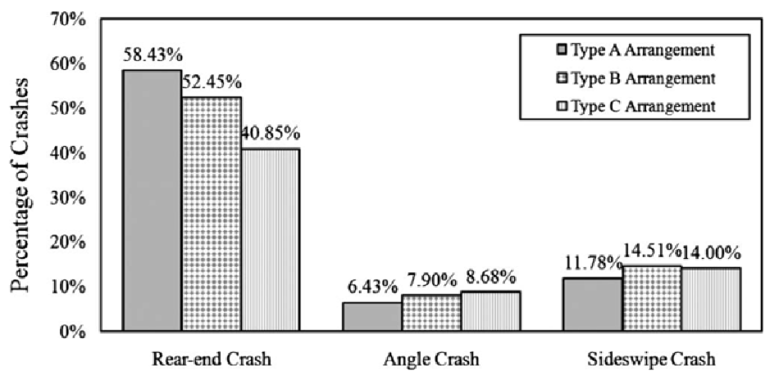


Figure 2-9. Comparison of Crash Type Evaluated in Liu et al. (2010).

As shown in Figure 2-9, among the three arrangements, the Type C arrangement had the lowest average crash frequency and crash rate. The Type B arrangement reported the highest average crash frequency, crash rate, and percentage of fatal plus severe injury crashes. The results suggested that the Type B arrangement should be used cautiously when entrance and exit ramps are closely spaced.

2.4.2 Kuhn et al. (2007)

According to the report, the use of auxiliary lanes can reduce vehicle crashes in merge and weaving areas, reduce vehicle conflicts in merge and weaving areas, channelize vehicles with different operating characteristics to ramps, and reduce the potential of rear-end collisions at ramps where congestion frequently occurs.

2.4.3 Mergia (2010)

The purpose of the study was to identify factors that affect crash injury severity and to understand how these factors affect injury severity. Candidate factors were categorized into driver-related, traffic, environmental, and geometric design factors. A statistical model was developed to predict the effects of these factors on severity of injuries sustained from crashes.

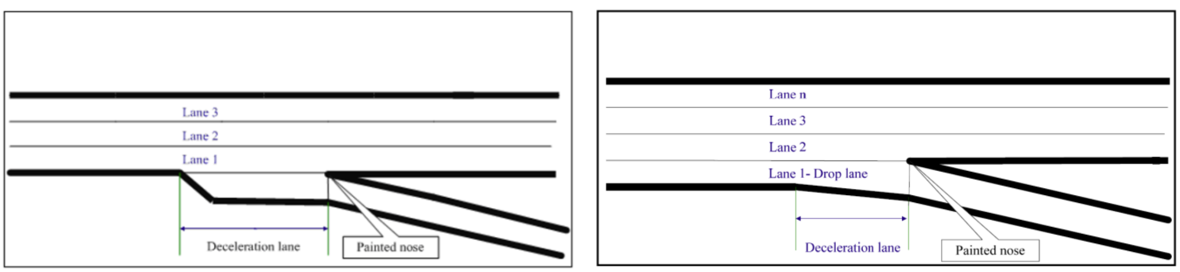
Police-reported crash data obtained from the Ohio Department of Public Safety (ODPS) at selected freeway merge influence areas (seven types of lane arrangements) and diverge influence areas (six types of lane arrangements) were used for developing the model. A generalized ordinal logit model and partial proportional odds model were applied to identify the factors that tend to increase the likelihood of one of five levels of injury severity: no injuries, possible/invisible injuries, non-incapacitating injuries, incapacitating injuries, or fatal injuries.

The results associated with this research project included:

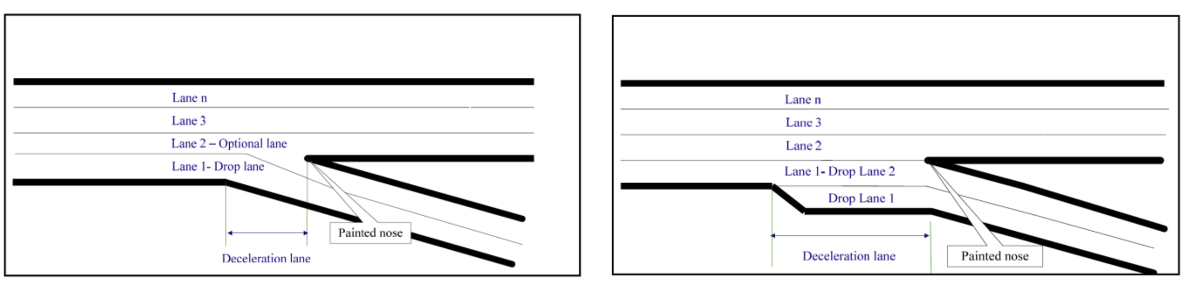
- The use of continuous auxiliary lanes between an entrance ramp and an exit ramp tends to increase the likelihood of severe injuries near the diverge areas.
- The number of ramp lanes has a significant effect on the frequency of severe injuries in merge and diverge influence areas.
- The number of mainline lanes can have a significant effect on the frequency of severe injuries in merge influence areas.

2.4.4 Lu et al. (2009)

In Florida, a total of 424 sample sites were collected for freeway diverge influence areas, including 220 sites for Type 1 exit ramps, 96 sites for Type 2 exit ramps, 77 sites for Type 3 exit ramps, and 31 sites for Type 4 exit ramps, as shown in Figure 2-10.



(a) Type 1 Parallel and One-Lane Exit (b) Type 2 Tapered and One-Lane Exit



(c) Type 3 Tapered and Two-Lane Exit (d) Type 4 Parallel and Two-Lane Exit

Figure 2-10. Types of Lane Arrangements of Diverge Influence Areas Evaluated in Lu et al. (2009).

Following are some important findings associated with the TxDOT research project described in this report:

- The Type 1 exit ramp has the best safety performance in terms of the lowest crash frequency and crash rate on freeway diverge influence areas. However, statistical tests showed that crash severity and crash types did not have significant differences among the four types at the 90 percent confidence level.
- A predictive model was built. The coefficients of the model showed that the crash counts at freeway diverge influence areas increased with the number of mainline lanes, deceleration lane length, mainline average daily traffic (ADT), ramp ADT, and posted speed limit difference between mainline sections and ramp sections, but decreased with the entire ramp length and posted speed limit on mainline sections.
- The model also quantified the impacts of the different exit ramp types on crash counts. For one-lane freeway exit ramps, replacing a Type 1 exit ramp with a Type 2 exit ramp increased crash counts at freeway diverge influence areas by 15.57 percent. For two-lane exit ramps, replacing a Type 3 ramp with a Type 4 ramp increased crash counts at freeway areas by 10.80 percent.

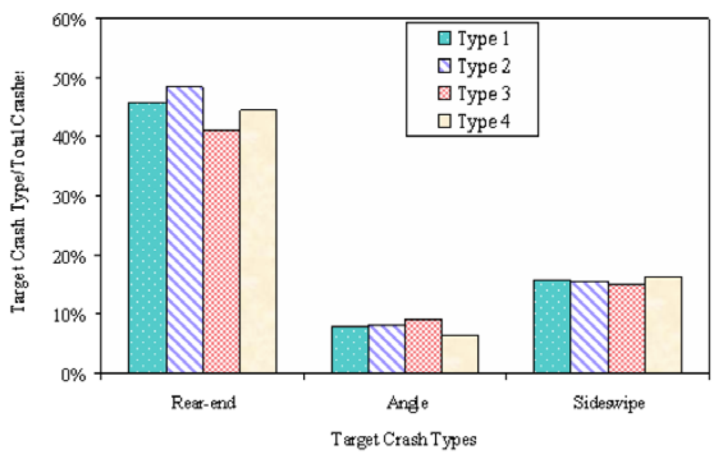


Figure 2-11. Percentages by Crash Types on Various Diverge Influence Areas Evaluated in Lu et al. (2009).

2.4.5 Sarhan et al. (2008)

The safety performance of freeways at merge and diverge influence areas is generally affected by a large number of factors that influence driver behavior in such areas. This research was focused on addressing the safety effects of merging and diverging and the interrelationship with geometric features. In this study, 26 interchanges along Highway 417, with a total of 94 segments including 34 weaving segments, were studied to investigate the effects of ramp terminal spacing and traffic volumes on safety performance.

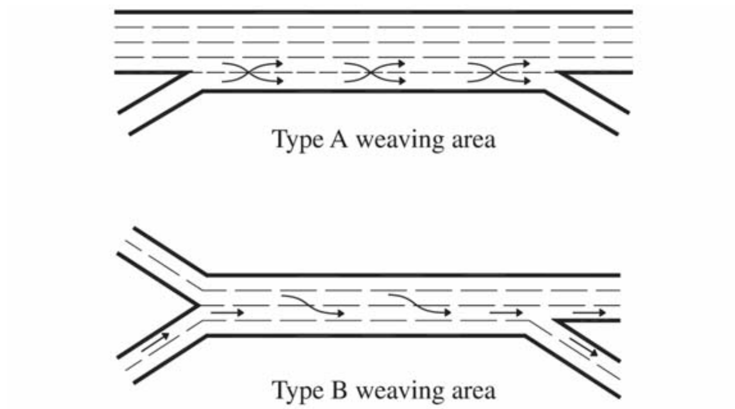


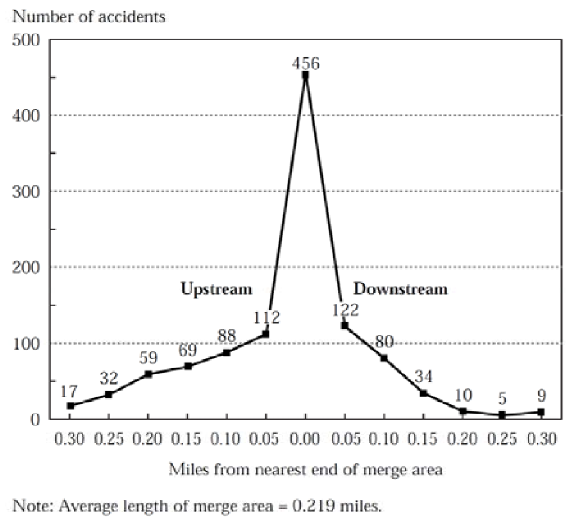
Figure 2-12. Types of Weaving Sections Evaluated in Sarhan et al. (2008).

Some important findings associated with this research project included:

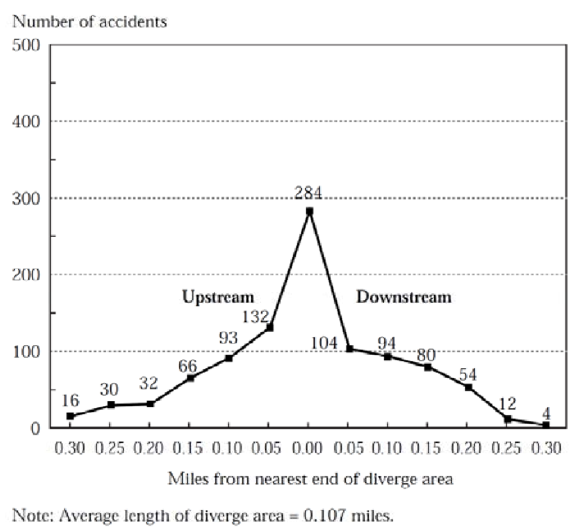
- The historical crash records at the 26 studied interchanges show that the use of continuous auxiliary lanes did not improve the safety performances significantly at these sites.
- Weaving Type A was associated with relatively lower collision frequencies when compared with weaving Type B.
- The number of collisions will decrease with increasing length of speed-change lane.

2.4.6 Janson et al. (1998)

The objectives of this study were to statistically compare truck accident experiences of four different ramp designs and to examine the effects of their design on interchange safety. It was shown that truck accident frequencies and rates were not significantly different by ramp type alone, but were significantly different by conflict locations. Figures 2-13 shows the spatial distribution of truck accidents both upstream and downstream of merge and diverge ramps in Washington State.



(a) Spatial distribution of accidents at merge influence areas



(b) Spatial distribution of accidents at diverge influence areas

Figure 2-13. Spatial Distribution of Accidents at Merge and Diverge Influence Areas.

(Source: Janson et al., 1998)

2.4.7 Glad et al. (2001)

The datasets analyzed in this study pinpointed that two-thirds of the rear-ends and one-third of the sideswipes occurred in the continuous auxiliary lanes through the weave segments, although the crashes were mainly attributed to weaving traffic instead of the presence of the auxiliary lanes.

2.4.8 Summary

Collectively, prior research regarding the safety performance can be summarized as follows:

- <u>Continuous auxiliary lane connecting an entrance ramp and a one-lane exit ramp.</u>
  Associated with the lowest crash frequency (Sarhan et al., 2008; Liu et al., 2010) but with an increased likelihood of severe injuries near the diverge areas (Mergia, 2010). The study by Sarhan et al. (2008) showed the use of continuous auxiliary lanes did not improve the safety performances significantly.
- <u>Continuous auxiliary lane connecting an entrance ramp and a two-lane exit ramp.</u>
  Associated with the highest average crash frequency, crash rate, and percentage of fatal plus severe injury crashes (Liu et al., 2010). The results suggested that this arrangement should be used cautiously when entrance and exit ramps are closely spaced.
- <u>Parallel exit ramp at an isolated diverge influence area.</u>
  One-lane parallel exit ramps are associated with the lower average crash frequency and crash rate compared to one-lane taper exit ramps. On the other hand, for two-lane exit ramps, taper exit ramps are safer than parallel exit ramps (Lu et al., 2009).
- <u>Contributing factors.</u>
  The factors that have been identified by previous studies as significant influencing factors to safety included number of mainline lanes, deceleration lane length, mainline ADT, ramp ADT, posted speed limit differential between the mainline and ramp, and the entire ramp length.

2.5 MERGE, DIVERGE, AND WEAVING BEHAVIOR

Generally, there are only a few existing studies that were focused on the underlying behavioral basis for merge maneuvers. No literature was found regarding the diverge or weaving behavior. The existing results provided a basis for the micro-simulation modeling chapters in this study.

Given different traffic and geometric conditions, the merge maneuvers can be categorized as follows:

- Free merge (relatively low volumes on both the mainline and entrance ramp; merge locations at arbitrary locations of the merge ramp).
- Challenged merge (high speed differentials between the mainline and entrance ramp, heavy traffic on the mainline; requiring a longer merge length due to the conflicts with freeway vehicles).
- Platoon merge (typically observed on urban freeway entrance ramps with a heavy entering traffic volume, especially when connected with a nearby signalized local intersection; merge locations centered near a narrow area on the merge lane).

2.5.1. Yi and Mulinazzi (2007a)

In this paper, the authors investigated the relationships between the minimum merge length needed by a majority of entrance-ramp drivers and studied traffic characteristics, including volumes and speeds on both the freeway and the entrance ramp.

An entrance ramp is considered to consist of two components, a ramp roadway and a merge lane (parallel acceleration lane), with the ramp nose being taken as the dividing point of the two components. The merge maneuvers were categorized as free merge, challenged merge, and platoon merge as described above.

Field observations revealed that the platoon-merge vehicles follow a natural smooth path when merging, with their merge locations centered near a narrow area on a merge lane; the free-merge vehicles merge at arbitrary locations, leaving difficulties in the prediction of their merge locations; and the challenged-merge vehicles require a longer merge length due to conflicts with freeway vehicles.

The results showed that, given relatively high volumes on Lanes 1 and 2 (on the rightmost of a mainline freeway), the merge length of an entrance-ramp lane is more significantly correlated with whether the merge type is platoon-merge volume or challenged-merge volume, and the freeway Lane 1 speed. A longer merge lane for an urban freeway entrance ramp is needed only when challenged-merge appears frequently, which is usually a result of the combination of high volumes on freeway Lanes 1 and 2 and a high speed on freeway Lane 1.

2.5.2. Yi and Mulinazzi (2007b)

The objectives of this study were to investigate the causes of the invasive influences of the entering traffic from an entrance ramp to the freeway and to evaluate the significance of the invasive influences.

A pre-merge influence area of 1,000 ft was defined as a stretch immediately upstream of the primary merge influence area defined in the HCM (2000). The pre-merge influence areas were videotaped to collect field data. In accordance with this observation, two criteria to identify a merging platoon as an invasive platoon were proposed: (a) the average percentage of the resultant slowdown events exceeded 85 percent, and (b) the average percentage of the resultant lane-change events exceeded 50 percent.

The authors concluded that the conventional methods used to model the freeway entrance-ramp merge process have not satisfactorily incorporated the invasive influences of the ramp merging flow on the freeway flow. The freeway flow was significantly impacted when platoons from the entrance ramp were present. When the length of the platoon from the entrance ramp increased from four to five cars, the average percentage of the slowdown events increased from 54 percent to 85 percent, and the average percentage of the lane-change events escalated from 21 percent to 64 percent.

2.5.3 Glad et al. (2001)

The authors found that:

- In cases of challenged merges, there are large speed differentials between the entrance ramp and the freeway mainline. Then, weaving vehicles become restricted to a limited portion of the roadway. This result is consistent with the findings presented in Yi and Mulinazzi (2007a).
- In the case of a heavy weaving section, speed differentials of weaving and non-weaving vehicles occur infrequently and tend to be smaller. Then, weaving vehicles would take up a larger portion of the roadway section.
- Where multilane entry and exit legs exist, weaving vehicles often occupy the majority of the roadway in the segment.

2.6 RESEARCH ON DESIGN RELATED TO FREEWAY AUXILIARY LANES

2.6.1 Ramp Spacing

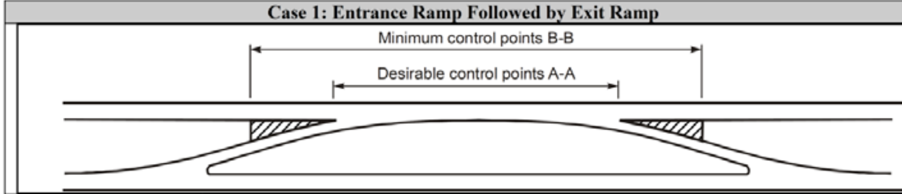
2.6.1.1 Fitzpatrick et al. (2010)

Understanding the relationship between interchange ramp spacing, speed, and freeway operations is important, especially in developing potential design values for higher speeds (e.g., 85 to 100 mph). The objectives of this project were to (a) investigate relationships between weaving length, speed, and overall vehicle operations on Texas freeways; and (b) propose updates to current TxDOT guidance on recommended distances between ramps. Suggested ramp spacing was developed for the entrance ramp to exit ramp and exit ramp to exit ramp conditions.

In this study, the research tools utilized include reviews of the literature and previous research projects, field data, and simulation. Simulation allows for flexible modeling of a complex weaving environment. Real-world data were collected to calibrate the simulation. The calibrated simulation was used to investigate a variety of different volumes and speeds. These combinations were used to determine the relationship of ramp spacing to design and operating speed on the freeway.

The suggestions for spacing between successive ramps are summarized in Figure 2-14. While the suggested dimensions are much greater than values currently recommended for Texas, they can provide the opportunity for flexibility in managing future operations. They also reflect the mobility emphasis for the proposed higher speed (e.g., 100 mph) corridors.

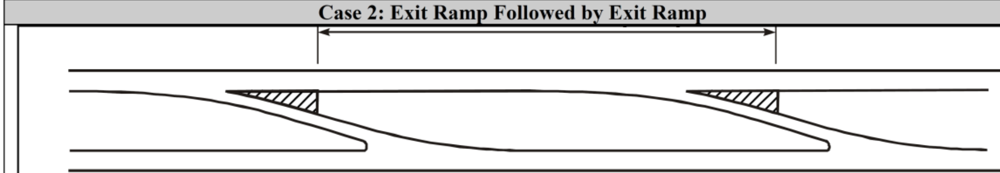
Case 1: Entrance Ramp Followed by Exit Ramp



Design Speed (mph)	Suggested Weaving Length (ft)		
	Alternative 1	Alternative 2	Alternative 3
Below 70	1500	6600	2500
70	2000	6600	4500
80	2600	6600	8500
90	3300	6600	12500
100	4100	6600	16500

Alternative 1 reflects the situation when a vehicle is at the design speed at the end of the entrance ramp and must come to a complete stop and then accelerate back to freeway speed.
Alternative 2 is based on England's recommendation for weaving lengths for rural motorways and consideration of preliminary safety findings.
Alternative 3 are the values calculated using regression equations developed from this project's field studies and low freeway/ramp volume and weaving ratio.

Case 2: Exit Ramp Followed by Exit Ramp



Design Speed (mph)	Suggested Length (ft)		
	Alternative 1	Alternative 2	Alternative 3
50	1000	1500	5280
60	1200	1700	5280
70	1400	1900	5280
80	1600	2200	5280
90	1800	2500	5280
100	2000	2800	5280

Alternative 1 is based on England's recommendation for ramp spacing, rounded.
Alternative 2 is based on decision sight distance using reaction time found for 70 year old and over group.
Alternative 3 is 1 mile selected because guide signing for interchanges is to begin at 1 mile.

Case 3: Entrance Ramp Followed by Entrance Ramp

This situation will be encountered only on infrequent occasions and special design treatment will be required. It will usually require an added freeway lane.

Case 4: Exit Ramp Followed by Entrance Ramp

The distance between an exit ramp followed by an entrance ramp will be governed by the geometrics of the connections to the adjacent roadway or connecting roadway.

Note

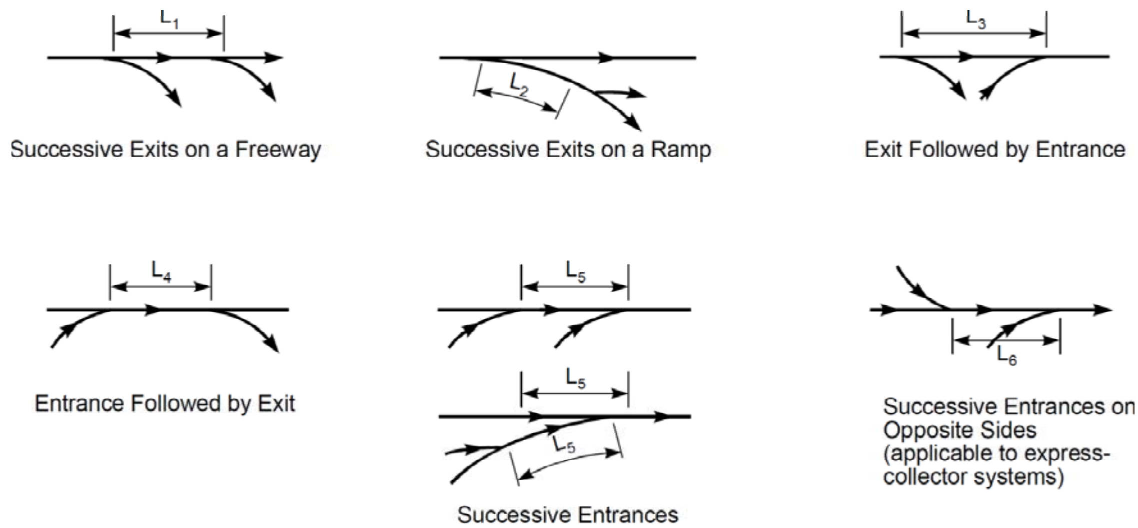
The distances shown above are generally used but reference should be made to the AASHTO publication *A Policy on Geometric Design of Highways and Streets* and the *Highway Capacity Manual* for more specific information since operational aspects are influenced by traffic volumes and may require longer distances. In addition, the spacing needed to accommodate the required signs for an exit ramp should also be considered. See TxDOT *Freeway Signing Handbook* for additional information on sign design.

Figure 2-14. Suggested Successive Ramp Dimensions.

(Source: Fitzpatrick et al., 2010)

2.6.1.2 Geometric Design Guide for Canadian Roads (Transportation Association of Canada, 1999)

The recommended spacing between successive entrance ramps in the Geometric Design Guide for Canadian Roads is based on the distance required for vehicles from the first entrance ramp to accelerate and merge with mainline traffic. The presence and length of an acceleration lane may ultimately influence recommended ramp spacing.



Spacing[1] (ft)	Main line design speed (mph) 50	55	60	70	75	80
L_1	980	1070	1150	1230	1230	1390
L_2	660	740	820	1230	980	1070
L_3	490	490	570	570	660	660
L_4	Based on weaving requirements Subsection 2.1.7.3					
L_5	Sufficient to allow for acceleration and merging length before second entrance					
L_6	60% of L_5					

[1] Minimum lengths from bullnose to bullnose

Figure 2-15. Ramp Terminal Spacing in Geometric Design Guide for Canadian Roads.

(Source: Transportation Association of Canada, 1999)

2.6.2 Ramp Length

2.6.2.1 Wang et al. (2013)

The authors developed minimum auxiliary lane length at isolated freeway on-ramp junctions with the use of the Highway Capacity Software (HCS, 2010). To develop the minimum auxiliary lane length, at first, the authors developed guidelines on when to use auxiliary lanes under different combinations of number of lanes, freeway volume, and ramp volume, See Figure 2-16. Auxiliary lanes were recommended for scenarios that fell into the shaded region. Those regions were identified by the following criteria:

- If there is no auxiliary lane at the on-ramp junction, the level of service (LOS) in the merge influence area is D or worse.
- With the inclusion of an auxiliary lane, the LOS in the merge influence area becomes C or better.

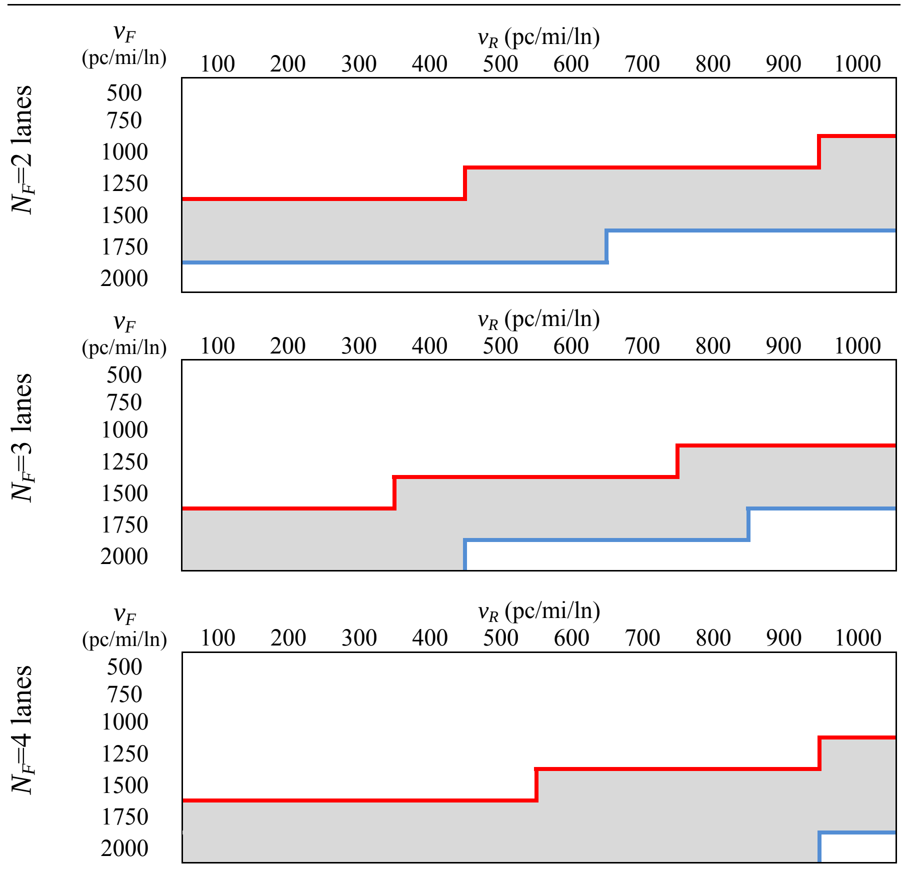


Figure 2-16. Design Scenarios in which Auxiliary Lanes of 150,330 ft Should Be Added.

To identify the minimum auxiliary lane length, for each scenario that fell into the shaded regions, the auxiliary lane length was increased from 0 to 1500 ft at increments of 100 ft. Minimum acceleration lane lengths were identified if the LOS went from D or worse to C or better. Table 2-2 shows the identified minimum length of auxiliary lanes at isolated freeway on-ramp junctions.

Table 2-2. Minimum Length of Auxiliary Lanes at Isolated Freeway On-Ramp Junctions.

Minimum L_A (ft) for N_F=2 lanes										
v_F (pc/h/ln)	v_R (pc/h/ln)									
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
500	-	-	-	-	-	-	-	-	-	-
750	-	-	-	-	-	-	-	-	-	-
1000	-	-	-	-	-	-	-	-	-	100
1250	-	-	-	-	200	300	400	500	600	700
1500	300	400	500	700	800	900	1000	1100	1200	1400
1750	900	1000	1200	1300	1400	1500	-	-	-	-
2000	-	-	-	-	-	-	-	-	-	-

(a) N_F=2 lanes

Minimum L_A (ft) for N_F=3 lanes										
v_F (pc/h/ln)	v_R (pc/h/ln)									
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
500	-	-	-	-	-	-	-	-	-	-
750	-	-	-	-	-	-	-	-	-	-
1000	-	-	-	-	-	-	-	-	-	-
1250	-	-	-	-	-	-	-	100	200	400
1500	-	-	-	200	300	500	600	700	900	1000
1750	400	600	700	800	1000	1100	1300	1400	-	-
2000	1100	1300	1400	1500	-	-	-	-	-	-

(b) N_F=3 lanes

Minimum L_A (ft) for N_F=4 lanes										
v_F (pc/h/ln)	v_R (pc/h/ln)									
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
500	-	-	-	-	-	-	-	-	-	-
750	-	-	-	-	-	-	-	-	-	-
1000	-	-	-	-	-	-	-	-	-	-
1250	-	-	-	-	-	-	-	-	-	100
1500	-	-	-	-	-	100	300	400	500	600
1750	100	200	300	400	500	600	800	900	1000	1100
2000	600	700	800	900	1000	1100	1300	1400	1500	-

(c) N_F=4 lanes

2.6.2.2 Fitzpatrick and Zimmerman (2004)

Where grades are present on ramps, merge and diverge lengths should be adjusted. A potential method for determining the adjustment factors for entrance terminals is to calculate the distance needed to accelerate from one speed to another on different grades. The ration between accelerating on grade to accelerating on a level road would then be the adjustment factor. This approach was used with a series of vehicle performance equations identified from the literature.

The suggested adjustment factors for acceleration and deceleration lanes are shown in Tables 2-3 and 2-4.

Table 2-3. Potential Adjustment Factors for PC-LT Vehicles for Acceleration Lanes.

(Source: Fitzpatrick and Zimmerman, 2004)

Highway Design Speed mph [km/h]	−6	−5	−4	−3	−2 to 2	3	4	5	6
50 [81] and below	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
60 [97]	1.00	1.00	1.00	1.00	1.00	1.05	1.10	1.15	1.20
70 [113]	0.85	0.89	0.93	0.96	1.00	1.08	1.15	1.23	1.30
80 [129]	0.80	0.85	0.90	0.95	1.00	1.10	1.20	1.30	1.40

Table 2-4. Potential Adjustment Factors for PC-LT Vehicles for Deceleration Lanes.

(Source: Fitzpatrick and Zimmerman, 2004)

Design Speed of Roadway	Ratio of Length on Grade to Length on Level								
	−6	−5	−4	−3	−2 to 2	3	4	5	6
All	1.15	1.12	1.09	1.07	1.00	0.94	0.93	0.91	0.89

2.6.2.3 Gattis et al. (2008)

The objective of this research project was to examine the speeds reached at certain distances by trucks accelerating onto the lanes of a mainline freeway, and to provide recommendations on the lengths of acceleration lanes necessary for heavy vehicles to accelerate to speeds closer to the speeds on the mainline freeway.

Data were collected at four separate commercial vehicle weigh stations in Arkansas and one in Missouri. The data were analyzed using both graphical and statistical techniques. The effects of truck weight, freeway volume, and roadway grade on the speeds of measured trucks were examined and compared among the sites. Table 2-5 compares the acceleration lane lengths recommended in the sources mentioned in the literature review with the models from this research project.

Table 2-5. Acceleration Lane Lengths from Reviewed Sources and Proposed Acceleration Lane Lengths.

(Source: Gattis et al., 2008)

		Deen 1957	AASHTO Green Book 2004	NCHRP Rept. 505 2003	Fitzpatrick and Zimmerman 2006	This study 2008
assumed initial speed (mph)		22	22	22	20	17
distance (ft) to reach	39 mph	-	550	850	-	-
	40 mph	1530	-	-	908	1203
	50 mph	-	1020	2230	1383	2119
	55 mph	-	1580	3260	1653	2731
	60 mph	-	-	-	1945	3655

Note: 1. Deen distances stated for semi-trailer trucks; 2. AASHTO 2004 distances are not specifically for trucks; are similar to 1965 distances stated for passenger cars; 3. NCHRP 505 distances are for a 180 lb/hp truck on a 0 percent grade; 4. Fitzpatrick and Zimmerman distances are for passenger cars. The values listed in each row of this table for Fitzpatrick and Zimmerman are their values for a design speed that is 10 mph above the speed in the row in this table; 5. 2008 distances were calculated with the revised "level" unimpeded average truck speed model.

The author also suggested that speed limits on four-lane freeways should not be raised where heavy volumes of trucks enter the freeway on short entry ramps. Raising the speed limit will increase the speed differential between traffic on the mainline lanes and entering trucks. This can result in more conflicts and congestion if the volume of entering trucks is such that it forces main lane traffic to divert to and consequently overload the inside lanes.

2.6.2.4 Summary

Existing research results were reviewed regarding ramp spacing and ramp length design. The results provided a basis for designing appropriate experimental scenarios in this study.

2.7 OPERATIONAL IMPACTS OF FREEWAY AUXILIARY LANES

2.7.1 Wang et al. (2013)

The authors quantified the reduction in density and improvement in the LOS in the merge influence area before and after the addition of auxiliary lanes. Study scenarios were designed with different values of freeway volume, ramp volume, and auxiliary lane length. The density and LOS for each study scenario were estimated with the HCS (2010). Table 2-6 lists the ranges in the reduction in density when auxiliary lanes of different lengths are added to an on-ramp junction.

Table 2-6. Reduction in Density after Adding Auxiliary Lanes.

L_A (ft)	Reduction in density after adding auxiliary lane of length L_A	
	Reduction in density (pc/mi/ln)	Percent reduction (%)
100	0.6	1-5
200	1.2-1.3	2-10
300	1.8-1.9	4-15
400	2.4-2.5	5-20
500	3.0-3.1	6-25
600	3.6-3.8	7-30
700	4.2-4.4	9-35
800	4.8-5.0	10-40
900	5.3-5.6	11-45
1000	5.9-6.3	12-50
1100	6.5-6.9	14-55
1200	7.1-7.5	15-60
1300	7.7-8.2	16-65
1400	8.3-8.8	17-71
1500	8.9-9.4	19-76

2.7.2 Walters et al. (2005) and Walters (2002)

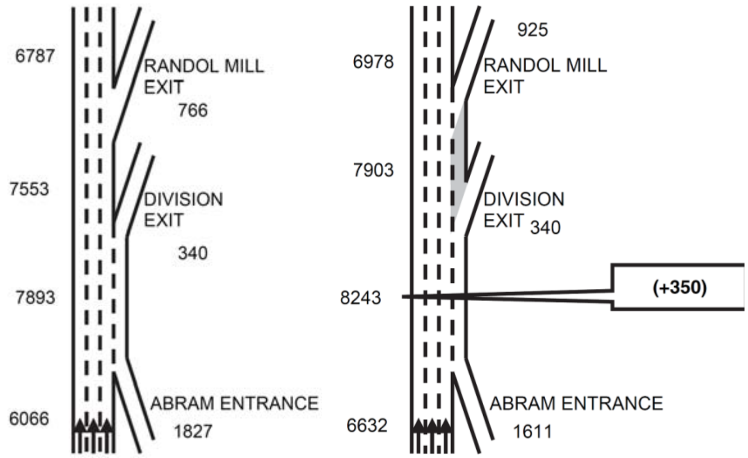
Using case studies involved in bottleneck removal projects in Texas, the authors summarized and evaluated the effects of relatively small geometric and operational improvements at freeway bottlenecks located in Dallas, Fort Worth, and El Paso. The safety analysis was based on historical crash analysis, and the operational benefits were quantified based on a floating-car survey before and after the auxiliary lanes were constructed. The results are presented as Table 2-7.

Table 2-7. Crash Summaries, Benefits, Costs, and Impacts of Auxiliary Lane Implementation in Texas.

TxDOT District	Freeways	Description of Bottleneck Improvements	Crash Rate Change (per 100 MVMT)	Safety Benefit (% change)	Annual Benefit (in Millions)	Cost	Benefit/ Cost	Impacts
Fort Worth	NB SH 360 @ Division (SH 180)	Converted outside shoulder to auxiliary lane between two closely spaced exit ramps	SH 360 (NB): 72.8 to 17.7	NB (+76%)	$0.2	$150 K	10:1	Increased volumes and speeds, improved safety
Dallas	NB IH 35E, IH 30 to Dallas North Tollway	Addition of two auxiliary lanes by inside shoulder conversion	IH 35E (NB): 112.1 to 72.2	NB (+36%)	$0.6	$130 K	37:1	Increased volumes, improved safety
El Paso	EB IH 10 @ US 54	Re-striped one-lane ramp to two lanes, dropped main lane at exit, added lane back at entrance, added auxiliary lane	US 54 (SB): 61.9 to 28.4 IH 10 (EB): 51.7 to 48.7	SB (+54%) EB (+6%)	$1.3	$530 K	20:1	Increased volumes and speeds, improved safety
Fort Worth	SB SH 360 to WB IH 20	Auxiliary lanes on SH 360, dropped main lane on IH 20 at SH 360 exit, added lane back at SH 360 entrance	SH 360 (SB): 65.9 to 30.3 IH 20 (WB): 35.9 to 34.1	SB (+54%) WB (+5%)	$0.03	$8 K	32:1	Improved speeds, volumes, and safety
Fort Worth	SB SH 360 @ Division (SH 180)	Closed entrance ramp, forcing traffic through signal, added auxiliary lane to next entrance	SH 360 (SB): 48.6 to 16.2	SB (+67%)	$1.0	$440 K	18:1	Reduced congestion, improved speeds, crash increase

Adapted from Walters et al., 2005

The results in this study established that auxiliary lanes can significantly improve safety and preserve mobility. Generally, the benefits were high enough to justify the temporary projects, even without including safety benefits or other potential benefits such as reduced driver stress.



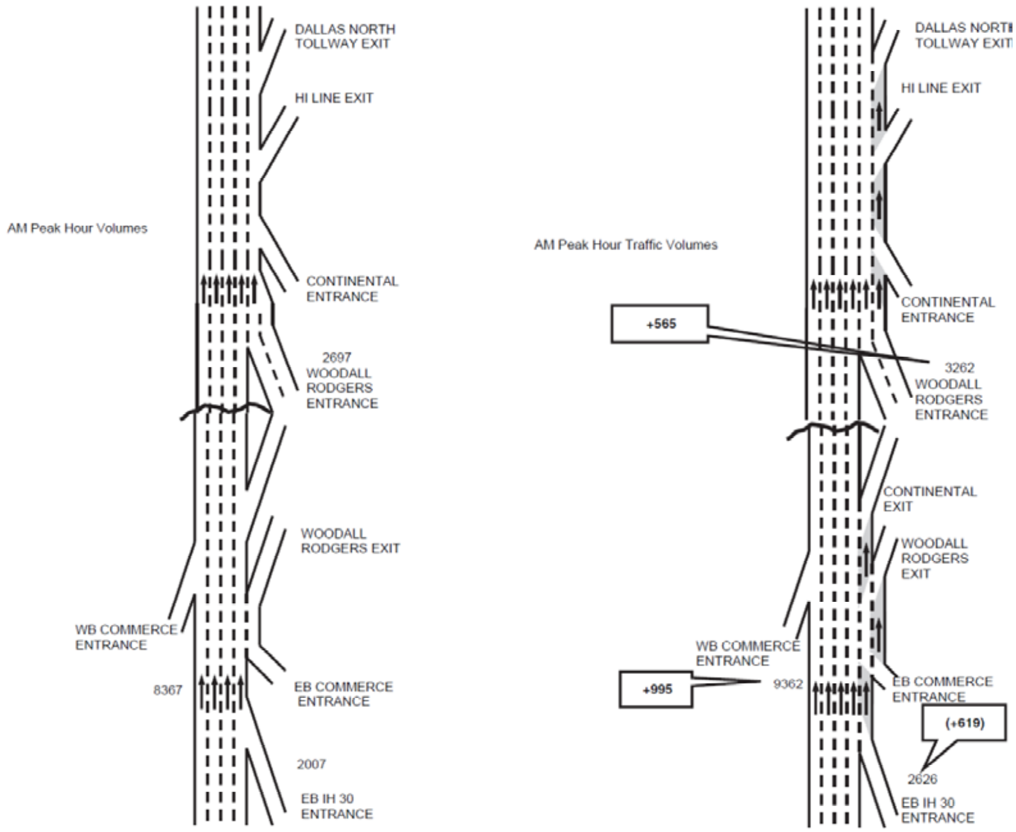
Before condition After condition

Figure 2-17. Northbound SH 360 at Division (SH 180): (a) Before and (b) After Study Lane Layout and Volumes.

(Source: Walters et al., 2005)

As one of the representative case studies that is associated with the use of auxiliary lanes, Figure 2-18 shows the layout in the before and after cases, along with a.m. peak-hour volumes for Northbound SH 360 at Division (SH 180). TxDOT elected to extend the auxiliary lane to the Randol Mill exit, thus effectively adding the use of a fourth lane to this bottlenecked section. This change required use of the outside shoulder under Division, and there was no inside shoulder. Despite some concerns about safety, TxDOT decided to implement the 700-ft auxiliary lane on a trial basis; the cost was only $150,000, and a contractor was already working in the area, installing fiber-optic cable for the intelligent transportation system (ITS) known as TransVision.

After two months of this implementation, the initial data collected showed a high benefit. Speeds through the bottleneck improved significantly and volumes increased as well. The calculated overall delay benefit was $200,000 per year, meaning that the improvement paid for itself in a year. However, another significant benefit was improved safety. Comparing two years of before data with two years of after data, researchers found that an injury crash reduction of 76 percent was sustained in this section after the improvement. In this case, loss of the outside shoulder over the short section was overbalanced by the improved traffic operations.



Before condition After condition

Figure 2-18. Northbound Interstate 35E, Interstate 30 to Dallas North Tollway Exit: (a) Before and (b) After Study Lane Layout and Volumes.

(Source: Walters et al., 2005)

As another of the representative case studies regarding this project, Figure 2-18 shows the layout in the before and after cases, along with morning peak-hour volumes for northbound Interstate 35E, Interstate 30 to Dallas North Tollway exit. After the implementation, the district office received a glowing letter of thanks from a driver on that movement saying that he had just been saved about 10 min per day. The calculated total annual benefit in delay reduction was $600,000, whereas the total cost was only $130,000, mostly for restriping, with some minor shoulder improvement required. An added benefit for this project has been the reduction in crash rate. The authors analyzed the crash rate for 2 years before and 2 years after the improvement and found a reduction of 36 percent in the injury crash rate.

The findings underlined that in addition to the auxiliary lanes designed specifically between an entrance and an exit ramp, providing extended auxiliary lanes between successive exit ramps or between successive entrance ramps can bring very positive operational and safety impacts.

2.7.3 Sato et al. (2011)

Based on field data collected from the Higashi-Meihan Expressway, Japan, the authors found that in the presence of continuous auxiliary lanes at weaving segments, the average breakdown flow at the inbound bottleneck increased by 6 percent (190 vph), and at the outbound bottleneck increased by 3 percent (100 vph). The total delay was reduced by 24 percent in the inbound direction, 62 percent in the outbound direction, and on average 33 percent in both directions, reducing the total delay caused by traffic congestion at the weaving segments.

2.7.4 Neudorff et al. (2003)

In the report, the authors stated that there are a number of parameters of particular importance to the operation of ramp-freeway junctions. The length of the acceleration or deceleration lane has a significant effect on merging and diverging operations. The free-flow speed of the mainline freeway is also an influential factor.

2.7.5 Lu et al. (2009)

In this study, the authors presented simulation results and mathematical models to evaluate operational performance of various types of exit ramps. As previously defined in Figure 2-10, the four types of exit ramps were compared in terms of various measures of effectiveness (MOEs), as shown in Table 2-8.

Table 2-8. Comparison of Exit Ramp Types in Terms of Various MOEs.

(Source: Lu et al., 2009)

MOE	Best → Worst
Number of Lane Change	Type I → Type III → Type II → Type IV
Standard Deviation of Speed	Type IV → Type II → Type III → Type I
Control Delay per Vehicle	Type II → Type IV → Type III → Type I

2.7.6 Cassidy et al. (2002)

Based on loop-detector data for a segment on southbound Interstate 5 in Orange County, California, the authors analyzed the impacts of exit-ramp queues on the freeway mainline traffic in presence of a parallel deceleration lane.

A bottleneck with a diminished capacity was shown to have arisen on a freeway segment whenever queues from the segment's exit ramp spilled over and occupied its parallel deceleration lane (mandatory exit lane). Although the ramp's queues were confined to the rightmost exit lane, non-exiting drivers reduced their speeds upon seeing these queues, and this diminished flows in all lanes. It was also shown that the lengths of these exit queues were negatively correlated with the discharge flows in the freeway segment's adjacent lanes, i.e., longer exit queues from the oversaturated exit ramp were accompanied by lower discharge rates for the non-exiting vehicles. Whenever the exit ramp queues were prevented from spilling over to the exit lane (by changing the logic of a nearby traffic signal), much higher flows were sustained on the freeway segment and a bottleneck did not arise there.

These observations underscored the value of geometric design and control strategies that enable diverging vehicles to exit a freeway unimpeded.

2.7.7 Batenhorst and Gerken (2000)

The authors compared the quality of service provided by a continuous auxiliary lane terminated in a one-lane exit ramp versus a two-lane exit ramp. A case study was conducted at 10 selected sites on the I-35 E corridor and 10 from the SH 114 corridor.

Three software packages, HCM, CORSIM, and Synchro/Simtraffic, were employed to assess the quality of service under the same given conditions at each location. The analysis summary is shown in Table 2-9.

Table 2-9. Summary of Operational Analysis in Batenhorst and Gerken (2000).

Facility	Direction	Location	Number of Upstream Basic lanes	Number of Lanes in Weaving Section	Length of Weaving Section (ft)	Peak Hour Volume (vph) Up-stream Freeway	En-trance Ramp	Exit Ramp	Down-stream Freeway	Exit Ramp Configuration Providing Best Operations HCS	CORSIM	Synchro/ Simtraffic
I-35E	Northbound	Mockingbird to Empire Central	3	4	1,400	4,760	510	270	5,000	1-lane	1-lane	1-lane
I-35E	Northbound	Regal Row to Raceway	3	4	2,100	5,680	1,010	790	5,900	1-lane	2-lane	1-lane
I-35E	Northbound	Northside to Whitlock	3	4	1,900	5,730	1,030	440	6,320	1-lane	1-lane	1-lane
I-35E	Northbound	Hebron Pkwy to Corporate Drive	3	4	2,200	5,690	1,120	590	6,220	1-lane	1-lane	1-lane
I-35E	Northbound	Corporate Drive to SH 121	3	4	1,900	6,220	630	1,000	5,850	1-lane	1-lane	1-lane
I-35E	Southbound	SH 121 to Corporate Drive	3	4	1,900	6,000	940	940	6,000	1-lane	2-lane	1-lane
I-35E	Southbound	Corporate Drive to Hebron Pkwy	3	4	2,300	6,000	520	1,200	5,320	1-lane	1-lane	1-lane
I-35E	Southbound	Vista Ridge to Frankford	3	4	2,700	4,930	810	1,010	4,730	1-lane	1-lane	1-lane
I-35E	Southbound	Regal Row to Empire Central	3	4	2,000	5,280	460	800	4,940	1-lane	1-lane	1-lane
I-35E	Southbound	Empire Central to Mockingbird	3	4	1,500	4,940	450	1,140	4,250	1-lane	1-lane	1-lane
SH 114	Eastbound	Freeport to Esters	3	4	1,400	6,170	330	500	6,000	1-lane	1-lane	1-lane
SH 114	Eastbound	Esters to Belt Line	3	4	3,600	6,000	440	1,060	5,380	1-lane	1-lane	1-lane
SH 114	Eastbound	Belt Line to Valley View	3	4	3,500	5,380	1,250	230	6,400	1-lane	1-lane	1-lane
SH 114	Eastbound	Valley View to Walnut Hill	3	4	2,100	5,090	710	410	5,390	1-lane	1-lane	1-lane
SH 114	Eastbound	O'Connor to Rochelle	2	3	1,900	4,300	420	800	3,920	1-lane	2-lane	1-lane
SH 114	Westbound	Rochelle to O'Connor	2	3	1,100	3,880	870	290	4,460	1-lane	2-lane	1-lane
SH 114	Westbound	O'Connor to Hidden Ridge	2	3	1,100	4,460	1,420	150	5,730	1-lane	2-lane	1-lane
SH 114	Westbound	Valley View to Beltline	3	4	2,200	6,850	900	840	6,910	1-lane	2-lane	1-lane
SH 114	Westbound	Belt Line to Esters	3	4	2,600	6,710	790	620	6,880	1-lane	1-lane	1-lane
SH 114	Westbound	Esters to Freeport	3	4	1,600	6,880	400	700	6,580	1-lane	2-lane	1-lane

The findings of this case study suggested that a one-lane exit ramp may provide the best traffic operations, regardless of the weaving length. A possible explanation may be that with a one-lane exit ramp (see Figure 2-2[a]), all of the exiting traffic must utilize the auxiliary lane. With a two-lane exit ramp (see Figure 2-2[b]), a portion of the exiting traffic remains in the second-right lane (to the left of the auxiliary lane). This would lead to an unevenly distributed traffic density, resulting in a higher density near the exit and additional delay for through traffic.

2.7.8 Summary

Collectively, prior research regarding the operational performance can be summarized as follows:

- Continuous auxiliary lane connecting an entrance ramp and an exit ramp.
  The presence of continuous auxiliary lanes generally provides better traffic operations (Walters et al., 2005; Sato et al., 2011). Batenhorst and Gerken (2000) showed that a one-lane exit ramp provides the best traffic operations, regardless of the weaving length, as opposed to a two-lane exit ramp terminating the auxiliary lanes.
- Parallel exit ramp at an isolated diverge influence area.
  In terms of operational performance, Lu et al. (2009) compared four types of exit ramps; Cassidy et al. (2002) showed that the capacity of the diverge segment was diminished significantly whenever queues occupied or spilled over from the parallel exit ramp.

2.8 ASSESSMENT METHODS FOR OPERATIONAL AND SAFETY PERFORMANCE

2.8.1 Assessment Methods for Freeway Ramp Influence Areas

2.8.1.1 Highway Capacity Manual 2000 (Chapter 25: Ramps and Ramp Junctions)

HCM 2000 provides procedures that allow for the identification of likely congestion at ramp-freeway terminals, LOS F, and for the analysis of operations at ramp-freeway junctions and on-ramp roadways at LOS A through E. The model applies to single-lane, right-hand entrance-ramp merge areas, and a length of 450 m (1,500 ft) ramp influence area is considered.

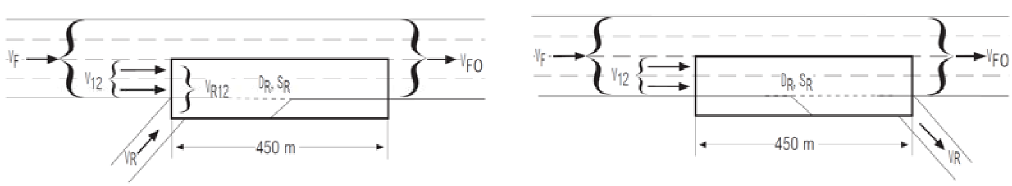


Figure 2-19. Ramp Influence Areas Defined by HCM 2000/2010.

As illustrated in Figure 2-19, a key process in the methodology is to estimate the flow rates of the two lanes on the rightmost of the mainline freeway based on a regression function of the mainline flow rate. If the demand flow is under a capacity that can be looked up in the manual, the LOS ranges from A to E. In addition to the estimated flow rates on the rightmost two lanes, the ramp flow rate and the length of the auxiliary lane (either acceleration lane or deceleration lane) are used to estimate the density at the ramp influence areas. Then, the estimated density can be mapped to different levels of service.

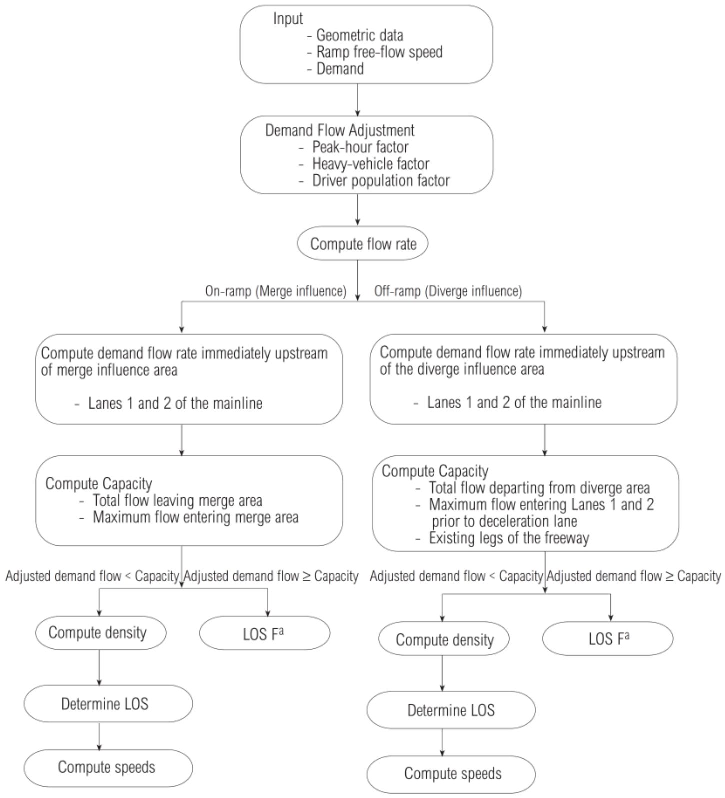


Figure 2-20. Methodology of HCM 2000 Method for Assessing Ramps Influence Areas.

2.8.1.2 Highway Capacity Manual 2010 (Chapter 13: Freeway Merge and Diverge Segments)/NCHRP Report 3-37 (1993)

Similar to the Highway Capacity Manual 2000, the methodology focuses on modeling the operating conditions within the merge/diverge influence area. The LOS is determined based on a similar procedure shown in Figure 2-20: at first, the volumes in Lane 1 and Lane 2 in the influence area are determined. Secondly, the density in the influence area is determined by the volume in Lanes 1 and 2 and the length of the acceleration/deceleration lane. Finally, LOS is determined according to density.

One of the significant differences between HCM 2000 and 2010 is the different equations for estimating density of merge/diverge influence areas.

2.8.2 Assessment Methods for Freeway Weaving Segments

2.8.2.1 Highway Capacity Manual 2000 (Chapter 24: Freeway Weaving)

Detailed procedures for the analysis of operations in freeway weaving segments were provided in this manual. The procedure is characterized by two concepts: operation type (unconstrained and constrained operations) and weaving configuration type (Type A, Type B, and Type C; see illustration in the manual). Look-up tables are provided to categorize a given condition into a specific operation type and a weaving configuration type. Then, separate equations are given to calculate the space mean speed within the weaving segment accordingly. Using the mean speed and the known demand flow rates, a density for the segment can also be computed. LOS is then assigned on the basis of the estimated density.

2.8.2.2 Highway Capacity Manual 2010 (Chapter 12: Freeway Weaving Segments)/Roess and Ulerio (2009)/NCHRP Report 3-75 (2008)

The primary objectives of the research were to produce an improved model for analysis of freeway weaving segments as opposed to the method in HCM 2000. The new method was reported to yield better predictions.

Compared to HCM 2000, another key improvement in this procedure is to estimate the number of weaving and non-weaving lane changes made in the section without having to categorize configuration type or use separate equations, each applying to a specific set of circumstances. Then, the average speed of weaving and non-weaving vehicles is estimated by using two separate equations. Based on the number of lane changes and the weaving flow rates, a density for the segment can also be computed. LOS is then assigned on the basis of the estimated density.

2.8.2.3 Kuhn et al. (2007)

According to the TxDOT report, the use of auxiliary lanes can provide priority access to a special class of users of a general-purpose facility and may delay the onset of congestion on the freeway corridor.

Regarding performance measures, the primary measure used in this guideline is average running speed. AASHTO also indicates that the average running speed is the most appropriate performance measure for evaluating LOS and operations. In addition, throughput can be used as a secondary performance measure.

2.8.3 Comparison between Existing Operational Assessment Methods and Simulation

The procedures in the Highway Capacity Manuals are supported by extensive research and a significant quantity of field data, and the analytical feature makes it easy for practitioners to use (no need for simulation efforts). The analytical feature can provide segment-level performance measures. For the HCM-based analytical approach, a computer-based tool, HCS (2010), can be used for estimating capacity, density, speed, and level of service at the freeway segments before and after the implementation of auxiliary lanes.

As an alternative analysis method, micro-simulation models normally enable users to estimate a wide variety of performance measures and pinpoint detailed problems that might otherwise be unnoticed with a macroscopic analysis. Micro-simulations can explicitly model complex combinations of weaving segments and oversaturated traffic conditions. Micro-simulation can provide corridor-level performance measures, such as corridor throughput, travel time, speed, and delay on the primary travel lanes. These models usually require a significant amount of field data as part of calibration efforts and are computationally intensive.

A comparison between the HCM procedures and micro-simulation models is shown in Table 2-10.

Table 2-10. Strengths and Limitations of the Candidate Approaches to Assessing Auxiliary Lanes.

<table>
<tr><th></th><th>Strengths</th><th>Limitations</th><th>Outputted Performance Measures</th></tr>
<tr><td>HCM (2010) weaving segments</td><td rowspan="2">• Procedures supported by extensive research and a significant quantity of field data
• Directly providing deterministic estimate of density and capacity
• Considering geometric characteristics (such as lane widths), which are rarely incorporated into simulation</td><td rowspan="2">• Inapplicable for oversaturated traffic conditions
• Not explicitly considering posted speed limits or level of police enforcement
• Inability to consider complex combinations of weaving segments</td><td>• Weaving segment capacity
• Speed (for weaving and non-weaving vehicles)
• Weaving segment density
• LOS of roadway segment</td></tr>
<tr><td>HCM (2010) merge and diverge segments</td><td>• Merge/Diverge influence area capacity
• Ramp roadway capacity
• Influence area density
• Speed (ramp influence area and outer lanes of freeway)
• LOS</td></tr>
<tr><td>Micro-Simulation</td><td>• A wider range of performance measures at both segment level and corridor level
• Explicitly model oversaturated traffic conditions
• Ability to model complex combinations of weaving segments</td><td>• Not always explicitly considering geometric characteristics (such as lane widths)
• Need for being calibrated using a significant quantity of field data</td><td>A wider range of performance measures at both segment level and corridor level, such as delay, stops, queue lengths (enabling both deterministic and stochastic analysis)</td></tr>
</table>

2.8.4 Assessment Methods of Safety Impacts of Auxiliary Lanes

Simulation-based safety analysis can be a suitable alternative to the traditional crash data analysis.

2.8.4.1 Le (2009)

This study focused on a typical lane arrangement in the presence of continuous auxiliary lanes between an entrance ramp and a one-lane exit ramp, as shown in Figure 2-2(a). Two surrogate safety measures, including deceleration rate and crash potential index, were formulated and used as safety indicators. Generally, the method is similar to the one that was proposed for this TxDOT research project.

Correlation analysis showed that using the traffic conflict technique, microscopic simulation can possibly be used for evaluating safety performance of weaving areas. Surrogate measures can reflect the pattern of crash history and can possibly be used as an alternative to crash history as traffic safety indicators. The authors stated that even with its current limitation, this technique can be used to evaluate safety performances of different designs of weaving sections, which in part justified the method selected for this TxDOT research project.

2.9 SUMMARY

To develop a full context for this project, a total of 46 journal/proceeding articles, research reports, and guidelines/manuals were reviewed. Related practices and prior studies were documented and synthesized in this chapter.

The researchers summarized the related guidelines in the AASHTO Green Book as well as guidelines in the highway design manuals of peer state DOTs. These guidelines provide the requirements in determining the lane arrangement at weaving/merge/diverge areas, such as consistency of basic number of lanes and principles of lane balance. Some detailed provisions in state DOT guidelines are also presented in this document, in terms of whether the design of freeways should explicitly comply with lane balance rules, what factors should be considered in designing auxiliary lanes, quantitative warrants, and length/width for auxiliary lanes and shoulders.

The researchers also synthesized the available results and findings on the safety and operational impacts of auxiliary lanes. Regarding safety performance, the lane arrangement has significant effects where the use of auxiliary lanes is considered. For example, an auxiliary lane connecting an entrance ramp and a one-lane exit ramp is generally safer than one connecting an entrance ramp and a two-lane exit ramp. Also, one-lane parallel exit ramps are associated with lower average crash frequency and crash rate compared to one-lane taper exit ramps. For two-lane exit ramps, taper exit ramps are safer than parallel exit ramps (Lu et al., 2009). In terms of operational performance, some research findings are available; for example, the presence of continuous auxiliary lanes generally provides better traffic operations. The capacity of the diverge segment is diminished significantly whenever queues occupy or spill over from the parallel exit ramp.

The researchers also reviewed driver behavior at merge/diverge/weaving segments, as well as assessment methods that were potentially useful to the conduct of this research.

Collectively, the review on the prior research further justified the critical needs for this research project, as the operational and safety benefits of auxiliary lanes depend on a wide range of design and operations factors. The prior work described in this report also provided a basis for better understanding the research issues/questions to be solved by this project. These resources helped the research team clearly map out specific strategies to accomplish the work described in the following chapters in this project.

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CHAPTER 3: SURVEY OF TRANSPORTATION ENGINEERS

To collect information, both within Texas and nationally, about current practices and implementations related to the design and scope of the impact of auxiliary lanes, the research team developed and conducted a survey of transportation professionals at state departments of transportation. This survey was developed with support and feedback from members of the Project Management Committee. This chapter presents the results and findings of the survey, which were useful for the activities described in subsequent chapters.

3.1 SURVEY DESIGN

The survey was developed to gather information about current practices and implementations of auxiliary lanes. The survey included both open-ended questions and multiple-choice questions.

The survey began with an introduction to the project. It continued with the definition of auxiliary lane and the figures describing typical design of weaving and entrance ramp/exit ramp segments with auxiliary lanes. Several questions regarding the design and use of auxiliary lanes were presented. These questions attempted to gather information about the current guidebooks, manuals, tools, and performance measures used at state DOTs. Additionally, questions were asked about the influencing areas at the upstream and downstream of the weaving segments, entrance ramp, and exit ramps. The final questions were open-ended and asked when respondents would consider the use of auxiliary lanes in highway geometric design, what respondents think of the impacts of using auxiliary lanes, and what respondents think of using freeway shoulders as auxiliary lanes. The last question requested respondents further provide their experiences, lessons, or issues related to the design and use of auxiliary lanes. The survey instrument is available in the Appendix.

3.2 SURVEY RESULTS

The survey was conducted through a website from November 9, 2011, to December 15, 2011. Invitations were emailed by Jane Lundquist, P.E., project director, to relevant staff identified within TxDOT. Other invitations were emailed by the research team to traffic engineers at state transportation departments throughout the country.

A total of 59 responses were received. Two engineers appeared to submit their responses twice. Therefore, only their second (latest) responses were analyzed, bringing the total to 57 unique responses. Of those, 26 were from within Texas and 31 were from states other than Texas. The number of respondents from Texas and other states are approximately the same. The respondents outside of Texas came from the following states, with the numbers included in brackets:

- Arizona (3).
- Arkansas.
- Connecticut.
- Illinois.
- Georgia.
- Kentucky (2).
- Kansas.
- Louisiana.
- Maine.
- Michigan.
- Minnesota.
- Mississippi.
- Montana.
- North Carolina.
- Nebraska (2).
- New Hampshire.
- New Mexico.
- Ohio.
- Oregon.
- Pennsylvania (2).
- California.
- Tennessee.
- Virginia.
- Vermont.
- Washington (2).

The following sections report the results obtained for each question. The respondent statements were deliberately not edited (including spelling or grammatical errors) in order to retain their real inputs. The respondent identities have also been kept anonymous in this report.

3.2.1 Question 1(a)—Design Manuals

Question 1(a): Do you use any manual when designing auxiliary lanes? (you may select more than one answer)

In this question, respondents were asked to select any manual they were using in the design of auxiliary lanes. The options include six national manuals, which are AASHTO's *A Policy for Geometric Design of Highways and Streets* 2004 and 2011 editions, also known as the Green Book (AASHTO, 2004, 2011), Manual of Uniform Traffic Control Devices 2006 and 2009 editions (FHWA, 2004, 2009), Highway Capacity Manual 2000 and 2010 editions (TRB, 2000, 2010), and others manuals. It was expected that engineers in Texas would fill in the Texas MUTCD (TxDOT, 2006). The number of respondents for this question was 50.

3.2.2.1 Selected Manuals

As shown in Figure 3-1, the majority of respondents in both Texas and other states selected AASHTO's A Policy for Geometric Design of Highways and Streets 2004 edition (AASHTO, 2004), followed by the HCM 2010 edition (HCM, 2010), MUTCD 2009 edition (MUTCD, 2009), and HCM 2000 edition (HCM, 2000). The AASHTO A Policy for Geometric Design of Highways and Streets 2011 edition (AASHTO, 2011), as a newly available manual, has not been widely used. The MUTCD 2006 edition (MUTCD, 2006) appeared to have been superseded by MUTCD 2009.

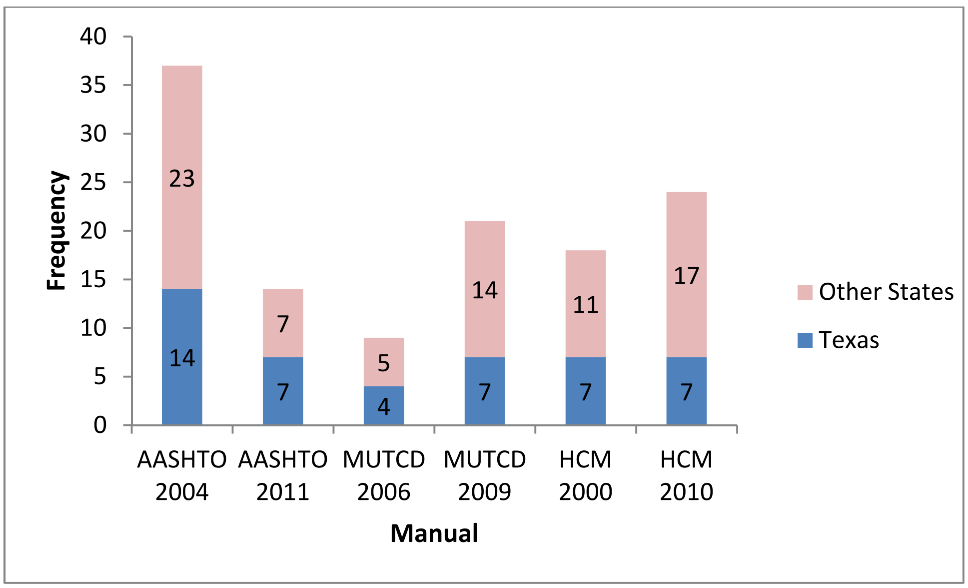

Figure 3-1. Current Manuals.

3.2.2.2 Other Manuals

For Texas respondents, the only manual specified was the TxDOT Roadway Design Manual. For other states' respondents, several manuals were specified, as listed in Table 3-1. These states appear to have their own manuals that are modified from or supplement the national manuals. Table 3-2 lists the unedited responses from all the 50 respondents.

Table 3-1. Manuals Used in Other States.

States	Other Design Manuals
Arizona	MUTCD 2003 Edition and Arizona Supplement to the 2003 MUTCD; we have not adopted the 2009 MUTCD—we expect to adopt this edition in January 2012
Arkansas	We will begin using the 2011 Green Book as soon as we receive it.
Illinois	I do not do design work, but I typically reference IDOT's Bureau of Design & Environment's design manual for policy issues and for complicated situations the 2010 HCM and the 2004 Green Book.
Kentucky	KYTC Design Guidance Manual and Design Memo (link provided in question #4)
Maine	MaineDOT Highway Design Guide
Michigan	DEPT. GEOMETRIC DESIGN
Ohio	At time of survey, those manuals are most current. Also use ODOT Location and Design Manual, Vol. 1
Oregon	Oregon Highway Design Manual
Washington	We primarily use our WSDOT Design Manual

Table 3-2. Complete Listing of All the Responses for Question 1.

State	Design Manuals						
	AASHTO 2004	**AASHTO 2011**	**MUTCD 2006**	**MUTCD 2009**	**HCM 2000**	**HCM 2010**	**Others, please specify**
Texas				X			
Texas							TxDOT Roadway Design Manual
Texas	X				X		
Texas		X		X		X	TxDOT’s Roadway Design Manual
Texas	X				X	X	
Texas	X		X				TxDOT Roadway Design Manual
Texas		X		X		X	Roadway Design Manual
Texas	X		X		X		
Texas							TxDOT Design Manual
Texas	X						TxDOT Roadway Design Manual
Texas		X		X			TxDOT Roadway Design Manual
Texas		X					TxDOT Roadway Design Manual
Texas		X					
Texas	X			X			TxDOT Roadway Design Manual
Texas	X						
Texas		X		X		X	
Texas	X		X				
Texas	X				X		
Texas	X			X		X	
Texas	X				X		TxDOT Roadway Design Manual
Texas	X	X			X	X	TxDOT Roadway Design Manual
Texas	X				X		
Texas	X		X			X	
Arizona	X				X		MUTCD 2003 Edition and Arizona Supplement to the 2003 MUTCD; we have not adopted the 2009 MUTCD—we expect to adopt this edition in January 2012
Arizona	X			X		X	
Arkansas	X			X		X	We will begin using the 2011 Green Book as soon as we receive it.

California	X		X		X		
Connecticut		X		X		X	
Georgia	X			X		X	
Illinois	X					X	I do not do design work, but I typically reference IDOT's Bureau of Design & Environment's design manual for policy issues and for complicated situations the 2010 HCM and the 2004 Green Book.
Kansas	X					X	
Kentucky	X		X		X		
Kentucky	X						KYTC Design Guidance Manual and Design Memo (link provided in question #4)
Louisiana	X		X			X	
Maine	X	X	X				MaineDOT Highway Design Guide
Michigan	X				X		DEPT. GEOMETRIC DESIGN
Minnesota	X	X				X	
Mississippi		X				X	
Montana	X			X			
Nebraska	X			X		X	
Nebraska	X	X		X	X	X	
New Mexico	X			X		X	
North Carolina					X	X	
Ohio	X					X	At time of survey, those manuals are most current. Also use ODOT Location and Design Manual, Vol. 1
Oregon	X			X	X	X	Oregon Highway Design Manual
Pennsylvania	X	X		X	X		
Pennsylvania		X		X	X	X	
Virginia	X			X		X	
Washington	X			X	X		
Washington	X		X	X	X		We primarily use our WSDOT Design Manual
No response	7						

3.2.2 Question 1(b)—Local Manuals and Guidelines

Question 1(b): Does your organization have any local manual/guideline? If yes, please provide the name of the manual/guideline

This question asked about the local manuals in use at state DOTs. The local manuals may be at the state, regional, county, or city level and developed based on local experience. Of the 57 respondents, 44 respondents provided feedback on their local manuals. For Texas respondents, the only local manual provided was the TxDOT Roadway Design Manual. For other states' respondents, several state manuals were mentioned, as summarized in Table 3-3. Table 3-4 lists the unedited inputs from all respondents.

Table 3-3. Local Manuals and Guidelines Used in Other States.

States	Local Manuals and Guidelines
Arizona	Arizona Roadway Design Guide
California	Caltrans Highway Design Manual
Connecticut	ConnDOT Highway Design Manual
Georgia	Georgia Standard Construction Drawings
Illinois	Bureau of Design & Environment's (IDOT) design manual
Kansas	KDOT Standard Drawings
Kentucky	KYTC's Highway Design Manual and the Auxiliary Turn Lane Policy
Kentucky	Design Memo at http://transportation.ky.gov/Highway-Design/Memos/Design,%20Permits,%20Traffic%2003-09.pdf
Maine	MaineDOT Highway Design Guide
Michigan	Geometric Design Guide
Minnesota	MnDOT Road Design Manual
Mississippi	MDOT Roadway Design Manual
Montana	MDT Traffic Engineering Manual
North Carolina	Roadway Design Manual
Ohio	ODOT Location and Design Manual, Vol. 1 (Section 500) http://www.dot.state.oh.us/Divisions/Engineering/Roadway/roadwaystandards/Pages/locationanddesignmanuals.aspx
Oregon	Oregon Highway Design Manual
Pennsylvania	Publication 13M (Design Manual 2) and Publication 46 (Traffic Engineering Manual)
Pennsylvania	Pub 46 section 11.17 ftp://ftp.dot.state.pa.us/public/PubsForms/Publications/PUB%2046.pdf
Virginia	VDOT Road Design Manual
Washington	WSDOT Design Manual/Standard Plans/Standard Specs.
Washington	WSDOT Design Manual

Table 3-4. Complete Listing of All the Responses for Question 1(b).

State	Does your organization have any local manual/guideline?	
	Response	If Yes, the name of the manual/guideline
Texas	Yes	TxDOT Roadway Design Manual
Texas	Yes	TxDOT Roadway Design Manual
Texas	Yes	Roadway Design Manual
Texas	Yes	TxDOT's Roadway Design Manual
Texas	Yes	TxDOT Roadway Design Manual
Texas	Yes	see question #3 above
Texas	Yes	Roadway Design Manual
Texas	No	
Texas	Yes	TxDOT Design Manual
Texas	Yes	TxDOT Roadway Design Manual
Texas	Yes	TxDOT Roadway Design Manual
Texas	Yes	TxDOT Roadway Design Manual
Texas	Yes	TxDOT Roadway Design Manual (5R Design Standards)
Texas	Yes	TxDOT Roadway Design Manual
Texas	Yes	TxDOT Roadway Design Manual
Texas	Yes	Roadway Design Manual
Texas	Yes	TxDOT Design Manual and Standards
Texas	Yes	Roadway Design Manual (general information)
Texas	Yes	Texas MUTCD
Texas	Yes	TxDOT Roadway Design Manual
Texas	Yes	TxDOT Roadway Design Manual
Texas	Yes	TxDOT Roadway Design Manual
Texas	Yes	Roadway Design Manual
Arizona	Yes	Arizona Roadway Design Guide
Arizona	No	
Arkansas	No	
California	Yes	Caltrans Highway Design Manual
Connecticut	Yes	ConnDOT Highway Design Manual
Georgia	Yes	Georgia Standard Construction Drawings
Illinois	Yes	Bureau of Design & Environment's (IDOT) design manual
Kansas	Yes	KDOT Standard Drawings
Kentucky	Yes	KYTC's Highway Design Manual and the Auxiliary Turn Lane Policy
Kentucky	Yes	Design Memo at http://transportation.ky.gov/Highway-Design/Memos/Design,%20Permits,%20Traffic%2003-09.pdf
Louisiana	No	
Maine	Yes	MaineDOT Highway Design Guide
Michigan	Yes	GEOMETRIC DESIGN GUIDES
Minnesota	Yes	MnDOT Road Design Manual
Mississippi	Yes	MDOT Roadway Design Manual
Montana	Yes	MDT Traffic Engineering Manual
Nebraska	No	
New Mexico	Yes	
North Carolina	Yes	Roadway Design Manual
Ohio	Yes	ODOT Location and Design Manual, Vol. 1 (Section 500) http://www.dot.state.oh.us/Divisions/Engineering/Roadway/roadwaystanda

		rds/Pages/locationanddesignmanuals.aspx
Oregon	Yes	Oregon Highway Design Manual
Pennsylvania	Yes	Publication 13M (Design Manual 2) and Publication 46 (Traffic Engineering Manual)
Pennsylvania	Yes	Pub 46 section 11.17 ftp://ftp.dot.state.pa.us/public/PubsForms/Publications/PUB%2046.pdf
Vermont	No	
Virginia	Yes	VDOT Road Design Manual
Washington	Yes	WSDOT Design Manual/Standard Plans/Standard Specs.
Washington	Yes	WSDOT Design Manual
No response	7	

3.2.3 Question 2—Performance Measures

Question 2: What are the performance measures you are using to measure the quality of service at weaving segments and entrance ramp/off ramp junctions? (you may select more than one answer)

In this question, respondents were asked to select performance measures they had been using to evaluate the quality of service at weaving segments and entrance-ramp/off-ramp junctions. The options included three performance measures: density, demand, and speed. The number of respondents for this question was 45. As shown in Figure 3-2, the majority of respondents in Texas selected demand, while the majority of respondents in other states selected density and/or speed. Overall, speed is the most frequently mentioned measure.

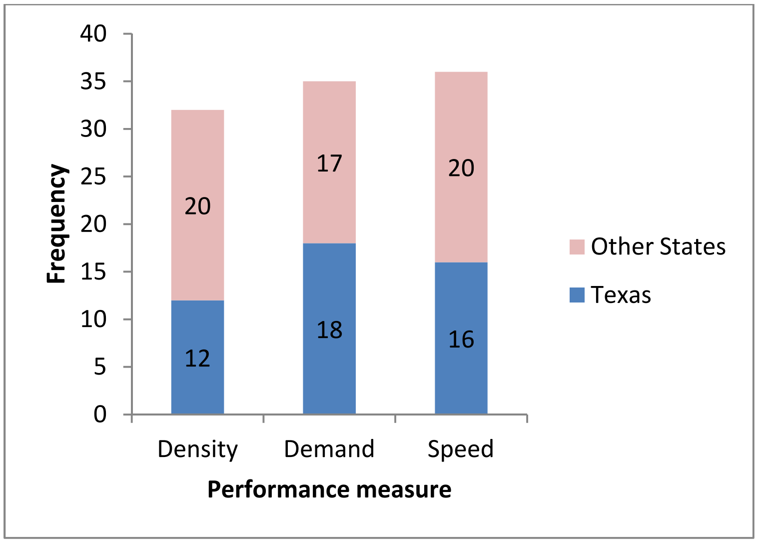

Figure 3-2. Performance Measures.

Table 3-5 lists the other performance measures used in Texas and other states. Table 3-6 lists the unedited results from all the 45 respondents.

Table 3-5. Other Performance Measures.

State	Other performance measures
Texas	Level of Service
Texas	Not measuring quality of service, just requesting them if we think they are needed for above reasons.
Texas	Location Topography
Texas	Distance between ramps and/or major interchanges can control aux. lane design
Nebraska	HCM 2010 Level of Service
Pennsylvania	Volume to Capacity, Level of Service, Delay
Washington	travel time, throughput of downstream lanes

Table 3-6. Complete Listing of All the Responses for Question 2.

State	Performance Measures			
	Density	Demand	Speed	Others
Texas		X	X	
Texas	X	X	X	
Texas		X	X	Level of Service
Texas	X	X	X	
Texas	X	X	X	
Texas	X	X	X	Not measuring quality of service, just requesting them if we think they are needed for above reasons.
Texas	X	X	X	
Texas		X	X	Location Topography
Texas			X	
Texas	X	X	X	
Texas	X	X	X	
Texas	X			
Texas			X	
Texas	X	X		
Texas		X	X	
Texas		X		
Texas	X	X		
Texas	X	X	X	
Texas	X	X	X	Distance between ramps and/or major interchanges can control aux. lane design
Texas		X	X	
Texas		X		
Arizona	X	X	X	
Arizona	X	X	X	
Arkansas	X	X	X	
California		X		
Connecticut	X	X	X	
Georgia	X	X	X	
Illinois	X		X	
Kansas	X	X		

Kentucky	X	X	X	
Kentucky	X	X	X	
Louisiana	X	X	X	
Maine	X		X	
Michigan	X		X	
Minnesota		X	X	
Mississippi				We don't currently use any performance measures
Nebraska	X	X	X	HCM 2010 Level of Service
Nebraska	X	X	X	
New Mexico		X	X	
North Carolina	X		X	
Ohio	X		X	
Pennsylvania	X	X	X	Volume to Capacity, Level of Service, Delay
Virginia	X	X	X	
Washington	X	X	X	travel time, throughput of downstream lanes
Washington	X			
No response	12			

3.2.4 Question 3—Tools and Software

Question 3: What tools and/or software are you using to determine the level of service at weaving segments and entrance ramp/off ramp junctions? Please list all the tools and software. Are these tools/software able to model operational and/or safety impact of adding an auxiliary lane? What kind of impact?

This question asked about the tools and software that were being used to determine the LOS at weaving segments and entrance-ramp/off-ramp junctions, and whether these tools and software could model the operational and/or safety impacts of adding an auxiliary lane. This was an open-ended question. The respondents were expected to provide their answers in text. The number of respondents for this question was 40. Table 3-7 lists the unedited returns from all the respondents.

Several tools for modeling operational impacts were frequently listed. They are HCS, VISSIM, CORSIM, Microstation, GeoPak, Synchro, VISSUM, Paramitics, TransModeller, and FREEVAL. Figure 3-3 shows the frequency count of these tools. As shown in Figure 3-3, the most commonly used software/tools for modeling operational impacts are HCS, VISSIM, and CORSIM.

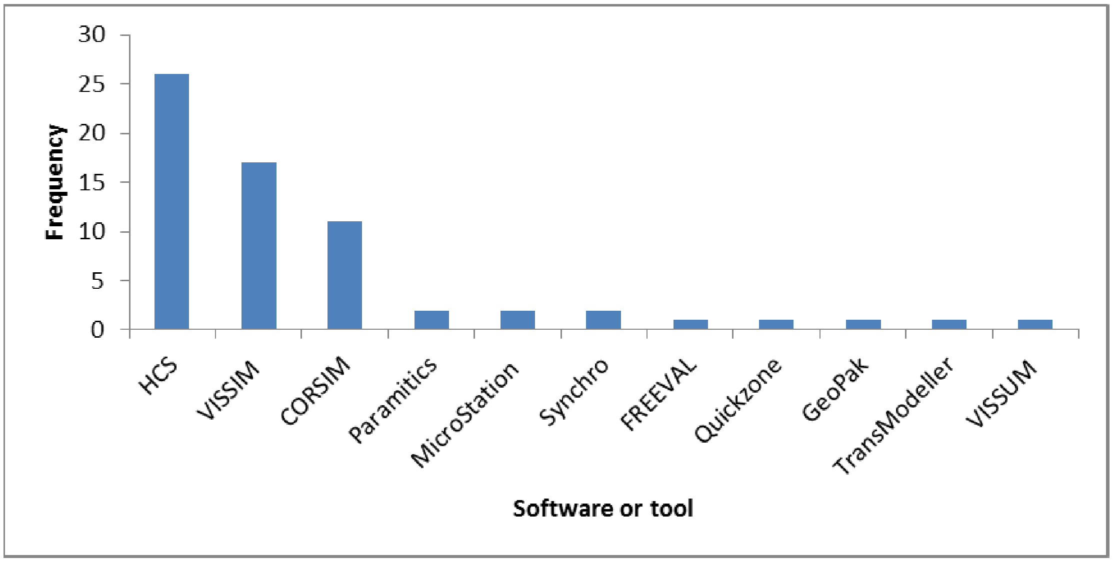

Figure 3-3. Software and Tools.

For modeling safety impacts, most of the respondents did not mention any software or tools. A few respondents stated that microscopic traffic simulation tools could not be used directly to assess the safety impact. This is consistent with the research team's experience. Only five respondents mentioned that they used the following methods to model the safety impacts: crash reports, FHWA Highway Safety Manual, Texas Roadway Safety Design software, VISSIM combined with Siemens Surrogate Safety Assessment Model (SSAM), and Safety Analyst.

Table 3-7. Complete Listing of All the Responses for Question 3.

State	Response
Texas	None
Texas	I work in the Plans Specifications and Estimate preparation section. We prepare and assemble the PS&E. We take the schematic and refine it to fit the survey. Level of service is determined by the section that develops the schematic called "Advanced Project Development". They use the Highway Capacity Manual and various computer software to design auxiliary lanes and we incorporate what they give us in our plans. We are bound to use what they give us since it goes through review at the schematic stage in Austin and at FHWA and is then presented at Public Hearings and is incorporated into the Environmental document. The PS& E must match the approved schematic.
Texas	In our district, we have these freeway segments analyzed by a consultant or transportation research agency (TTI). Typically they use the Synchro modeling software.
Texas	CORSIM HCS VISSIM Yes, they model operational impact of adding an auxiliary lane. They model speed, density, and other MOEs. The safety impact is not typically quantitative, however relatively new research in Crash Modification Factors may lend themselves to providing an expected safety improvement.
Texas	Have not used any type of modeling software, just requesting auxiliary lanes if there are high accidents to back up their use or anticipate traffic problems associated with a new business or development coming in.
Texas	Most recent average daily traffic counts. MicroStation GeoPak third party softwares. No.
Texas	None
Texas	CORSIM, Highway Capacity Manual. Not sure about CORSIM being able to model operational and/of safety impact of adding an auxiliary lane. Not an expert in CORSIM.
Texas	I do not use other tools

Texas	Various Manuals
Texas	None
Texas	In my capacity as a Plan Reviewer, I only make reference to and use as guides the manuals available to ensure that minimum design criteria are met.
Texas	VISSUM SOFTWARE; Highway Capacity Manual; AASHTO; Texas Roadway Manual; Texas MUTCD
Texas	Highway Capacity Manual Software
Texas	HCS (Highway Capacity Software)—determines LOS with safety factors Highway Capacity Manual—determines LOS with safety factors Corsim—traffic model, does not handle safety issues as well VISSIM—for large multimodal corridors Microstation—Capacity software can recommend an aux lane in a certain location, but it may not be geometrically feasible. This can result in an iterative process between geometric design and traffic analysis.
Texas	Highway Capacity Software (Operational Impact) Texas Roadway Safety Design software (Safety Impact)
Texas	HCM 2010 Crash Reports
Arizona	Highway Capacity Manual Software.
Arizona	HCM/HCS, VISSIM. We use both to evaluate the operational performance.
Arkansas	HCM/HCS, VISSUM. We use both to evaluate the operational performance.
California	Simulation modeling software tools are used (Corsim, Paramics, Vissim, TransModeller) to provide LOS for weaving and on\off ramp junctions. Caltrans' Highway Design manual recommends Leisch method and LOS D methods to evaluate weaving. These tools can model the operational impacts of auxiliary lanes if the model is properly developed including the control at the ramp terminal. Type of impacts include delay, capacity, queuing, and speed.
Connecticut	Highway Capacity Manual (HCS), VISSIM. VISSIM can model the operational impacts but not the safety impacts. We are about the receive training on the FHWA Highway Safety Manual, hopefully that will allow us to model the safety impacts.
Georgia	HCS 2010 CORSIM
Illinois	I do not use any software, but IDOT and IDOT's project consultants will use the Highway Capacity Software and for complicated projects VISSIM or CORSIM.
Kansas	Modeling Software—VISSIM, Synchro, Corsim, Quickzone, HCM Software. These are used to measure operational impacts, particularly Level of Service (Queuing and Delay).
Kentucky	HCM and maybe CORSIM or VISSIM
Kentucky	Highway Capacity Manual, VISSIM, Corsim are some that are consultants use.
Louisiana	2010 HCM software
Michigan	HCM
Minnesota	Highway Capacity Manual VISSIM CORSIM All used to model the traffic operational aspects of aux lane provision and design, typically to assess the benefit (versus) cost of such provision or comparative benefit of different designs (lengths usually).
Mississippi	HCM
Nebraska	HCM 2010 via HCS; The HCS software only models operational aspects. The impacts are delay, etc. at a macroscopic level. Microsimulation via CORSIM and VISSIM: These tools model density, speeds, throughput, weaving, etc. at the microscopic level.
New Mexico	We use HCS 2010 weaving module, AASHTO 2004 and state Access manual for guidance. The tools provide operational impact.
North Carolina	HCM2000 (we don't have HCM2010 software yet) including FREEVAL. CORSIM, VISSIM. All will analyze operational impacts of auxiliary lanes, with the simulations doing a better job. In theory, VISSIM combined with SSAM can show safety impacts, but in practice it's not quite there yet.
Ohio	HCS 2000, recently switched to HCS 2010. Also, simulation tools may be used to supplement analysis. ODOT uses VISSIM and sometimes CORSIM. None of these tools model safety impacts of auxiliary lanes.

Pennsylvania	Highway Capacity Software is used for simple evaluations. For more complex evaluations advanced simulation models such as VISIM or Parametics may be used if approved by the appropriate Department Engineering District. Most of the Department's focus on software is geared towards access management along arterial segments. We have begun to use Real-Time Traffic Speed Information (INRIX, inc.) to begin to provide some information when calibrating the analysis. The Department is currently evaluating the 2010 HCM and associated software platforms to determine the appropriate criteria and analysis methodologies it should be completing for each type of project. Once completed with this effort, a more systematic way of performing these type of analysis will be available to those performing the analysis in Pennsylvania.
Pennsylvania	HCM
Virginia	Highway Capacity Software CORSIM
Washington	HCS+T7F and VISSIM
Washington	2000 Highway Capacity software (HCS) VISSIM Just beginning to analyze the safety part of the operation using Safety Analyst
No response	17

3.2.5 Question 4(1)—Influence Areas of Weaving Segments

Question 4(1): What are the operational or safety influencing areas at the upstream and downstream of the weaving segments? Please give estimates of the influencing distances as shown in the following figure based on your experience.

This question asked respondents what they thought was the operational or safety influencing areas at the upstream and downstream of the weaving segments. The number of respondents for this question was 29. The low number of respondents perhaps reflected that in practice, some of the engineers did not consider upstream and/or downstream areas in the design of auxiliary lanes. Among the respondents, 14 out of the 29 provided specific thresholds of the influence area. Table 3-8 analyzes the thresholds provided. Table 3-9 lists the unedited answers from all the respondents.

From the analysis in Table 3-8, it appears that the results from the Texas respondents are lower than those from other states' respondents, for all of the average, minimum, and maximum values.

Among the respondents who did not provide specified threshold values (see Table 3-9), some of them did not measure the influence area by distance. Some others thought that the lengths of the influencing areas are dependent on the following factors:

- Sight distance.
- Demand.
- Geometry.
- Number of lanes.
- Type of vehicles entering traffic flow (heavy trucks, buses, etc.).

Table 3-8. Thresholds of Influence Areas at Weaving Segments.

State		Distance on the entrance ramp, L_r (ft)	Distance on the upstream of mainline freeway, L_u (ft)	Distance on the downstream of mainline freeway, L_d (ft)
Texas		200	150	200
Texas		1500	1500	1500
Texas		500	1000	500
Texas		50	25	25
Texas		700	1000	NA
Texas		200	500	200
Texas		500	1500	1500
Texas		150	500	200
Texas		200-300	1000	500
Texas		1500	850	850
California		250	2000	2000
Kentucky		250	600	300
Michigan		1500	3000	1500
Mississippi		500	1000	500
New Mexico		500	500	500
Washington		500	1000	500
Average	**Texas**	**555**	**803**	**608**
	Other States	**583**	**1350**	**883**
	All	**566**	**1008**	**718**
Minimum	**Texas**	**50**	**25**	**25**
	Other States	**250**	**500**	**300**
	All	**50**	**25**	**25**
Maximum	**Texas**	**1500**	**1500**	**1500**
	Other States	**1500**	**3000**	**2000**
	All	**1500**	**3000**	**2000**

Table 3-9. Complete Listing of All the Responses for Question 4(1).

State	The distance on the entrance ramp, L_r	The distance on the upstream of mainline freeway, L_u	The distance on the downstream of mainline freeway, L_d
Texas	200	150	200
Texas	Per the TxDOT Roadway Design Manual the minimum weaving length with an auxiliary lane is 1500 ft measured from gore to gore.	Per the TxDOT Roadway Design Manual the minimum weaving length with an auxiliary lane is 1500 ft measured from gore to gore.	Per the TxDOT Roadway Design Manual the minimum weaving length with an auxiliary lane is 1500 ft measured from gore to gore.
Texas	500 feet	1000 feet	500 feet
Texas	Consider merging sight distance, entrance ramp demand, entrance ramp geometry, type of vehicles entering traffic flow(ex. heavy trucks, buses, etc.)	Look through lane sight distance, cross slope control location	Look at cross slope control location, vertical and horizontal alignments
Texas	?—all depends on traffic volumes and geometry,.	1000' feet to 0.5 mile maybe more depending on volumes	1000'-1500'

		and geometric elements	
Texas	not designed for this situation, but try to maintain 300" from gore point for safety sake	same as above	same as above
Texas	50	25	25
Texas	700 feet	1000 Feet	NA
Texas	would follow AASHTO recommendation	would follow AASHTO recommendation	would follow AASHTO recommendation
Texas	200 FT	500 FT	200 FT
Texas	500'	1500'	1500'
Texas	150	500	200
Texas	200-300	1000	500
Texas	1500	850	850
Arizona	Peak Hours (i.e., 6-9 a.m. & 3-7 p.m.): 1000 feet; Non-Peak Hours: 50 feet	Peak Hours: 2500 feet; Non-Peak Hours: 100 feet	Peak Hours: 200 feet; Non-Peak Hours: 0 feet
Arizona	For a one lane on/off ramp as shown, we typically do not estimate this value.	It can vary substantially, we do not use a single value. However, in our experience, the value shown in the HCM is too low.	We typically do not estimate this value.
Arkansas	For a one lane on/off ramp as shown, we typically do not estimate this value.	It can vary substantially. We do not use a single value. However, in our experience, the value shown in the HCM is too low.	We typically do not estimate this value.
California	250'	2000'	2000'
Illinois	I could not view image	I could not view image	I could not view image
Kansas	Not Measured	Not Measured	Not Measured
Kentucky	250	600	300
Louisiana	Varies based on volume, where merging occurs, and the # of lanes	Varies based on volume/# of lanes, weaving type/length, other access	Varies based on # of through lanes, other access, weaving type
Michigan	1500	3000	1500
Minnesota	No data or valid estimate available.	No data or valid estimate available.	No data or valid estimate available.
Mississippi	500'	1000'	500'
Nebraska	Lr—the driver will be influenced by the weave as soon as they enter the ramp. There will be almost no influence when a driver exits the ramp.	Highly dependent on volume, density, the length of the weaving segment, etc. The driver can be influence many miles in advance (by moving into the correct lane) if the conditions are bad. I do not believe there is a specific distance that applies to all situations.	Only a short distance. 100 to 500'
New Mexico	500'	500'	500'
Virginia	Varies based on design speed/AASHTO Ex 10-70	distance governed by weaving considerations	taper length based on design speed

Washington	approx 500 feet (depends upon sight distance, v/h curvature, veh mix, volume etc.)	approx 1000 feet (depends upon the aggressivity of the veh mix, upstream distance to prior I/C, % wanting to exit etc.)	approx 500 feet (L1 will be more dense for a while because traffic takes some time to normalize)
No response	28		

3.2.6 Question 4(2)—Influence Areas of Entrance-Ramp Junctions

Question 4(2): What are the operational or safety influencing areas at the upstream and downstream of the entrance ramps? Please give estimates of the influencing distances as shown in the following figure based on your experience.

This question asked about the operational or safety influencing areas at the upstream and downstream of entrance ramps. The number of respondents for this question was 31. The low number of respondents is an indication that some engineers did not consider the traffic operations at the upstream and/or downstream area in the design of entrance ramp junctions. Table 3-10 summarizes the numerical values of the thresholds obtained. Table 3-11 lists the unedited answers received from all the respondents. Comparing Tables 3-8 and 3-10, the average, minimum, and maximum Ld of weaving segments are all smaller than the corresponding statistics of the entrance-ramp junctions.

Table 3-10. Thresholds of Influence Areas at Entrance Ramp Junctions.

State		Distance on the entrance ramp, L_r (ft)	Distance on the upstream of mainline freeway, L_u (ft)	Distance on the downstream of mainline freeway, L_d (ft)
Texas		200	150	1040
Texas		500	1000	2000
Texas		30	30	40
Texas		700	1000	1200
Texas		1350	NA	2500
Texas		300	500	1500
Texas		500	1500	1500
Texas		150	500	1500
Texas		250	1000	1000
Texas		1500	850	850
California		250	2000	2000
Kentucky		250	600	600
Michigan		1500	1500	1500
Mississippi		500	1000	1500
New Mexico		500	1500	500
Washington		500	1000	500
Average	**Texas**	**548**	**726**	**1313**
	Other States	**583**	**1267**	**1100**
	All	**561**	**942**	**1233**
Minimum	**Texas**	**30**	**30**	**40**
	Other States	**250**	**600**	**500**
	All	**30**	**30**	**40**
Maximum	**Texas**	**1500**	**1500**	**2500**
	Other States	**1500**	**2000**	**2000**
	All	**1500**	**2000**	**2500**

Table 3-11. Complete Listing of All the Responses for Question 4(2).

State	The distance on the entrance ramp, L_r	The distance on the upstream of mainline freeway, L_u	The distance on the downstream of mainline freeway, L_d
Texas	200	150	1040
Texas	Per the TxDOT Roadway Design Manual we taper the ramp from a 14.00 ft lane and 7.00 ft gore at 50:1 taper over 450.00 ft to a 12.00 ft lane. Then we taper from the 12.00 ft lane to 0.00 ft at 50:1 over 600.00 ft.	Per the TxDOT Roadway Design Manual we taper the ramp from a 14.00 ft lane and 7.00 ft gore at 50:1 taper over 450.00 ft to a 12.00 ft lane. Then we taper from the 12.00 ft lane to 0.00 ft at 50:1 over 600.00 ft.	Per the TxDOT Roadway Design Manual we taper the ramp from a 14.00 ft lane and 7.00 ft gore at 50:1 taper over 450.00 ft to a 12.00 ft lane. Then we taper from the 12.00 ft lane to 0.00 ft at 50:1 over 600.00 ft.
Texas	500 feet	1000 feet	2000 feet
Texas	Consider merging sight distance, entrance ramp demand, entrance ramp geometry, type of vehicles entering traffic flow(ex.	Things considered are through lane sight distance, cross slope control location	This distance based on standard transitional taper of 50:1, many times this is lengthened to accommodate slower moving traffic like

	heavy trucks, buses, etc.)		heavy trucks and or slow moving heavy equipment.
Texas	?	depends on traffic could be 0.5 miles	1000 to 2500 feet
Texas	same as above	" " "	" " "
Texas	30	30	40
Texas	700 feet	1000 feet	1200 feet
Texas	1350	not sure	2500
Texas	This distance is based on a 2 degree curve and the distance of the frontage road from the mainlines.	This distance varies, but the Childress District typically uses the width of the outside shoulder (10'), plus the width of the inside shoulder of the ramp (2'), plus 8' for a total of 20'.	1050'
Texas	300 FT	500 FT	1500 FT
Texas	500'	1500'	1500'
Texas	150	500	1500
Texas	200-300	1000	1000
Texas	1500	850	850
Arizona	Peak Hours (i.e., 6-9 a.m. & 3-7 p.m.): 1000 feet; Non-Peak Hours: 50 feet	Peak Hours: 2500 feet; Non-Peak Hours: 100 feet	Peak Hours: 500 feet; Non-Peak Hours: 100 feet
Arizona	For a one lane on/off ramp as shown, we typically do not estimate this value.	We typically do not estimate this value.	We typically do not estimate this value.
Arkansas	For a one lane on/off ramp as shown, we typically do not estimate this value.	We typically do not estimate this value.	We typically do not estimate this value.
California	250'	2000'	2000'
Illinois	I could not view image	I could not view image	I could not view image
Kansas	Not Measured	Not Measured	Not Measured
Kentucky	250	600	600
Louisiana	See response to Number 7	See response to Number 7	Varies based on # of lanes, length of acceleration lane, & other entrances/exits
Michigan	1500	1500	1500
Minnesota	No data or valid estimate available.	No data or valid estimate available.	No data or valid estimate available.
Mississippi	500'	1000'	1500'
Nebraska	see #7	see #7	the entire length of the merge area plus a few hundred feet.
New Mexico	500'	1500' min based on length of aux lane	500'
Ohio			1500 feet (per HCM 2010)
Virginia	varies based on design speed	based on capacity/gap acceptance	varies based on design speed/AASHTO Ex 10-70
Washington	approx 500 feet (depends upon sight distance, v/h curvature, veh mix, volume etc.)	approx 1000 feet (depends upon the aggressivity of the veh mix, upstream distance to prior I/C, % wanting to exit etc.)	dist. = from Lr/Lu intercept point (gore) to approx 500 feet past mainline merge point at end of taper
No response	26		

3.2.7 Question 4(3)—Influence Areas of Exit-Ramp Junctions

Question 4(3): What are the operational or safety influencing areas at the upstream and downstream of the exit ramps? Please give estimates of the influencing distances as shown in the following figure based on your experience.

This question asked about the operational or safety influencing areas at the upstream and downstream of exit ramps. Thirty-one responses were collected for this question. Table 3-12 summarizes the numerical values of the answers obtained, including the average, minimum, and maximum values of each threshold. Table 3-13 lists the unedited answers received from all the respondents. By comparing Tables 3-10 and 3-12, it is observed that entrance-ramp junctions have smaller average, minimum, and maximum Lu values compared to exit-ramp junctions. On the other hand, entrance-ramp junctions have larger average, minimum, and maximum Ld values compared to exit-ramp junctions

Table 3-12. Thresholds of Influence Areas at Exit-Ramp Junctions.

State		**Distance on the exit ramp, L_r (ft)**	**Distance on the upstream of mainline freeway, L_u (ft)**	**Distance on the downstream of mainline freeway, L_d (ft)**
Texas		200	1000	200
Texas		500	2000	1000
Texas		30	40	30
Texas		350	800	NA
Texas		820	2600	NA
Texas		300	2000	500
Texas		500	1500	100
Texas		200	600	150
Texas		150	1500	500
Texas		1500	850	850
California		250	2000	2000
Kentucky		250	600	300
Michigan		1500	1500	1500
Mississippi		500	1500	500
New Mexico		500	1500	500
Washington		500	1000	500
Average	**Texas**	**455**	**1289**	**416**
	Other States	**583**	**1350**	**883**
	All	**503**	**1312**	**616**
Minimum	**Texas**	**30**	**40**	**30**
	Other States	**250**	**600**	**300**
	All	**30**	**40**	**30**
Maximum	**Texas**	**1500**	**2600**	**1000**
	Other States	**1500**	**2000**	**2000**
	All	**1500**	**2600**	**2000**

Table 3-13. Complete Listing of All the Responses for Question 4(3).

State	The distance on the exit ramp, L_r	The distance on the upstream of mainline freeway, L_u	The distance on the downstream of mainline freeway, L_d
Texas	200	1000	200
Texas	Per the TXDOT Roadway Design Manual for a highway speed of 70 mph and a ramp speed of 45 mph, the taper would be 300 ft and the deceleration lane would be 390 ft.	Per the TXDOT Roadway Design Manual for a highway speed of 70 mph and a ramp speed of 45 mph, the taper would be 300 ft and the deceleration lane would be 390 ft.	Per the TXDOT Roadway Design Manual for a highway speed of 70 mph and a ramp speed of 45 mph, the taper would be 300 ft and the deceleration lane would be 390 ft.
Texas	500 feet	2000 feet	1000 feet
Texas	Many times controlled by proximity of frontage road, departure angle and grade is also a governing factor	Consider type of vehicle departing the mainlines, geometry of exit ramp affects length of Lu	Consider roadway geometry
Texas	?	1000'-1500'	1000'
Texas	same as above		
Texas	30	40	30
Texas	350 feet	800 feet	NA
Texas	820	2600	n/a, don't use
Texas	This distance varies, based on the distance of the frontage road from the mainline.	Based on a 2 degree curve coming off the mainline down to the frontage road/ramp.	Same as Lu for an entrance ramp....noted above
Texas	300 FT	2000 FT	500 FT
Texas	500'	1500'	1000'
Texas	200	600	150
Texas	100-200	1500	500
Texas	1500	850	850
Arizona	Peak Hours (i.e., 6-9 a.m. & 3-7 p.m.): 500 feet; Non-Peak Hours: 50 feet	Peak Hours: 1000 feet; Non-Peak Hours: 100 feet	Peak Hours: 100 feet; Non-Peak Hours: 0 feet
Arizona	For a one lane on/off ramp as shown, we typically do not estimate this value.	It can vary substantially, we do not use a single value. However, in our experience, the value shown in the HCM is too low.	We typically do not estimate this value.
Arkansas	For a one lane on/off ramp as shown, we typically do not estimate this value.	It can vary substantially. We do not use a single value. However, in our experience, the value shown in the HCM is too low.	We typically do not estimate this value.
California	250'	2000'	2000'
Illinois	I could not view image	I could not view image	I could not view image
Kansas	Not Measured	Not Measured	Not Measured
Kentucky	250	600	300
Louisiana	Depends on exit ramp queue, length of exit ramp	Depends on exit ramp queue and exit speed	Depends on exit ramp queue and volume
Michigan	1500	1500	1500
Minnesota	No data or valid estimate available.	No data or valid estimate available.	No data or valid estimate available.
Mississippi	500'	1500'	500'

Nebraska	There will be almost no influence when a driver exits the ramp.	See #7	Only a short distance. 100 to 500'
New Mexico	500'	1500' min based on the length of aux lane	500'
Ohio		1500 feet (per HCM 2010)	
Virginia	based on design speed	varies based on design speed/AASHTO Ex 10-70	based on design speed
Washington	approx 500 feet (depends upon sight distance, v/h curvature, veh mix, volume etc.)	approx 1000 feet (depends upon the aggressivity of the veh mix, upstream distance to prior I/C, % wanting to exit to downstream I/C etc.)	approx 500 feet (assuming Lr vol is high, L2 could be more dense for a while because traffic will want to avoid the diverge issues and thus will take some time to normalize)
No response	26		

3.2.8 Question 5—Design Conditions

Question 5: Please tell us under which condition you will consider auxiliary lanes in highway design and if so, how do you determine the length of auxiliary lanes?

This open-ended question requested respondents indicate under which conditions auxiliary lanes will be considered and how they determine the length of auxiliary lanes. The total number of respondents was 33. Table 3-14 lists the unedited replies of all the respondents.

Based on the results shown in Table 3-14, it can be concluded that auxiliary lanes are considered under the following conditions:

- When the entrance or exit ramp has a high percentage of trucks.
- When the entrance or exit ramp has high volumes.
- When the traffic density is high.
- When the on and off ramps are very close (e.g., less than 1000 ft).
- If there are safety or operational issues.
- If the predicted LOS is D or worse for the design year peak-hour traffic.

In addition, two respondents stated that auxiliary lanes should be used on all controlled-access freeway designs and should be considered on all divided highway designs. Another respondent (from Kansas) stated that he/she used auxiliary lanes on all freeway interchange ramps. In cases of short (approximately 1/4 mile) distances between an entrance ramp and an exit ramp, an auxiliary lane will be added to facilitate the weaving movements.

After considering the placement of an auxiliary lane, the length of the auxiliary lane is determined based on the following factors:

- The horizontal and vertical geometrics of the ramp(s).
- Deceleration requirements or storage requirements.

- The speeds on the ramp curve and the freeway.
- Availability of gaps for merging.

Table 3-14. Complete Listing of All the Responses for Question 5.

State	Please tell us under which condition you will consider auxiliary lanes in highway design and if so, how do you determine the length of auxiliary lanes?
Texas	adding/dropping of lanes
Texas	As stated previously these are designed in the "Houston Advanced Project Development" section.
Texas	Typically, we have used the X ramp configuration and we have utilized an auxiliary lane between the on and off ramps. The lengths of the auxiliary lanes have been determined based on the horizontal and vertical geometrics for the ramps.
Texas	Look at functionality of proposed ent/exit ramp (i.e. is it located in a heavy industry location). Another thing is general roadway geometry proximity of next ramp Green Book offers good guidance on Exit/Exit, Ent/Ext etc... spacing.
Texas	significant entrance and exit volumes. length of aux lane is usually a function of available geometry or design standards and traffic modeling.
Texas	I have not had much experience with freeway design. The auxiliary lanes I am familiar with are in relation to traffic generator type developments coming in or right or left turn lanes requested due to high accident locations on rural roads. I generally look at traffic volume entering and exiting the roadway in relation to roadway ADT, speed differential between auxiliary lane and roadway, and future potential or existing accidents.
Texas	When traffic density becomes an issues that traffic coming onto a highway does not have enough run-up length to get to speed to properly merge with traffic. To determine length, I will utilize standards and guidelines as set forth in TxDOT Roadway Design Manual.
Texas	Auxiliary lanes should be used on all controlled access freeway design. And should be considered on all divided highway design. Length is dependent on speed, grade, and sight distance.
Texas	I have not used auxiliary lanes in any design, but would think they would need to be used when high ADT on and off ramps exist.
Texas	We don't utilize auxiliary lanes very often since we are located in the rural area of Texas. We have very few entrance and exit ramps and weaving is never a problem since our traffic counts are extremely low.
Texas	Between on and off ramps.
Texas	Auxiliary Lane will be necessary when consecutive on and off ramp are very close say less than 1000 ft
Texas	In congested areas an aux lane can provide relief. In situations with closely spaced ramps, aux lanes are required. In areas upstream and downstream of major interchanges, aux lanes are required to better handle traffic volumes and line up traffic. In all cases 1500 ft. is a minimum distance. Aux lanes can be extended for longer distances to get traffic through "choke points"
Texas	Auxiliary lanes are generally considered where weaving of traffic streams is present. The most common occurrence is where an entrance ramp is closely followed (less than 2500') by an exit ramp. Auxiliary lanes are also used to provide lane balance at major interchanges and two-lane ramps. In this case, the auxiliary lane(s) are continued to the next exit ramp. It is our practice to provide auxiliary lanes wherever possible to facilitate weaving and traffic entering/exiting the main lanes.
Texas	Corridor congestion HCM 2010
Arizona	Auxiliary lanes will be considered when the length between interchanges is 1 mile or less. Auxiliary lanes will be considered if there are safety or operational issues. Typically, auxiliary lanes are placed between interchanges that are one mile apart.

Arizona	If the predicted LOS is less than D for design year peak hour traffic. Or, for exit ramps, if extra deceleration length is needed to accommodate the expected back-of-queue (I think we have used different percentiles, but typically a conservative number). Or, for entrance ramps, if extra acceleration length is needed for heavy vehicles (which isn't factored in the HCM methodology). Or, if we need to achieve lane balance or any other design reasons from the Green Book. This answer is assuming freeway operations only, i.e., not auxiliary lanes prior to turn lanes, arterials, etc.
Arkansas	If the predicted LOS is less than D for design year peak hour traffic. Or, for exit ramps, if extra deceleration length is needed to accommodate the expected back-of-queue (We have used different percentiles, but typically a conservative number). Or, for entrance ramps, if extra acceleration length is needed for heavy vehicles (which isn't factored in the HCM methodology). Or, if we need to achieve lane balance or any other design reasons from the Green Book. This answer is assuming freeway operations only, i.e., not auxiliary lanes prior to turn lanes, arterials, etc.
California	Guidance is in the Highway Design Manual. Factors include the volumes and merging and weaving analyses. When on ramps are closely followed by off ramps (such as less than 2000') auxiliary lanes are built. When the distances are longer, it is based on the analyses.
Connecticut	Dependent on the spacing of interchanges and volumes. If an entrance ramp is followed closely by an exit ramp we may choose to combine them into an auxiliary lane, however the preferred treatment would be to space the ramps far enough apart that they could operate independently and minimize the weaving condition. At independent on and off ramps, we typically use a taper design for new designs. older designs used auxiliary lanes for acceleration and deceleration. Their lengths were based on the speeds of the mainline traffic and the ramps, taking into account whatever geometric feature of the ramp that controls speed.
Illinois	The survey seems to focus on freeways so that is the type of facility I will address. Your question regarding how the length of the auxiliary lane is determined can be interpreted in two ways. One way is when analyzing for capacity purposes. Another way is determining what length to use based on need. Between an entrance ramp and exit ramp. As an acceleration lane following an entrance ramp. As a merge lane for capacity purposes following an entrance ramp. As a deceleration lane preceding an exit ramp. As a storage lane preceding and exit ramp.
Kansas	We use auxiliary lanes on all freeway interchange ramps. In cases of short (approximately 1/4 mile) distances between entrance and exit ramps, we will sometimes make them continuous. The lengths utilized are determined by guidance from the AASHTO Greenbook.
Kentucky	An auxiliary lane is the section of the roadway adjacent to the through lanes that is utilized for: □ Speed changes □ Left- and right-turning movements □ Storage □ Weaving maneuvers □ Truck-climbing lanes □ Other various purposes Auxiliary lanes may also be added to improve the safety and the capacity of an intersection or interchange. The length of an auxiliary lane is based on the deceleration requirements, storage requirements, or both.
Louisiana	To improve flow. Length is determined from capacity analysis, field conditions, and engineering judgment.
Florida	1500 FT. Based on the speed on the ramp curve and the freeway
Minnesota	Accel and decel lanes beyond the standard length of provision: 1. If the standard design does not provide the minimum required acceleration or deceleration length based on AASHTO Green Book criteria. 2. If the standard acceleration design does not provide adequate merging or gap acceptance length based on the design traffic conditions/density. In that case, an unspecified individual traffic analysis should be done to assess the appropriate length. Continuous freeway auxiliary lane between entrance and exit terminals: An individual traffic analysis is made—usually microsimulation, although HCM methods can also be judged adequate by traffic engineering staff.
Mississippi	Always, if geometrically possible

Nebraska	If there is a short distance between ramps that creates a significant merge or diverge problem. If the auxiliary lane is an on ramp and doesn't connect to a diverging ramp, the length is determined by: mainline speed, the time it takes drivers on the ramp to get within 10 mph of the mainline speed, and availability of gaps for merging. If the auxiliary lane is for diverging, it would need to be of sufficient length to comfortably decelerate a vehicle to conditions on the ramp.
New Mexico	Our state Access Manual defines the need for auxiliary lane based on through and turning volumes. There is a table in the access manual that is based on AASHTO guidelines
Ohio	When successive ramp noses are less than 1500 feet apart, auxiliary lanes should be provided. If ramp spacing exceeds 1 mile, the lane should be dropped 2000 feet to 3000 feet as a taper beyond the downstream interchange. For distances between 1500 feet and 1 mile, the need for an auxiliary lane is based on operational analysis.
Pennsylvania	HCM
Virginia	Auxiliary lanes are considered based on design speed, capacity and weaving considerations. Lengths are based on AASHTO guidelines.
Washington	Our Design Manual guidance is based initially on AASHTO but then goes beyond that based on our state's experience and other research. Expertise in WSDOT is often specialized so I need to state that I'm a traffic analysis engineer and although I have spent some time as a designer, that was years ago and I wouldn't make design decisions in my current role. Traffic analysis can speak to this issue with micro simulation but we would not recommend anything less than what is stated in our Design Manual or AASHTO.
No response	24

3.2.9 Question 6—Impacts of Auxiliary Lanes

Question 6: What do you think auxiliary lanes can positively or negatively impact the operations, safety, or other aspects at weaving segments, entrance ramp and/or off ramp junctions?

This was an open-ended question. It asked about the positive and negative impacts of adding one or more auxiliary lanes on freeways to the traffic operations and safety. The total number of respondents was 33. Table 3-15 lists the unedited results from all the respondents.

Of the 33 respondents, 23 respondents indicated that auxiliary lanes can positively impact the operations and/or safety at weaving segments and entrance-ramp and/or off-ramp junctions. Of the 23 respondents, 7 respondents said that an auxiliary lane has operational benefits, 3 respondents thought it has safety benefits, while 7 respondents cited that it has both operational and safety benefits. There were 6 respondents who mentioned positive impacts but did not specify whether they were operational or safety benefits. The remaining 10 respondents thought that the impacts are dependent on the length of the auxiliary lanes.

Table 3-15. Complete Listing of All the Responses for Question 6.

State	Traffic operation and safety impacts of adding auxiliary lanes
Texas	positive
Texas	If the auxiliary lane is long enough it can be a positive addition to the design. If it is over a mile it becomes "added capacity" under FHWA's guidelines. At on ramp/off ramp locations I believe auxiliary lanes add safety. Sometimes they are hard to incorporate when working in an existing urban interchange where we are widening the freeway and adding ramps and not doing a complete reconstruction.

Texas	We view auxiliary lanes as extremely beneficial to the operations of the through travel lanes provided that the length of the auxiliary lanes adequately address the weaving movements between the on and off ramps.
Texas	Without a doubt auxiliary lanes provide a positive impact from an operations viewpoint.
Texas	effectively reduce congestion at heavy ent and exit ramps. also improve safety related to congestion.
Texas	I do think auxiliary lanes can positively impact traffic operations if they don't get too long such that drivers think they are a new freeway lane or they can't see where the lane begins and ends.
Texas	If given enough distance, auxiliary lanes can have a positive impact to traffic flow and safety. If not enough length is given for proper weaving it can become an issue especially for older drivers. Also in heavily urbanized areas with large amounts of traffic, off ramps can become a problem if there is not enough storage and traffic starts to back up onto the main highway.
Texas	Definitely improves safety.
Texas	I would think they would make the weaving for the ramps safer by allowing the motorist to accelerate and merge into traffic or decelerate moving out of traffic. A positive impact.
Texas	I think auxiliary lanes are an excellent way to safely move/weave traffic at on and off ramps.
Texas	Positive impact. Allows for easier merging of traffic.
Texas	I think traffic using auxiliary lanes positively impact the operation of weaving segments between entrance ramp and exit ramp junctions by allowing other mainline through traffic within these limits to also weave within the inside lanes in advance of the next weaving segment, thus reducing the total weaving required at that segment.
Texas	Auxiliary Lane facilitates weaving conditions in providing adequate lane balancing. Design speed should always be a factor in this regard.
Texas	A properly designed aux lane can positively impact a freeway in most situations. This may be related to the extensive use of frontage roads in Texas.
Texas	Auxiliary lanes generally have a positive impact on safety and operations in both weaving segments and ramp junctions. The auxiliary lanes provide more space for vehicles to maneuver resulting in decreased density and increased speeds.
Texas	Auxiliary lanes can be positive improvement for safety and operations.
Arizona	Auxiliary lanes posivity impact traffic operations and safety. The greatest benefit to adding auxiliary lanes is when the corridor has a poor level of service—this typically occurs during peak hours in our urban areas.
Arizona	This question is not state clearly. I think you meant to remove the word "What" from your question. If so, then my answer is I think the impacts are positive.
Arkansas	I think the impacts are positive as long as they are of adequate length.
California	Auxiliary lanes positively impact the operations and safety most of the time.
Connecticut	We try to avoid them if possible, preferring to use taper designs and spacing that allows for independent operations and acceleration/deceleration to occur separate from the mainline traffic. When that is not possible, auxiliary lanes at independent ramps allow for speed change which helps reduce conflicts. At weaving areas between an entrance ramp and adjacent exit ramp, if the auxiliary lanes are long enough, they can help to allow independent operation, but if too short they create typical weaving conflicts.
Illinois	Yes.
Kansas	Auxiliary lanes positively impact traffic safety and operations by providing for speed change and weaving maneuvers.
Kentucky	At ramps, auxiliary lanes that are too short do not allow the vehicles to get up to speed, which causes main line traffic to adjust. This negatively affects operations and safety.
Louisiana	Question is poorly worded.
Michigan	IT DEPENDS
Minnesota	The wording of the question is not clear.
Mississippi	Mainly if they are too short and don't allow adequate time and distance to accelerate or decelerate to match adjacent vehicles

Nebraska	Impacts are highly dependent on the context. In general, I believe they produce more positive than negative impacts. However, Interstate/Freeway operations in Nebraska are different than in Texas. We don't deal with some of the serious operational issues that Texas may have.
New Mexico	The impact are generally positive.
Ohio	Certainly the auxiliary lane length provided in combination with traffic volumes affects safety and operation.
Virginia	Auxiliary lanes long enough to reduce speed differentials impact capacity positively. Auxiliary lanes that are too long can delay the weave beyond expectations of through traffic.
Washington	Depends on the situation—volumes of through, weave, merge, diverge and their associated vehicle mix, roadway geometry, ramp metering and countless other factors can influence just how helpful these lanes can be. First, we have to get the ROW and that can be an issue at times. Then, there is the issue of funding. Assuming all that is fine, in general, where the mainline is experiencing perturbation due to lane change issues, Aux Lanes can help smooth and increase traffic flow—and by that, increase safety.
No response	24

3.2.10 Question 7—Use of Shoulders as Auxiliary Lanes

Question 7: In urban areas, right-of-way is at a premium. Please describe your experience, if any, concerning the use of freeway shoulders to improve performance of weaving/merge/diverge segments (as a form of auxiliary lanes).

This open-ended question asked about the use of freeway shoulders to improve performance of weaving/merge/diverge segments as a form of auxiliary lanes. The use of shoulders as auxiliary lanes may be temporary or permanent. The total number of respondents was 32. Table 3-16 lists the detailed results from all the respondents.

It appears that only Houston in Texas, Illinois, and Kentucky have converted freeway shoulders to auxiliary lanes. Some respondents expressed concerns that converting shoulders into auxiliary lanes may pose safety and liability issues (because of the lack of shoulder for emergency use). Another respondent pointed out that the Federal Highway Administration is considered converting shoulders to auxiliary lanes of longer than 1 mile as a capacity addition. This requires extensive environmental documentation.

Table 3-16. Complete Listing of All the Responses for Question 7.

State	Use of Freeway Shoulders as a Form of Auxiliary Lanes
Texas	we don't use shoulders for that
Texas	I have no experience in this area.
Texas	Have not had any experience with this.
Texas	Have never viewed freeway shoulders as a means of improving weaving/merging/diverging performance.
Texas	the use of shoulders for aux lanes must be considered carefully. this can be an effective method for reducing congestion/bottlenecks in constrained areas with limited funds, however the safety implications must be assessed.
Texas	Some people will use a shoulder to exit or enter a roadway, but others won't dare cross that solid white line. There could also be bike traffic that might discourage people using shoulders. On rural roads I tend to see more use of a 10' shoulder to accel or decel so it seems more effective in that situation. Urban settings generally need to be spelled out for people and actually striped as a

	separate lane.
Texas	In the areas in which I have done most of my work, I have not had an issue with ROW.
Texas	When designers don't use the proper weaving/merge/diverge segments drivers will utilize shoulders to make these maneuvers.
Texas	No experience.
Texas	N/A
Texas	None.
Texas	Freeway shoulders should not be designated to improve weaving conditions as shoulders have specific functions for stall vehicles and as refuge for passengers involved in a crash condition
Texas	I have prepared "TSM" (transportation system management) projects along US 290, IH 45, US 59, IH 610, and SH 288 in congested areas around the Houston area. In all projects, additional aux lanes were proposed. The completed projects have seen significant congestion relief. A limiting factor however is FHWA and environmental rulings that consider aux lanes beyond 1 mile in length to be added capacity. Added capacity projects would require more extensive environmental documentation.
Texas	The use of shoulders as auxiliary lanes (or the reduction of shoulder width to provide auxiliary lanes) is a common practice to increase operational performance in TSM projects, but this practice compromises safety. For new construction and reconstruction projects, full shoulders should be used.
Texas	Auxiliary lanes are taken from existing footprint by reducing shoulder widths. This helps ease corridor bottlenecks.
Arizona	We have discussed using shoulders, however, we have not used them as travel lanes, because we have concerns regarding safety and tort liability.
Arizona	On freeways, I do not think we have re-striped shoulders as an auxiliary lane. On non-freeways, we have.
Arkansas	We have not re-striped shoulders as an auxiliary lane on Freeways.
California	In some urban locations shoulder width has been sacrificed to construct auxiliary lanes. As for using shoulders temporarily for part time auxiliary lanes there is limited experience due to historical concerns related to driver confusion.
Connecticut	We have not done this, to my knowledge.
Illinois	Except for a Bus-on-Shoulder pilot project in the Chicago area, IDOT does not use shoulders as auxiliary lane for or any other capacity purposes. Although it is a loose interpretation of your question of the use of shoulders to improve performance in a restricted corridor, IDOT will decrease shoulder width to provide an auxiliary lane.
Kansas	We use 10 foot wide outside shoulders on all freeways but do not design for, nor encourage, the use of shoulders as driving lanes.
Kentucky	When r/w is tight, we have used shoulder width to help create "auxiliary lane." The thought is that the area available is best used as an auxiliary lane versus a shoulder.
Louisiana	Shoulders are not used
Michigan	WE DO NOT USE SHOULDER
Minnesota	The question is not completely clear. If it refers to the employ of dynamic shoulders to act as auxiliary lanes under high demand conditions, our agency is beginning to consider implementing schemes of that sort under actively managed conditions.
Mississippi	I have no problem with it.
Nebraska	It is illegal to drive on shoulders in Nebraska. We do not allow for their use to improve operations.
New Mexico	We try not use shoulders. We have not had any need to do so.
Ohio	Use of shoulders for such purposes in Ohio is rare. I cannot think of any such application in the last 20 years.
Virginia	Shoulders are utilized wherever practical. Shoulders are recognized as increasing capacity, but are not utilized as an auxiliary lane.

Washington	Time of Day shoulder running is currently being used near our Purdey interchange. This is a bandaid fix that has helped or state route. Funding and ROW were the issue here so economic pragmetizm resulted in the temporary shoulder running fix. Mainline interstate shoulder running has been proposed for I-5 in the Joint Base Lewis McCord area of Pierce county under a Tiger III grant. We'll see what happens with that grant. VISSIM micro simulation was used to demonstrate a substantial benefit between Berkeley and Thorn Lane interchanges if we metered the onramp of the upstream (Thorne) and added an Aux lane between the two interchanges. Modeling is one thing, if we get the grant, we'll get back to you with the actual measured throughput increase.
No response	25

3.2.11 Question 8—Other Experiences

Question 8: Can you share some of your experience, lessons, or issues related to the design and use of auxiliary lanes with us?

This was an open-ended question. It asked the respondents to share some experiences, lessons, or issues related to the design and use of auxiliary lanes. The total number of respondents was 26. Table 3-17 lists the complete unedited entries collected from all the respondents.

Two respondents pointed out that designers (engineers) and drivers may be confused by the lane stripping that separates main lanes (through lanes) and auxiliary lanes. It appears that the distinction between a through lane and merge-ahead lane is not clear, or there is a need to increase driver awareness. Two respondents also suggested research reports in California and Kentucky that researchers incorporated into the literature review.

Table 3-17. Complete Listing of All the Responses for Question 8.

State	Experience, Lessons, or Issues Related to the Design and Use of Auxiliary Lanes
Texas	only used to end lanes at ramps
Texas	As stated previously, these are designed in the "Houston Advanced Project Development" section.
Texas	When we first started to implement auxiliary lanes, their lengths were much too short to adequately address the weaving movements. As a result of this experience, we have been very conscientious and have been conservative since then regarding the lengths of the auxiliary lanes.
Texas	Have used auxiliary lanes extensively on freeway interchange designs to remove "decision-makers" away from the main traffic stream.
Texas	We have implemented numerous auxiliary lanes on expressways in the SA area.
Texas	Our TxDOT Roadway Design Manual has guidelines to follow concerning auxiliary lane design. I have compared them to the AASHTO Manual and they appear to be the same information. Main issue I have is they are both difficult to understand when designing for accel lanes or decel lanes, or median turn lanes. There always is confusion on length of straight-away versus taper length versus merge area. Is there some way to simplify this mess and make it easier for the designer to read and understand at a glance?
Texas	Issues relating to auxiliary lanes are as important in the design of traffic control during construction as in permanent design.
Texas	No experience.
Texas	N/A
Texas	Auxiliary lanes should be considered where widening of roadways is impractical due to lack of ROW. Should also be considered when traffic volume is high and widening is prohibited; re-striping could be initiated to include provision of Auxiliary Lane

Texas	Auxiliary lanes are a valuable tool in addressing congestion, especially in urban areas. It is an iterative process between design and analysis. When aux lanes become longer than 1 mile you are considered to be adding capacity.
Texas	For new construction, we use auxiliary lanes on almost all ramps in the urban setting. We have several TSM projects in the works that include the addition of auxiliary lanes to improve operations. Proper signing and pavement markings are important to convey to the driver that this is an auxiliary lane rather than a through lane.
Texas	Although long auxiliary lanes may ease congestion, there is merging issue as drivers are forced or wait to enter the traffic flow at the end of the auxiliary lane.
Arizona	We have installed numerous miles of auxiliary lanes in the Phoenix metropolitan area within the last 15 years. As a result of the auxiliary lanes, traffic operations and safety has been improved.
Arkansas	It seems that if an auxiliary lane is not of adequate length, drivers tend to ignore the fact that they need to merge and sometimes assume they can drive straight into the through lane without yielding.
California	Yes, there are two research reports available that are relevant: 1. Weaving Analysis, Evaluation and Refinement by Alexander Skabardonis and Amy Kim of the Institute of Transportation Studies of the University of California at Berkeley in February 2010 2. Quantifying the Performance of Countermeasures for Collision Concentration Related to Ramp/Freeway Mainline Junctions by Joon ho Lee, Ching-Yao Chan, and David R. Ragland of CALIFORNIA PARTNERS FOR ADVANCED TRANSIT AND HIGHWAYS in January 2009
Connecticut	Weaving segments are especially problematic and when possible we are eliminating them. They were used at older cloverleaf design interchanges and often had very short lengths which makes them even more of a problem. Use of auxiliary lanes at on and off ramp junctions is less problematic, but when possible we prefer the taper design that keeps the accelerating and decelerating traffic physically separated from the mainline traffic.
Illinois	As a reviewer, I promoted auxiliary lanes frequently between entrance ramps and exit ramps. Since Illinois is very flat, the use of an auxiliary lane as an acceleration lane following an entrance ramp is rare, however it is more common to be use following an entrance ramp to increase capacity for merging in congested areas. Also in congested areas IDOT will also use auxiliary lanes for storage preceding exit-ramps due to inadequate capacity at the ramp terminal at the cross road.
Kansas	Auxiliary lanes are essential to safe and efficient freeway operations. Sometimes they are expensive to construct, especially if they cross an adjacent mainline bridge. Drivers expect auxiliary lanes, particularly for acceleration/deceleration maneuvers. The most prevalent issue we see is that some may be too short if they were constructed many years ago and/or traffic growth exceeded forecasts. This is particularly true for weave areas at cloverleaf type interchanges. Auxiliary lanes can be a cost effective method/treatment to increase capacity particularly in cases where the facility experiences high entrance and exits from adjacent interchanges.
Kentucky	We use the term “auxiliary lane” to mean a lot more than just entrance ramp and/or off ramp junctions. We published a policy to help our designers size auxiliary lanes: http://transportation.ky.gov/Highway-Design/Memos/Design,%20Permits,%20Traffic%2003-09.pdf
Michigan	if THE DISTANCE OF THE BETWEEN RAMPS BETWEEN 1500 AND 3000FT ,WE WILL TAKE A CLOSE LOOK IF THE WEAVE LANE COULD BE BENEFICIAL
Minnesota	My personal philosophy is that the robust design of “connections” on the freeway system is overall one of the highest benefit/cost propositions available to transportation agencies, and the robust design of auxiliary lanes—where judged beneficial—is a key part of that strategy. It follows the long-standing engineering principle of robustly designing connections so they are not the weak point of any system or structure. I consider freeway ramp terminals (i.e., acceleration and deceleration auxiliary lanes) and continuous auxiliary lanes between interchanges to constitute “connections” for the purposes of design and planning.
New Mexico	We have used our access manual to enforce the use of auxiliary lanes where it has been warranted for private, local and state facilities. We see it as a positive measure.

Ohio	Ohio uses a fairly conservative accel and decel length for ramps, especially for two lane entrance and exits. We feel it provides a good level of safety and operation versus the minimum levels recommended in AASHTO. We have begun investigating extension of the auxiliary lane past the downstream ramp per AASHTO in some cases where weaving operations were projected be particularly heavy and safer operation was necessary.
Virginia	Deficiencies can occur due to improper interpretations of AASHTO Criteria/Capacity Analysis.
Washington	See above and call for others.
No response	31

3.2.12 Question 9—Preferred Methods of Contact

Question 12: Can we contact you if we need further information?

This question asked if the research team could contact the respondents to seek clarification or to provide more information. If the respondent's answer was positive, he/she was asked to indicate his/her preferred method(s) of contact.

Table 3-18 lists the respondents' replies. Thirty respondents were willing to be contacted by the research team, with 28 using email and 16 by telephone. The other 26 respondents did not answer this question.

Table 3-18. Preferred Methods of Contact.

State	Contact by telephone	Contact by email
Texas	Yes	Yes
Texas		Yes
Texas	Yes	Yes
Texas	Yes	
Texas	Yes	
Texas		Yes
Texas	Yes	Yes
Texas		Yes
Texas		Yes
Texas		Yes
Texas		Yes
Texas	Yes	Yes
Texas		Yes
Texas		Yes
Arizona	Yes	Yes
Arizona	Yes	Yes
Arkansas	Yes	Yes
California		Yes
Connecticut	Yes	Yes
Illinois	Yes	Yes
Kansas	Yes	Yes
Kentucky	Yes	Yes
Louisiana	Yes	Yes
Michigan		Yes
Minnesota	Yes	Yes

Mississippi		Yes
New Mexico		Yes
Ohio		Yes
Virginia		Yes
Washington	Yes	Yes
No response	26	

3.3 SUMMARY

The major findings of the survey are summarized as follows:

- The majority of respondents in both Texas and other states selected, in order of popularity, AASHTO 2004, HCM 2010, MUTCD 2009, and HCM 2000 as their design manuals. The AASHTO 2011, as a newly available manual, has not been widely used. The MUTCD 2006 appears to have been superseded by MUTCD 2009.
- For the performance measures, the majority of respondents in Texas selected demand, while the majority of respondents in other states selected density and/or speed. However, speed is the most popular measure, followed by demand and then density.
- The most commonly used software/tools for modeling operational impacts are HCS and VISSIM. HCS is a macroscopic LOS determination tool, while VISSIM is a microscopic traffic simulation tool.
- For the operational or safety influencing areas at the upstream and downstream of the weaving segments, the average distance on the entrance ramp is 566 ft, the average distance on the upstream of the mainline freeway is 1008 ft, and the average distance on the downstream of the mainline freeway is 718 ft.
- For the operational or safety influencing areas at the upstream and downstream of the entrance ramps, the average distance on the entrance ramp is 561 ft, the average distance on the upstream of the mainline freeway is 942 ft, and the average distance on the downstream of the mainline freeway is 1233 ft.
- For the operational or safety influencing areas at the upstream and downstream of the exit ramps, the average distance on the entrance ramp is 503 ft, the average distance on the upstream of the mainline freeway is 1312 ft, and the average distance on the downstream of the mainline freeway is 616 ft.
- Auxiliary lanes are considered under the following conditions:
    - When the entrance or exit ramp has a high percentage of trucks.
    - When the entrance or exit ramp has high volumes.
    - When the traffic density is high.
    - When the on and off ramps are very close (e.g., less than 1000 ft).
    - If there are safety or operational issues.
    - If the predicted LOS is D or worse for the design year peak-hour traffic.
- The lengths of the auxiliary lanes are determined based on the following factors:

  - The horizontal and vertical geometrics of the ramp(s).
  - Deceleration requirements, or storage requirements.
  - The speeds on the ramp curve and the freeway.
  - Availability of gaps for merging.
- The majority of the respondents thought that an auxiliary lane has a positive impact on traffic operations and/or safety at weaving segments and entrance-ramp and/or off-ramp junctions. Some respondents thought that the impacts are dependent on the length of the auxiliary lanes.
- Use of a shoulder as an auxiliary lane is not popular; it is only used in the Houston area in Texas and in Kentucky and Illinois. The major concern is safety and liability.

3.4 REFERENCES

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CHAPTER 4: OPERATIONAL IMPACTS OF AUXILIARY LANES AT THE SEGMENT LEVEL

The purpose of the project objective described in this chapter was to estimate operational effects of adding auxiliary lanes at merge/diverge or weaving segments. To this end, the researchers designed experimental scenarios without and with an auxiliary lane given various combinations of traffic and geometric conditions, modeled these scenarios using VISSIM simulation software, and summarized the results of the simulation experiments. Micro-simulation was selected as the primary method for the experiments because earlier results from this study showed that the HCM methods have some problems in analyzing a weaving segment without an auxiliary lane.

For a weaving segment without auxiliary lanes, the HCM approach suggests to:

- Compute density and speed separately for the on-ramp junction and the off-ramp junction in the ramp module in HCM 2010.
- Use a higher density and lower speed on the on-ramp and off-ramp.

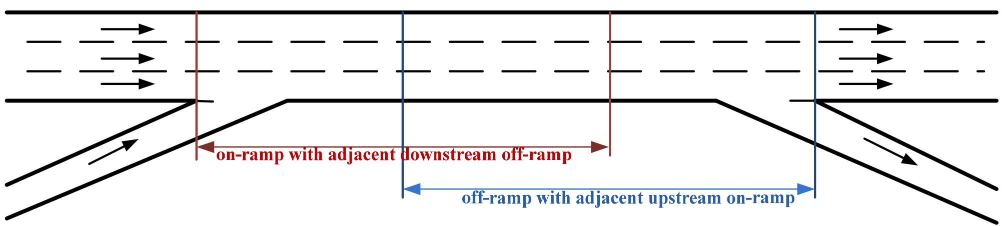
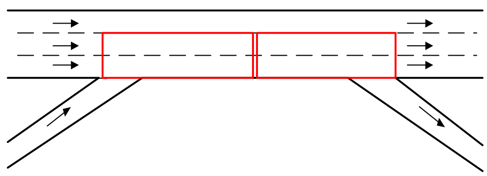


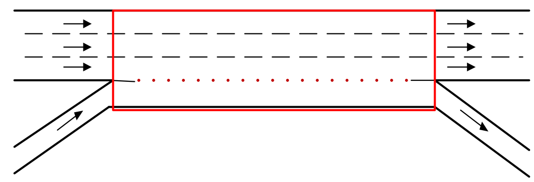
Figure 4-1. HCM Approach for Weaving Segment without Auxiliary Lanes.

This approach has two problems:

- The HCM model for weaving segments is only for the segments with an auxiliary lane, and it yields results (e.g., density and speed) for all lanes within the weaving segment (please see Figure 4-2[b]). For the weaving segments without auxiliary lanes, the HCM approach (Figure 4-2[a]) yields results (e.g., density and speed) only for the two mainline lanes next to the shoulder (i.e., two ramp influence areas). Thus, the modeling results of these two cases cannot be compared directly.
- The results (e.g., density and speed) of Case A (without auxiliary lanes, modeled as two joint ramp influence areas) sometimes were better than those of Case B (with auxiliary lanes, modeled by HCM standard method), which is not reasonable because installing an auxiliary lane should not make the segment performance worse, and the two outer lanes next to the shoulder should be affected more than the inner lanes by the diverging and merging traffic.



Case A: Modeling weaving segments without auxiliary lanes as two joint ramp influence areas as suggested by HCM



Case B: Modeling weaving segments with an auxiliary lane using HCM weaving procedures

Figure 4-2. HCM Analysis for Weaving Segment without and with an Auxiliary Lane.

Therefore, simulation was used instead of the HCM method for weaving segments with and without an auxiliary lane. For consistency purposes, the simulation approach was also used for isolated ramp junctions with and without parallel acceleration/deceleration lanes.

4.1 SCENARIO DESIGN

Study scenarios were designed for various types of auxiliary lanes under different traffic and geometric conditions.

The methodology of designing the study scenarios was as follows:

- Separate the designs into three types of freeway facilities in which auxiliary lanes may be incorporated:
    - Weaving segments.
    - Isolated on-ramps.
    - Isolated off-ramps.
- For each type of facility, perform the following steps:
    - Review the results obtained in the literature review and engineer survey in order to identify the significant design factors that contribute to the operational and safety impacts. Examples of significant factors include number of lanes at the on-ramp and number of lanes at the off-ramp.
    - For each of the factors, identify several typical design values.
    - Examine the proposed values and eliminate some scenarios that do commonly coexist with auxiliary lanes or for which the impacts of auxiliary lanes are similar to other scenarios. For example, for analyzing the performance of isolated on-ramps and off-ramps, only the two rightmost freeway lanes are considered in the Highway Capacity Manual 2010 procedure. Therefore, when designing scenarios for isolated on-ramps and off-ramps, it is not necessary to consider a freeway with more than three through lanes.

4.1.1 Design Scenarios for Weaving Segments

4.1.1.1 Significant Design Factors

After conducting the literature review and engineer survey, the following important geometric features were identified in the design of auxiliary lanes in weaving segments.

- Number of lanes at the on-ramp, N_{ON}.
- Number of lanes at the off-ramp, N_{OFF}.
- Length of auxiliary lane (also known as weaving segment length), L_s.

Figure 4-3 illustrates that L_s is measured between the end points of barrier markings (solid white lines) that discourage lane changing. The definition of L_s is taken from the Highway Capacity Manual (TRB, 2010). The notations, as defined in HCM 2010, are also used in this report.

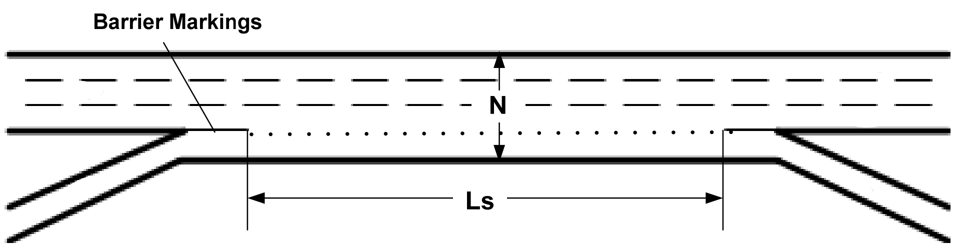


Figure 4-3. Geometric Factors of a Weaving Segment.

In addition to the highway geometry, the operational and safety impact of a weaving segment is also affected by the traffic demand. In a weaving segment, there are four traffic movements that are important inputs for the design and analysis of a weaving segment:

- Freeway-to-freeway volume, v_{FF}.
- Freeway-to-ramp volume, v_{FR}.
- Ramp-to-freeway volume, v_{RF}.
- Ramp-to-ramp volume, v_{RR}.

The notations of the movement volumes are taken from HCM 2010. Their units are vehicles per hour. Figure 4-4 illustrates the four movements and their volumes.

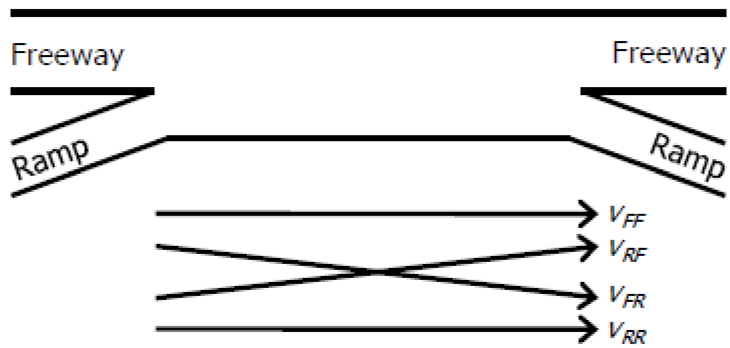


Figure 4-4. Traffic Movements at a Weaving Segment.

Other factors such as freeway free-flow speed, freeway capacity, minimum segment speed, and terrain were initially considered. However, after conducting sensitivity tests on the effect of these factors on the LOS and density (the LOS criteria) using the HCM 2010 analysis procedure implemented in HCS 2010 (McTrans, 2010), these factors were found to have little impact on the weaving segment's density. Therefore, they were not considered in the scenario design.

4.1.1.2 Possible Design Values

The common design values were also observed from the literature, in particular the HCM 2010 and the closely related HCS 2010, survey results, and field observations. The following attributes are possible in the design of weaving segments.

- Number of lanes at on-ramp, N_{ON}: 1 and 2 lanes.
- Number of lanes at off-ramp, N_{OFF}: 1 and 2 lanes.
- Length of auxiliary lane, L_s: 750, 1500, 2250 ft.

For L_s, although the minimum distance of 1500 ft is specified in the TxDOT Roadway Design Manual (TxDOT, 2010), sites with smaller weaving segment lengths have been found in El Paso, Texas. Other states have used up to 2,500 ft. Depending on the traffic volume, HCM 2010 may consider an on-ramp and an off-ramp with L_s more than 3,000 ft as isolated ramps. Therefore, three L_s values were assigned: 750 ft, 1500 ft and 2250 ft.

As for the volumes, the research team decided to use two levels of volume, namely low and high volume (in vehicles per hour per lane, or vphpl) for v_{FF}, v_{FR}, v_{RF}, and v_{RR}, respectively. The numerical values of volumes were decided based on traffic counts at selected study sites. Low volume was set to be 500 vphpl, and high volume was set to be 1500 vphpl for main lanes. Values of 500 vph and 1500 vph were set for v_{FR} and v_{RF}.

4.1.1.3 Combined Design Attributes

The following facts were observed at the weaving segments in Texas:

- As the HCM 2010 analysis procedure requires the total number of lanes in the weaving segment (*N*) as input, the research team conducted another sensitivity test on the effect of *N* on LOS and density. The test results show that the number of freeway lanes has no significant impact when the number of main lanes is greater than three. In addition, two main lanes are not common on urban freeways. Therefore, the scenarios were restricted to three main lanes.
- Most of the on-ramps in Texas have either one or two lanes.
- Most of the off-ramps in Texas have either one or two lanes.

With the above observations, the geometric attributes were reduced to:

- Three main lanes.
- Number of lanes at on-ramp, N_{ON}: one lane and two lanes; two-lane on-ramp is only possible when off-ramp has one lane.
- Number of lanes at off-ramp, N_{OFF}: one and two lanes; two-lane off-ramp is only possible when on-ramp has one lane.
- Length of auxiliary lane L_s: 750, 1500, and 2250 ft.

The volumes of the four movements at a weaving segment, namely v_{FF}, v_{FR}, v_{RF}, and v_{RR}, were next considered.

- The two volume levels of v_{FF} remained unchanged, 500 vphpl and 1500 vphpl.
- For the entering and exiting vehicles (v_{RF} and v_{FR}), the total weaving volume of $v_W=v_{FR}+v_{RF}$ was considered to be 500 vphpl and 1500 vphpl instead.
- From preliminary volume counts at selected weaving segments in El Paso, v_{RR} was negligible. It accounted for less than 1 percent of the total traffic volume at the weaving segments. Therefore, v_{RR} was set to be 10 vphpl for all the design scenarios.

Table 4-1 lists the possible design scenarios after imposing the additional restrictions as mentioned. Note that for each scenario, both the before condition (without auxiliary lane, $N_A = 0$) and after condition (with auxiliary lane, $N_A = 1$) were included.

Table 4-1. Design Scenarios for Weaving Segments.

Scenario	N_{ON}	N_{OFF}	N_A		L_s (ft)	v_{FF} *(vphpl)*	$v_W = v_{FR} + v_{RF}$ *(vphpl)*	v_{RR} *(vphpl)*
			Before	*After*				
W01	1	1	0	1	750	500	500	10
W02	1	1	0	1	750	500	1500	10
W03	1	1	0	1	750	1500	500	10
W04	1	1	0	1	750	1500	1500	10
W05	1	1	0	1	1500	500	500	10
W06	1	1	0	1	1500	500	1500	10
W07	1	1	0	1	1500	1500	500	10
W08	1	1	0	1	1500	1500	1500	10
W09	1	1	0	1	2250	500	500	10
W10	1	1	0	1	2250	500	1500	10
W11	1	1	0	1	2250	1500	500	10
W12	1	1	0	1	2250	1500	1500	10
W13	1	2	0	1	750	500	500	10
W14	1	2	0	1	750	500	1500	10
W15	1	2	0	1	750	1500	500	10
W16	1	2	0	1	750	1500	1500	10
W17	1	2	0	1	1500	500	500	10
W18	1	2	0	1	1500	500	1500	10
W19	1	2	0	1	1500	1500	500	10
W20	1	2	0	1	1500	1500	1500	10
W21	1	2	0	1	2250	500	500	10
W22	1	2	0	1	2250	500	1500	10
W23	1	2	0	1	2250	1500	500	10
W24	1	2	0	1	2250	1500	1500	10
W25	2	1	0	2	750	500	500	10
W26	2	1	0	2	750	500	1500	10
W27	2	1	0	2	750	1500	500	10
W28	2	1	0	2	750	1500	1500	10
W29	2	1	0	2	1500	500	500	10
W30	2	1	0	2	1500	500	1500	10
W31	2	1	0	2	1500	1500	500	10
W32	2	1	0	2	1500	1500	1500	10
W33	2	1	0	2	2250	500	500	10
W34	2	1	0	2	2250	500	1500	10
W35	2	1	0	2	2250	1500	500	10
W36	2	1	0	2	2250	1500	1500	10

4.1.2 Design Scenarios for Isolated On-Ramps

4.1.2.1 Significant Design Factors

The design factors for isolated on-ramps may be grouped as freeway factors and on-ramp factors. The notations of the factors, if provided, are adopted from HCM 2010. Otherwise, they are defined in this report.

The freeway factors are:

- Number of lanes on freeway (mainline) N_F.
- Volume on freeway, v_F.
- Free-flow speed of freeway, FFS_F.

The on-ramp factors are:

- Number of lanes on on-ramp, N_R.
- Volume on on-ramp, v_R.
- Free-flow speed of on-ramp, FFS_R.
- Length of acceleration lane, L_A.

In the HCM 2010 analysis procedure, the length of acceleration lane includes the tapered portion of the ramp (white solid line). It is measured from the merge point or tip of the ramp nose. Figure 4-5 illustrates how L_A should be measured.

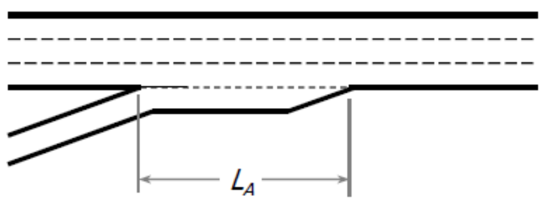


Figure 4-5. Length of Acceleration Lane.

4.1.2.2 Possible Design Values

The design values for the freeway factors are:

- Number of lanes on freeway, N_F: two, three, and four.
- Volume on freeway, v_F: 500 vphpl, 1500 vphpl.
- Free-flow speed of freeway, FFS_F: 65, 70, 75 mph.

HCM 2010 requires freeway free-flow speed as an input. In Texas, the speed limits on freeways are 60, 65, 70, and 75 mph, with 60 and 65 mph commonly found in urban areas. In practice, drivers always drive at free-flow speeds above the speed limit. Therefore, the possible free-flow speeds are more likely to be 65, 70, and 75 mph.

The design values for the on-ramp factors are:

- Number of lanes on on-ramp, N_R: one and two.
- Volume on on-ramp, v_R: 250 vphpl, 750 vphpl.
- Free-flow speed of on-ramp, FFS_R: not known.
- Length of acceleration lane, L_A: 500, 1000, and 1500 ft.

HCM 2010 requires freeway free-flow speed at the on-ramp as an input. In Texas, there is no posted speed limit at on-ramps.

4.1.2.3 Combined Design Attributes

The HCM 2010 analysis procedure considers the merge influence area at the vicinity of an on-ramp as the area in the two rightmost main lanes on the freeway and the acceleration lane, from the end of the taper (merge point) to 1500 ft downstream (see Figure 4-6). Three main lanes were assumed as a most typical setting. In Texas, most of the on-ramps have only one lane that merges into the freeway. Therefore, the number of lanes on the on-ramp was restricted to one lane only.

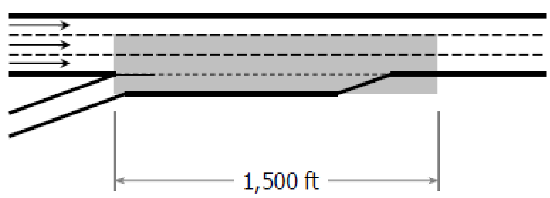


Figure 4-6. Merge Influence Area.

The research team conducted a sensitivity test in HCS 2010 on the effect of freeway free-flow speed on LOS and traffic density (which is the LOS criteria) in the merge influence area. The freeway free-flow speeds of 65, 70, and 75 mph did not result in any change in LOS and density. This could be because vehicles are no longer traveling at the free-flow speed in the merge influence area. That is, the average operating speed of the vehicles in the merge influence area is lower than the free-flow speed. It was therefore concluded that the freeway free-flow speed has no significant effect on the traffic operations in the merge influence area, and a free-flow speed of 65 mph was used for the design scenarios.

The research team performed another sensitivity test in HCS 2010 on the effect of free-flow speed at the on-ramp on LOS and traffic density in the merge influence area. Again, changing the free-flow speed at on-ramps did not result in any change in the LOS and density in the merge influence area. The on-ramp free-flow speed of 35 mph was assumed for the design scenarios.

With the above discussions, Table 4-2 lists the design scenarios and their attributes for on-ramps. Note that for each scenario, both the before condition (without auxiliary lane, L_A = 0) and after condition (with auxiliary lane, L_A = 500, 1000, or 1500 ft) were included.

Table 4-2. Design Scenarios for Isolated On-Ramps.

Scenario	N_F	FFS_F (mph)	N_R	FFS_R (mph)	L_A(ft)		v_F *(vphpl)*	v_R *(vphpl)*
					Before	*After*		
ON01	3	65	1	35	0	500	500	250
ON02	3	65	1	35	0	500	500	750
ON03	3	65	1	35	0	500	1500	250
ON04	3	65	1	35	0	500	1500	750
ON05	3	65	1	35	0	1000	500	250
ON06	3	65	1	35	0	1000	500	750
ON07	3	65	1	35	0	1000	1500	250
ON08	3	65	1	35	0	1000	1500	750
ON09	3	65	1	35	0	1500	500	250
ON10	3	65	1	35	0	1500	500	750
ON11	3	65	1	35	0	1500	1500	250
ON12	3	65	1	35	0	1500	1500	750

4.1.3 Design Scenarios for Isolated Off-Ramps

4.1.3.1 Significant Design Factors

The design factors for isolated on-ramps may be grouped as freeway factors and on-ramp factors. The notations of the factors, if provided, are adopted from HCM 2010. Otherwise, they are defined in this report.

The freeway factors are:

- Number of lanes on freeway (mainline) N_F.
- Volume on freeway, v_F.
- Free-flow speed of freeway, FFS_F.

The on-ramp factors are:

- Number of lanes on off-ramp, N_R.
- Volume on off-ramp, v_R.
- Free-flow speed of on off-ramp, FFS_R.
- Length of deceleration lane, L_D.

In the HCM 2010 analysis procedure, the length of deceleration lane is measured from the tapered portion of the ramp (start of the dotted line) to the diverge point (tip of the chevron), including the white solid line. Figure 4-7 illustrates how L_D should be measured.

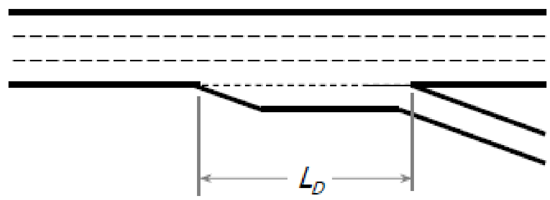


Figure 4-7. Length of Deceleration Lane.

4.1.3.2 Design Values

The design values for the freeway factors are:

- Number of lanes on freeway, N_F: 2, 3 and 4.
- Volume on freeway, v_F: 500 vphpl, 1500 vphpl.
- Free-flow speed of freeway, FFS_F: 65, 70, 75 mph.

These values are the same as those proposed for on-ramp sites.

The design values for the off-ramp factors are:

- Number of lanes on off-ramp, N_R: 1 and 2.
- Volume on off-ramp, v_R: 250 vphpl, 750 vphpl.
- Free-flow speed of off-ramp, FFS_R: not known.
- Length of deceleration lane, L_D: 500, 1000 and 1500 ft.

HCM 2010 requires freeway free-flow speed at off-ramp as an input. In Texas, there is no posted speed limit at off-ramps. The posted speeds (yellow rectangular signs) are advisory in nature. The common advisory speeds are 35 and 40 mph.

4.1.3.3 Combined Design Attributes

The HCM 2010 analysis procedure considers the diverge influence area at the vicinity of an off-ramp as the area in the two rightmost main lanes on the freeway, and the deceleration lane, from the diverge point (tip of chevron) to 1500 ft upstream (see Figure 4-8). The LOS is determined based on the estimated traffic density in this area. Therefore, traffic using the left lane(s) on the freeway other than the two rightmost main lanes appears to have no effect on the LOS criteria. Therefore, the number of main lanes on freeway is limited to 2 and 3. It is expected that freeways with more than three main lanes will results in LOS same as freeway with three lanes.

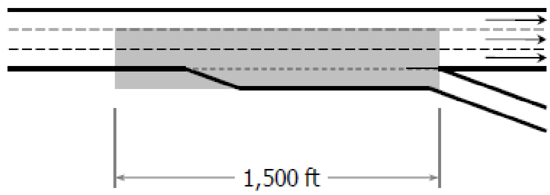


Figure 4-8. Diverge Influence Area.

The research team conducted a sensitivity test in HCS 2010 on the effect of freeway free-flow speed on LOS and density (which is the LOS criteria) in the diverge influence area. Similar to the finding for the merge influence area, the freeway free-flow speeds of 65, 70 and 75 mph did not result in any change in LOS and density in the diverge influence area. This may be due to the fact that vehicles are no longer traveling at the free-flow speed in the diverge influence area. It was therefore concluded that the freeway free-flow speed has no significant effect on the traffic operations in diverge influence area, and a free-flow speed of 65 mph is assumed for the design scenarios.

The research team performed another sensitivity test in HCS 2010 on the effect of free-flow speed at off-ramp on LOS and density in the diverge influence area. Again, changing the free-flow speed at off-ramps did not result in any change in the LOS and density in the merge influence area. The advisory speed of 35 mph is more commonly found in Texas and is therefore recommended as the value of off-ramp free-flow speed for the design scenarios.

With the above discussions, Table 4-3 lists the design scenarios and their attributes for on-ramps. Note that, for each scenario, both the before condition (without auxiliary lane, L_D =0) and after condition (with auxiliary lane, L_D =500, 1000 or 1500 ft) were included.

Table 4-3. Design Scenarios for Isolated On-Ramps.

Scenario	N_F	FFS_F (mph)	N_R	FFS_R (mph)	L_D(ft)		v_F *(vphpl)*	v_R *(vphpl)*
					Before	*After*		
OFF01	3	65	1	35	0	500	500	250
OFF02	3	65	1	35	0	500	500	750
OFF03	3	65	1	35	0	500	1500	250
OFF04	3	65	1	35	0	500	1500	750
OFF05	3	65	1	35	0	1000	500	250
OFF06	3	65	1	35	0	1000	500	750
OFF07	3	65	1	35	0	1000	1500	250
OFF08	3	65	1	35	0	1000	1500	750
OFF09	3	65	1	35	0	1500	500	250
OFF10	3	65	1	35	0	1500	500	750
OFF11	3	65	1	35	0	1500	1500	250
OFF12	3	65	1	35	0	1500	1500	750
OFF13	3	65	2	35	0	500	500	250
OFF14	3	65	2	35	0	500	500	750
OFF15	3	65	2	35	0	500	1500	250
OFF16	3	65	2	35	0	500	1500	750
OFF17	3	65	2	35	0	1000	500	250
OFF18	3	65	2	35	0	1000	500	750
OFF19	3	65	2	35	0	1000	1500	250
OFF20	3	65	2	35	0	1000	1500	750
OFF21	3	65	2	35	0	1500	500	250
OFF22	3	65	2	35	0	1500	500	750
OFF23	3	65	2	35	0	1500	1500	250
OFF24	3	65	2	35	0	1500	1500	750

4.2 EFFECTIVENESS OF SIMULATION METHODS

A comparison between real data, HCM weaving procedure, and VISSIM simulation is presented in this section. The comparison was performed to investigate whether VISSIM simulation is an appropriate tool to evaluate the impacts of auxiliary lanes.

4.2.1 HCM Weaving Procedure vs. Real Data

While the results of this study showed that the HCM methods have problems in analyzing a weaving segment without an auxiliary lane, the method suggested in Chapter 12 of the Highway Capacity Manual 2010 can be a useful tool for Texas traffic engineers in evaluating a weaving segment with an auxiliary lane. The LOS analysis procedure in HCM 2010 is the outcome of NCHRP Project 3-75 (Roess et al., 2008). This procedure estimates the average space mean speed of all vehicles (S) in a freeway weaving segment and converts it into density (D) before determining the LOS.

A validation effort was made by the researchers in validating the procedure for the following reasons:

- The model has not been validated with an independent database.
- The new model was developed with the traffic data collected from 14 sites in six states, i.e., Arizona, California, Florida, Maryland, Ohio, and Oregon.
- Data from Texas are not included in the development data set. The highway designs, traffic patterns, and driver behaviors on Texas highways might be different than those in other states.

Based on Texas data, researchers validated the HCM 2010 LOS analysis procedure, which is coded in the Highway Capacity Software 2010 (McTrans, 2010), for weaving segments. The validation procedure was as follows:

- Step 1: select site.
- Step 2: conduct field video recording and field data collection.
- Step 3: estimate space mean speed by running HCS 2010.
- Step 4: measure space mean speed from the field videos.
- Step 5: compare space mean speed estimated by HCS 2010 with speed measured from the videos.

4.2.2.1 Step 1: Site Selection

Three weaving segment sites with different geometric configurations were selected in El Paso, Texas. Table 4-4 lists the locations of these three sites, as well as the dates and hours selected for data collection and video recordings. Only these three sites in El Paso met the criteria of having (a) an auxiliary lane; (b) lane markings that conform to the latest edition of the Manual of Uniform Traffic Control Devices (FHWA, 2009); (c) at least a traffic surveillance camera with the necessary view for recording the video; and (d) no proximity to any work zone or unusual traffic pattern. All the three sites have one auxiliary lane, a one-lane entrance ramp, and a one-lane exit ramp. Figure 4-9 to Figure 4-11 show the geometric layouts of these sites.

Table 4-4. Data Collection for Validation.

Freeway	Upstream entrance ramp from	Downstream exit ramp to	L_S (ft)	N	Date	Time of video recording
US 54 southbound	Hondo Pass Ave	Hercules Ave	752	4	2/23/2012	7:00 a.m. to 8:00 a.m.
						12:00 p.m. to 1:00 p.m.
						4:00 p.m. to 5:00 p.m.
US 54 northbound	Hercules Ave	Hondo Pass Ave	680	3	3/13/2012	7:45 a.m. to 8:45 a.m.
						3:00 p.m. to 4:00 p.m.
						5:00 p.m. to 6:00 p.m.
I-10 eastbound	Artcraft Rd	Redd Rd	697	3	3/13/2012	9:00 a.m. to 10:00 a.m.
						3:00 p.m. to 4:00 p.m.

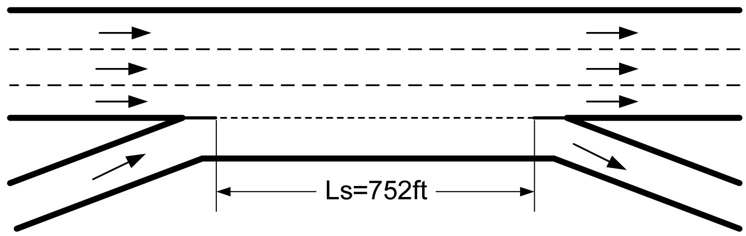


Figure 4-9. US 54 Southbound at Hondo Pass.

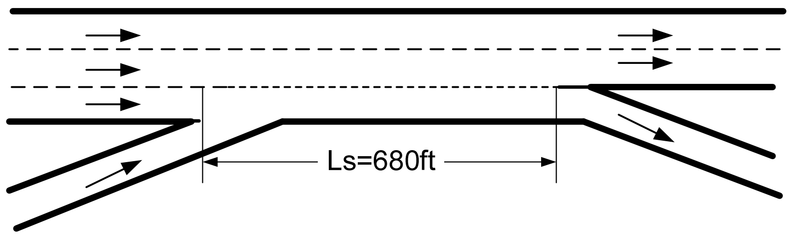


Figure 4-10. US 54 Northbound at Hondo Pass.

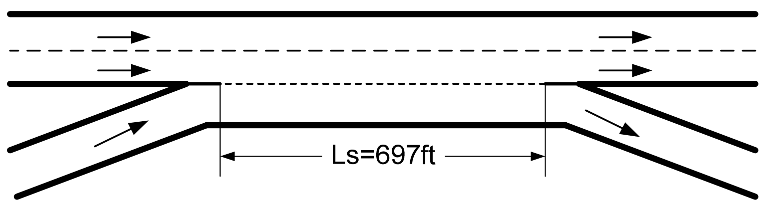


Figure 4-11. I-10 Eastbound at Artcraft.

4.2.2.2 Step 2: Field Video Recording and Field Data Collection

Video recordings of traffic operations at the hours (usually the morning and afternoon peak hours) as listed in Table 4-4 were obtained from TxDOT El Paso District's TransVista Traffic Management Center. As an example, a screen shot of the video of US 54 southbound at Hondo Pass is shown in Figure 4-12. The video recordings were replayed in the laboratory for data extraction. For each hour, traffic volumes of the four movements were counted:

- v_{FF}: freeway-to-freeway demand flow rate in the weaving section (pc/h/ln).
- v_{RF}: ramp-to-freeway demand flow rate in the weaving section (pc/h/ln).
- v_{FR}: freeway-to-ramp demand flow rate in the weaving section (pc/h/ln).
- v_{RR}: ramp-to-ramp demand flow rate in the weaving section (pc/h/ln).

Figure 4-12. Sample of Traffic Video.

4.2.2.3 Step 3: Estimate Speed by Running HCS 2010

The following information measured in the field and extracted from the videos was entered into HCS 2010 to estimate *S*:

- The configuration of weaving segment, including number of lanes, length of weaving segment, and minimum lane changes from ramp to freeway and freeway to ramp.
- Traffic volumes for the four movements.

4.2.2.4 Step 4: Measure Speed from Video Recording

To measure field speeds, approximately 30 vehicles were sampled from the weaving and non-weaving movements, respectively, per hour of video. The travel time of each selected vehicle between fixed markers was measured from the video clock. For each of the weaving and non-weaving movements, the average movement speed from the sample was first computed. The site's space mean speed was then estimated by taking the average value of the movement speeds, weighted by the hourly volumes of each movement.

4.2.2.5 Step 5: Compare Speed Estimated By HCS 2010 with Speed Measured from Video Recording

Table 4-5 lists the speeds measured from the videos and the speeds estimated by HCS 2010. Figure 4-13 plots the speeds estimated by HCS 2010 against the speeds obtained from the field data for the eight observed hours. The space mean speed was used as the performance measure during the validation because it was easier to measure speed than density from the videos. The plotted data points in Figure 4-13 all scatter around the 45-degree line. The fitted line that passes through the origin has a gradient of 1.0028, which is very close to 1.0. A statistical test on the gradient of the fitted line showed that this value was not significantly different from 1.0 at a significance level of 0.01.

Table 4-5. Comparison of Space Mean Speeds.

Sites	Video Time	Speed Measured from Video Recording (mph)	Speed Estimated by HCS 2010 (mph)
US 54 SB at Hondo Pass	7:00 a.m. to 8:00 a.m.	54.7	52.6
	12:00 p.m. to 1:00 p.m.	56.3	57.9
	4:00 p.m. to 5:00 p.m.	58.0	56.5
US 54 NB at Hondo Pass	7:45 a.m. to 8:45 a.m.	59.9	61.7
	3:00 p.m. to 4:00 p.m.	57.2	59.0
	5:00 p.m. to 6:00 p.m.	56.0	57.0
I-10 EB at Artcraft	9:00 a.m. to 10:00 a.m.	52.0	51.2
	3:00 p.m. to 4:00 p.m.	52.7	51.9

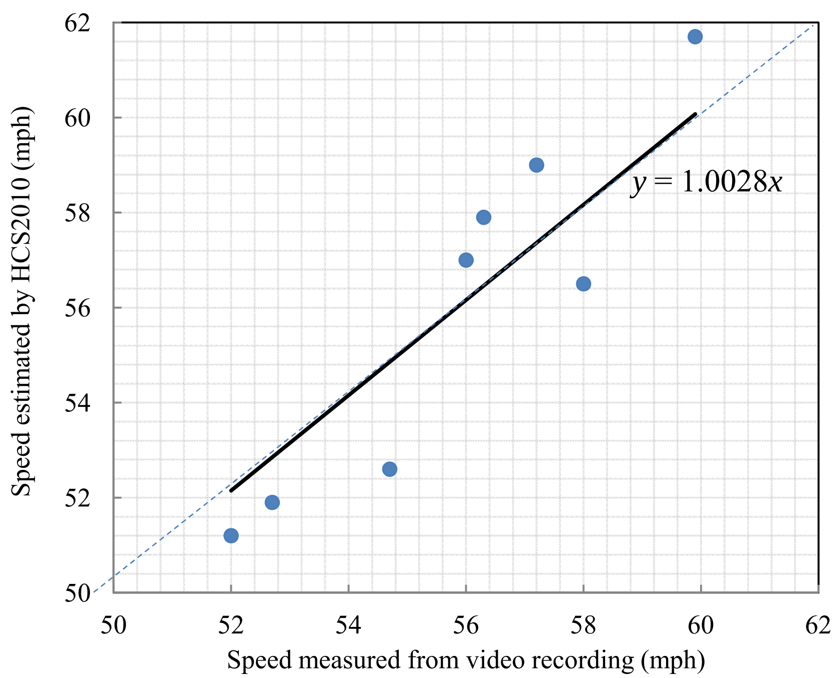


Figure 4-13. Comparison of Space Mean Speeds.

Based on the field data collected in El Paso, Texas, the results indicated that the HCM 2010 (Chapter 12) LOS analysis procedure and the HCS 2010 produced satisfactory estimates of speed for freeway weaving segments with an auxiliary lane.

4.2.2 HCM Weaving Procedure vs. VISSIM Simulation

A comparison was performed between the HCM weaving procedure and VISSIM simulation. In terms of speed estimated, the outcomes of VISSIM models were significantly correlated with the outcomes of the HCM weaving procedure, as plotted in Figure 4-14.

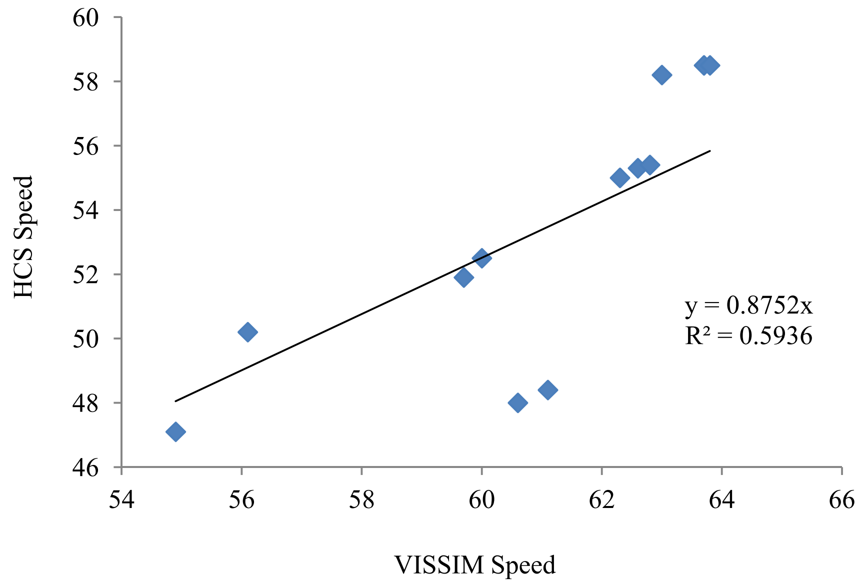


Figure 4-14. Comparison of HCM Speeds and VISSIM Speeds for Weaving Segment with Auxiliary Lane.

In terms of density estimated, the outcomes of VISSIM models were significantly correlated with the outcomes of the HCM weaving procedure, as plotted in Figure 4-15 through Figure 4-17.

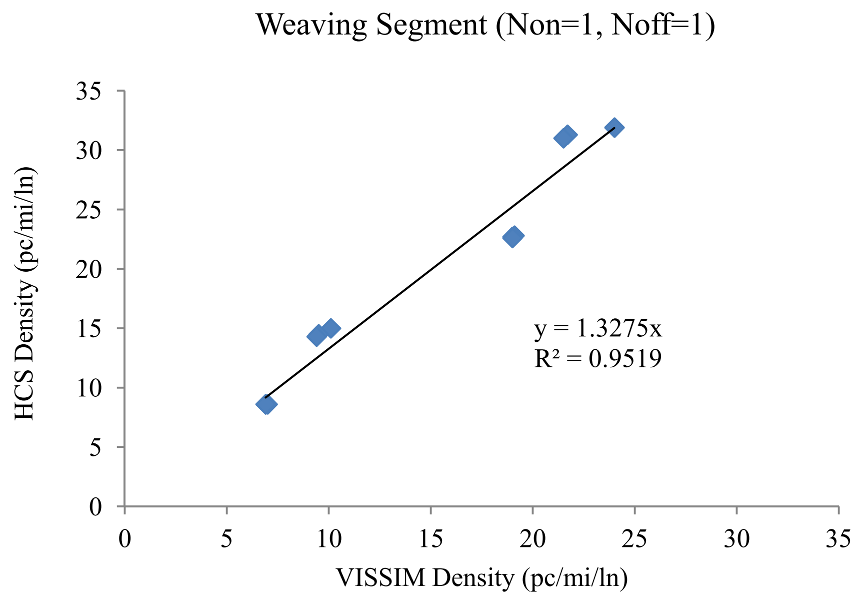


Figure 4-15. Comparison of Density by HCM and VISSIM for Weaving Segment with Auxiliary Lane (One Entrance Lane and One Exit Lane).

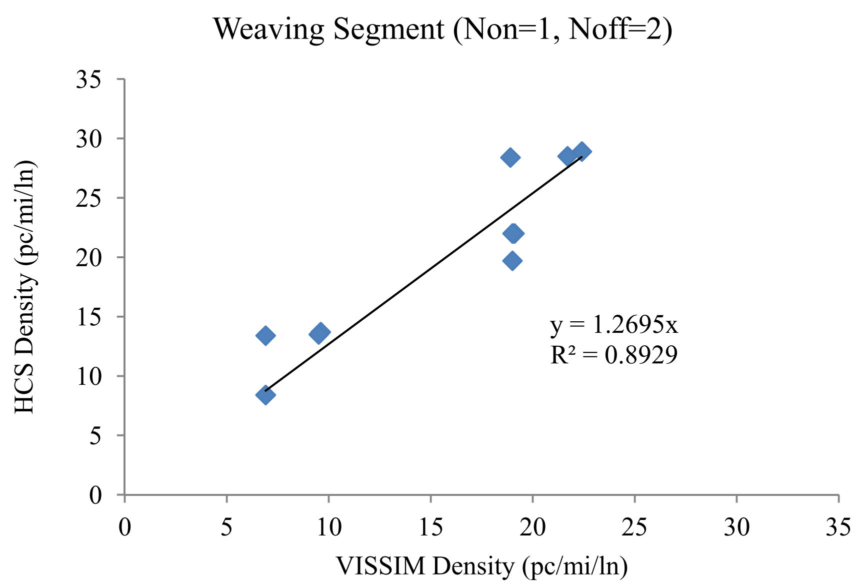


Figure 4-16. Comparison of Density by HCM and VISSIM for Weaving Segment with Auxiliary Lane (One Entrance Lane and Two Exit Lanes).

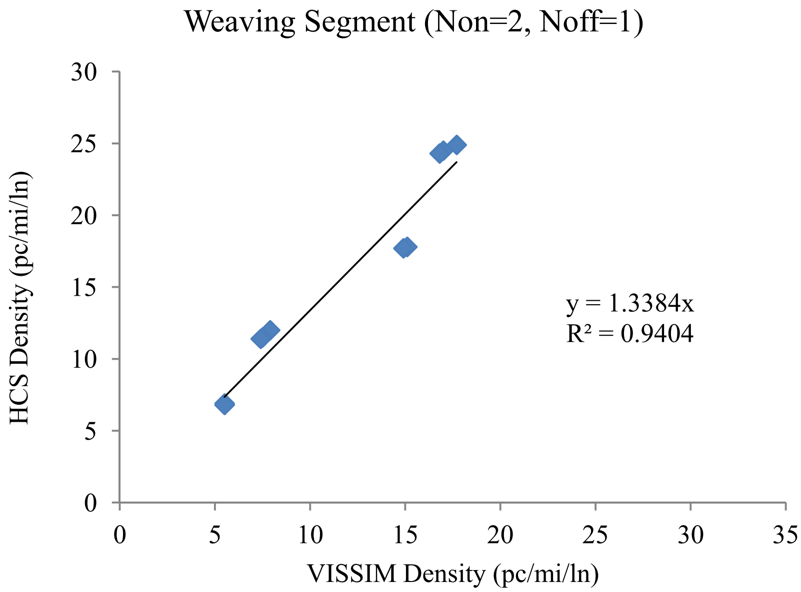


Figure 4-17. Comparison of Density by HCM and VISSIM for Weaving Segment with Auxiliary Lane (Two Entrance Lanes and One Exit Lane).

The results indicated that VISSIM can just as effectively represent the trend of changes due to the different volumes and geometrics as the HCM weaving procedure does, which was validated in the previous section.

4.3 OPERATIONAL BENEFITS FROM ADDING AUXILIARY LANES AT THE SEGMENT LEVEL

In this section, the results of the simulation experiments are presented regarding the operational benefits of adding an auxiliary lane at freeway weaving segments, entrance-ramp influence areas, and exit-ramp influence areas. Density, speed, and capacity were compared before and after an auxiliary lane was added. Then, look-up tables were developed to enumerate the operational impacts under various conditions.

4.3.1 Methods for Estimating Performance Measures

4.3.1.1 Speed and Density

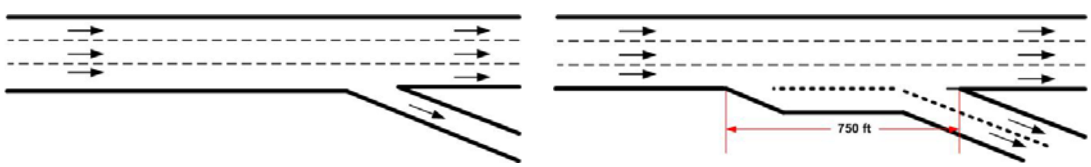
The VISSIM simulation data of speed and density were collected. These two measures are primary factors that are widely used to determine the level of service of freeway facilities in the existing procedures (e.g., the HCM methodology).

4.3.1.2 Capacity

The Highway Capacity Manual (2010) is the publication most often used to estimate capacity. The current published version defines the capacity as “the maximum hourly rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period, under prevailing roadway, traffic and control conditions.” Specifically for freeway facilities, capacity values are observable when the freeway will become congested and break down (i.e., transition from a non-congested state to a congested state) as demand exceeds the specified capacity value.

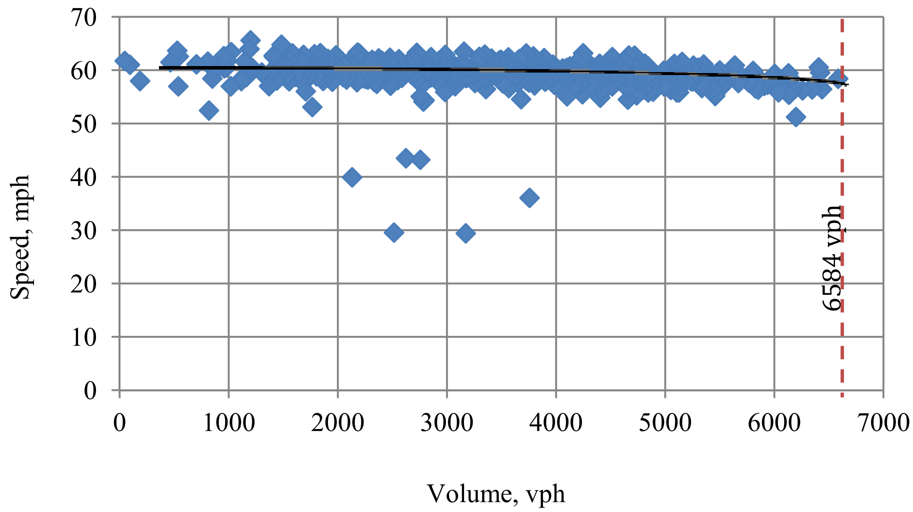
Using the HCM 2010 method, the estimated capacity of the isolated ramp-freeway junction depends solely on the number of freeway main lanes, regardless of the presence of a parallel auxiliary lane. Considering this limitation, simulation approaches can be more appropriate for estimating capacity for weaving segments with and without auxiliary lanes.

In this task, VISSIM simulation models were developed, and simulation data of speed, volume, and density in 15-minute intervals were collected through the VISSIM data collection functionality. The data were used to draw speed-flow curves for the weaving segments and isolated on-ramp/off-ramp influence areas. Then, the capacity values (i.e., the breakdown points) were acquired. Figures 4-18 and 4-19 show a sample illustrating how the researchers estimated the capacities. Figure 4-19 shows the speed-flow curves for the ramp influence areas shown in Figure 4-18.

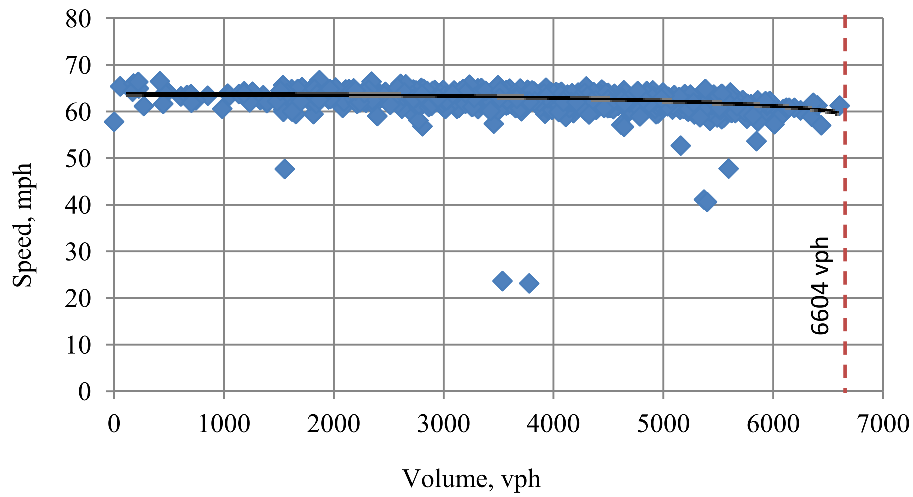


(a) Before Conditions (b) After Conditions

Figure 4-18. Before and After Conditions in Illustrative Sample.



(a) Before Conditions



(b) After Conditions

Figure 4-19. Estimation of Segment Capacity Based on Simulated Speed-Flow Curves in Illustrative Sample.

4.3.2 Results for Weaving Segments

For each study scenario, the following parameters were collected/calculated from the simulations:

- Density without and with an auxiliary lane.
- Speed without and with an auxiliary lane.
- Segment capacity without and with an auxiliary lane.
- Percentage of change in density, speed, and capacity.

$$\text{Percentage Change in Density} = \frac{\text{Density After - Density Before}}{\text{Density Before}} \times 100\%$$

$$\text{Percentage Change in Speed} = \frac{\text{Speed After - Speed Before}}{\text{Speed Before}} \times 100\%$$

$$\text{Percentage Change in Capacity} = \frac{\text{Capacity After - Capacity Before}}{\text{Capacity Before}} \times 100\%$$

Table 4-6 shows that at a weaving segment with a one-lane entrance and one-lane exit, the addition of an auxiliary lane led to a reduction in density in all of the scenarios. On average, the density was reduced by 26.45 percent. The changes in LOS are also compared in Table 4-6. With the presence of the auxiliary lane, the LOS remained the same or became better. The operating speed of the weaving segments was increased by 1.99 percent with the addition of an auxiliary lane, on average. The capacity of the weaving segment was increased dramatically by 42.18 percent due to the installation of the auxiliary lane.

Table 4-7 shows that the addition of an auxiliary lane and an additional exit-ramp lane at a weaving segment led to a reduction in density in all of the scenarios. On average, the density was reduced by 29.62 percent. With the presence of an auxiliary lane, the LOS remained the same or became better. On average, the operating speed of the weaving segments was increased by 4.01 percent with the addition of an auxiliary lane. The capacity of the weaving segment was increased dramatically by 43.63 percent due to the installation of the auxiliary lanes.

Table 4-8 shows that the addition of an auxiliary lane and an additional entrance-ramp lane at a weaving segment led to a reduction in density in all of the scenarios. On average, the density was reduced by 42.33 percent. With the presence of an auxiliary lane, the LOS remained the same or became better. On average, the operating speed of the weaving segments was increased by 3.89 percent with the addition of an auxiliary lane. The capacity of the weaving segment was increased dramatically by 56.01 percent after the geometric modifications.

Table 4-6. Operational Impacts of Auxiliary Lanes on Weaving Segments (One-Lane Entrance Ramp and One-Lane Exit Ramp).

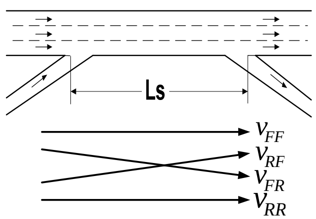
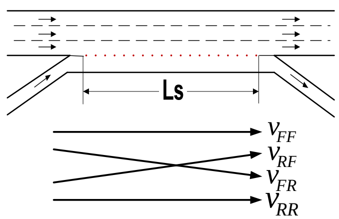
Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Ramp Spacing (ft), L_s	Freeway-to-Freeway volume (pc/h/ln), v_{FF}	Weaving Volume (pc/h), $v_{FR}+v_{RF}$	Density Before (vpm)	Density After (vpm)	% of Change in Density	Speed Before (mph)	Speed After (mph)	% of Change in Speed	Capacity Before (veh/h)	Capacity After (veh/h)	% of Change in Capacity	LOS Before	LOS After
		750	500	500	9.5	7.0	-26.32%	61.8	63.0	1.94%	5908	8198	38.77%	A	A
				1500	13.3	10.1	-24.06%	56.9	56.1	-1.41%				B	B
			1500	500	26.2	19.1	-27.10%	60.7	62.3	2.64%				C	B
				1500	31.5	24.0	-23.81%	55.7	54.9	-1.44%				D	C
		1500	500	500	9.4	6.9	-26.60%	62.7	63.7	1.59%	5914	8421	42.39%	A	A
				1500	13.1	9.5	-27.48%	57.8	59.7	3.29%				B	A
			1500	500	25.8	19.0	-26.36%	61.6	62.6	1.62%				C	B
				1500	30.4	21.7	-28.62%	57.7	60.6	5.03%				D	C
		2250	500	500	9.3	6.9	-25.81%	62.9	63.8	1.43%	5962	8668	45.39%	A	A
				1500	12.9	9.4	-27.13%	58.0	60.0	3.45%				B	A
			1500	500	25.7	19.0	-26.07%	61.9	62.8	1.45%				C	B
				1500	29.9	21.5	-28.09%	58.6	61.1	4.27%				D	C
						Average:	-26.45%		Average:	1.99%		Average:	42.18%		

Table 4-7. Operational Impacts of Auxiliary Lanes on Weaving Segments (One-Lane Entrance Ramp and Two-Lane Exit Ramp).

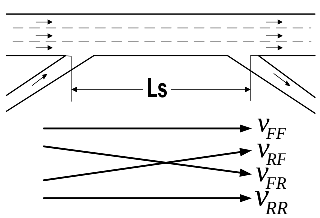
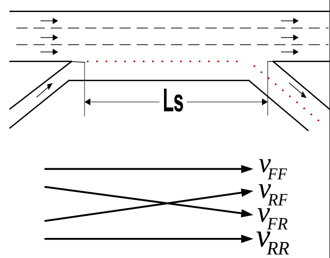
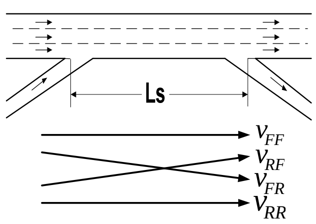
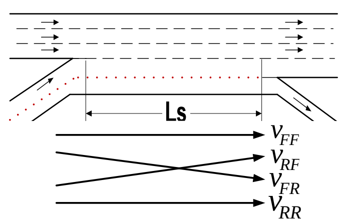
Before Implementation of Auxiliary lanes	After implementation of Auxiliary lanes	Ramp Spacing (ft)	Freeway-to-freeway volume (pc/h/ln)	Weaving volume (pc/h) $v_{FR}+v_{RF}$	Before Density	After Density	% of Density	Before Speed (mph)	After Speed (mph)	% of Speed	Before Capacity (veh/h)	After Capacity (veh/h)	% of Capacity	LOS Before	LOS After
		750	500	500	9.5	6.9	-27.37%	61.8	63.5	2.75%	5908	8249	39.62%	A	A
				1500	13.3	9.6	-27.82%	56.9	59.3	4.22%				B	A
			1500	500	26.2	19.1	-27.10%	60.7	62.5	2.97%				C	B
				1500	31.5	22.4	-28.89%	55.7	58.9	5.75%				D	C
		1500	500	500	9.4	6.9	-26.60%	62.7	63.8	1.75%	5914	8631	45.94%	A	A
				1500	13.1	9.5	-27.48%	57.8	60.0	3.81%				B	A
			1500	500	25.8	19.0	-26.36%	61.6	62.7	1.79%				C	B
				1500	30.4	21.7	-28.62%	57.7	60.7	5.20%				D	C
		2250	500	500	9.3	6.9	-25.81%	62.9	64.0	1.75%	5962	8665	45.34%	A	A
				1500	12.9	6.9	-46.51%	58.0	63.4	9.31%				B	A
			1500	500	25.7	19.0	-26.07%	61.9	62.8	1.45%				C	B
				1500	29.9	18.9	-36.79%	58.6	62.9	7.34%				D	B
						Average:	-29.62%		Average:	4.01%		Average:	43.63%		

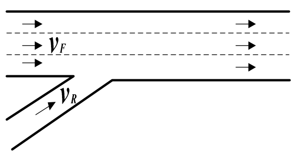
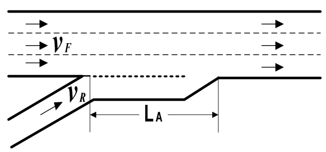
Table 4-8. Operational Impacts of Auxiliary Lanes on Weaving Segments (Two-Lane Entrance Ramp and One-Lane Exit Ramp).

Before Implementation of Auxiliary lanes	After implementation of Auxiliary lanes	Ramp Spacing (ft), L_s	Freeway-to-Freeway volume (pc/h/ln), v_{FF}	Weaving Volume (pc/h), $v_{FR}+v_{RF}$	Density Before (vpm)	Density After (vpm)	% of Change in Density	Speed Before (mph)	Speed After (mph)	% of Change in Speed	Capacity Before (veh/h)	Capacity After (veh/h)	% of Change in Capacity	LOS Before	LOS After
		750	500	500	9.5	5.5	-42.11%	61.8	63.5	2.75%	5908	8767	48.39%	A	A
				1500	13.3	7.9	-40.60%	56.9	57.1	0.35%				B	A
			1500	500	26.2	15.1	-42.37%	60.7	63.0	3.79%				C	B
				1500	31.5	17.7	-43.81%	55.7	59.6	7.00%				D	B
		1500	500	500	9.4	5.5	-41.49%	62.7	63.6	1.44%	5914	9441	59.64%	A	A
				1500	13.1	7.5	-42.75%	57.8	60.2	4.15%				B	A
			1500	500	25.8	15.1	-41.47%	61.6	63.3	2.76%				C	B
				1500	30.4	17.0	-44.08%	57.7	62.0	7.45%				D	B
		2250	500	500	9.3	5.5	-40.86%	62.9	64.0	1.75%	5962	9539	60.00%	A	A
				1500	12.9	7.4	-42.64%	58.0	61.1	5.34%				B	A
			1500	500	25.7	14.9	-42.02%	61.9	63.8	3.07%				C	B
				1500	29.9	16.8	-43.81%	58.6	62.6	6.83%				D	B
						Average:	-42.33%		Average:	3.89%		Average:	56.01%		

4.3.3 Results for Entrance-Ramp Influence Areas

Table 4-9 lists the results of simulation experiments for the entrance-ramp influence areas. It shows that after the addition of a parallel acceleration lane, there was a reduction in density in each scenario. In addition, the changes in LOS are also compared. With a parallel acceleration lane, the LOS remained the same or became better. On average, the operating speed of the influence areas was decreased slightly by 0.28 percent with the addition of a parallel acceleration lane, which could be a result of merging traffic having easier access and interfering with the mainline traffic. The capacity of the weaving segment was increased slightly by 1.97 percent due to the installation of the parallel acceleration lane.

Table 4-9. Operational Impacts of Parallel Acceleration Lane on Merge Influence Area with a One-Lane Entrance Ramp.

Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Parallel Acceleration Length (ft), L_A	Freeway-to-Freeway volume (pc/h/ln), v_F	Merging Volume (pc/h), v_R	Density Before(vpm)	Density After (vpm)	% of Change in Density	Speed Before (mph)	Speed After (mph)	% of Change in Speed	Capacity Before (veh/h)	Capacity After (veh/h)	% of Change in Capacity	LOS Before	LOS After
		500	500	250	9.2	7.1	-22.83%	63.8	62.5	-2.04%	6892	6970	1.13%	A	A
				750	12.5	9.5	-24.00%	60.5	59.8	-1.16%				B	A
			1500	250	25.9	19.6	-24.32%	61.5	61.0	-0.81%				C	B
				750	30.4	24.4	-19.74%	57.7	53.9	-6.59%				D	C
		1000	500	250	9.2	6.9	-25.00%	63.8	63.9	0.16%	6892	7055	2.37%	A	A
				750	12.5	9.3	-25.60%	60.5	60.9	0.66%				B	A
			1500	250	25.9	19.1	-26.25%	61.5	62.4	1.46%				C	B
				750	30.4	21.9	-27.96%	57.7	60.2	4.33%				D	C
		1500	500	250	9.2	6.9	-25.00%	63.8	63.9	0.16%	6892	7059	2.42%	A	A
				750	12.5	9.3	-25.60%	60.5	61.1	0.99%				B	A
			1500	250	25.9	19.1	-26.25%	61.5	62.4	1.46%				C	B
				750	30.4	21.8	-28.29%	57.7	60.4	4.68%				D	C
						Average:	-25.07%		Average:	-0.28%		Average:	1.97%		

4.3.4 Results for Exit-Ramp Influence Areas

With a one-lane exit available, the results showed that after the addition of a parallel deceleration lane, there was a reduction in density in each scenario. The speed of vehicles slightly increased with the presence of the parallel deceleration lane. The LOS remained the same or became better. On average, the operating speed of the weaving segments was increased slightly by 5.10 percent with the addition of the parallel deceleration lane. The capacity of the ramp influence area basically remained the same (increased slightly by 0.82 percent) at the diverge area.

With a two-lane exit available, after the addition of a parallel deceleration lane, there was a reduction in density in each scenario. The speed of vehicles slightly increased with the presence of an auxiliary lane and an additional exit-ramp lane. With an auxiliary lane, the LOS remained the same or became better. On average, the operating speed of the weaving segments was increased slightly by 6.35 percent with the addition of the parallel deceleration lane and the additional exit-ramp lane. The capacity of the ramp influence area remained the same (increased slightly by 6.24 percent) at the diverge area before and after the geometric modifications.

Table 4-10. Operational Impacts of Auxiliary Lane on Diverge Influence Area with a One-Lane Exit Ramp.

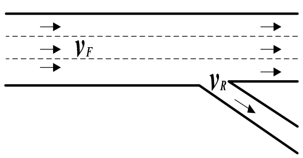
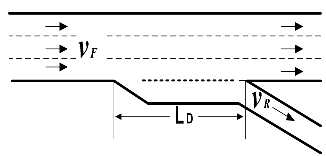
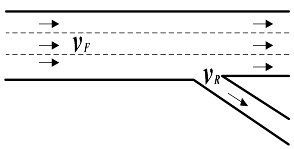
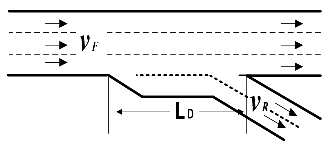
Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Parallel Deceleration Length (ft), L_D	Freeway-to-Freeway volume (pc/h/ln), v_F	Diverging Volume (pc/h), v_R	Density Before(vpm)	Density After (vpm)	% of Change in Density	Speed Before (mph)	Speed After (mph)	% of Change in Speed	Capacity Before (veh/h)	Capacity After (veh/h)	% of Change in Capacity	LOS Before	LOS After
		500	500	250	8.1	6.0	-25.93%	62.0	63.4	2.26%	6584	6636	0.79%	A	A
				750	8.4	6.3	-25.00%	59.6	59.7	0.17%				A	A
			1500	250	26.3	18	-31.56%	60.5	62.6	3.47%				C	B
				750	29.7	18.3	-38.38%	59.4	61.6	3.70%				C	B
		1000	500	250	8.1	5.8	-28.40%	62.0	65.3	5.32%	6584	6637	0.80%	A	A
				750	8.4	5.9	-29.76%	59.6	64.3	7.89%				A	A
			1500	250	26.3	17.6	-33.08%	60.5	64.0	5.79%				C	B
				750	29.7	17.8	-40.07%	59.4	63.5	6.90%				C	B
		1500	500	250	8.1	5.8	-28.40%	62.0	65.6	5.81%	6584	6640	0.85%	A	A
				750	8.4	5.9	-29.76%	59.6	63.6	6.71%				A	A
			1500	250	26.3	17.7	-32.70%	60.5	63.9	5.62%				C	B
				750	29.7	17.7	-40.40%	59.4	63.9	7.58%				C	B
						Average:	-31.95%		Average:	5.10%		Average:	0.82%		

Table 4-11. Operational Impacts of Auxiliary Lane on Diverge Influence Area with a Two-Lane Exit Ramp.

Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Parallel Deceleration Length (ft), L_D	Freeway-to-Freeway volume (pc/h/ln), v_F	Diverging Volume (pc/h), v_R	Density Before (vpm)	Density After (vpm)	% of Change in Density	Speed Before (mph)	Speed After (mph)	% of Change in Speed	Capacity Before (veh/h)	Capacity After (veh/h)	% of Change in Capacity	LOS Before	LOS After
		500	500	250	8.1	5.9	-27.16%	62.0	64.2	3.55%	6584	6995	6.24%	A	A
				750	8.4	6.0	-28.57%	59.6	63.4	6.38%				A	A
			1500	250	26.3	17.9	-31.94%	60.5	62.9	3.97%				C	B
				750	29.7	18.1	-39.06%	59.4	62.5	5.22%				C	B
		1000	500	250	8.1	5.7	-29.63%	62.0	65.7	5.97%	6584	6995	6.24%	A	A
				750	8.4	5.8	-30.95%	59.6	65.0	9.06%				A	A
			1500	250	26.3	17.7	-32.70%	60.5	63.7	5.29%				C	B
				750	29.7	17.7	-40.40%	59.4	63.7	7.24%				C	B
		1500	500	250	8.1	5.7	-29.63%	62.0	66.0	6.45%	6584	6995	6.24%	A	A
				750	8.4	5.8	-30.95%	59.6	65.4	9.73%				A	A
			1500	250	26.3	17.7	-32.70%	60.5	63.9	5.62%				C	B
				750	29.7	17.6	-40.74%	59.4	64.0	7.74%				C	B
						Average:	-32.87%		Average:	6.35%		Average:	6.24%		

4.4 SUMMARY

In this chapter, the operational effects of adding auxiliary lanes at freeway weaving segments, entrance-ramp junctions, and exit-ramp junctions were quantified. The results of the simulation experiments of various scenarios that involved various traffic and geometric conditions were presented. Density, speed, and capacity were selected as performance measures of auxiliary lanes. The simulation results led to the following findings that can be useful to researchers and practitioners.

4.4.1 Density

- Generally, adding an auxiliary lane at weaving segments or ramp influence areas can lead to a lower density, which means more freedom of maneuvers from a driver's standpoint. Since density represents the conventional criteria in determining LOS, LOS will generally be improved.

4.4.2 Speed

- For weaving segments, on average, operating speed can be increased slightly by less than 5 percent by adding an auxiliary lane.
- For entrance-ramp influence areas, adding a parallel acceleration lane can slightly reduce the speed probably because the outside mainline lane is more exposed to interference of the merge traffic.
- For exit-ramp influence areas, adding a parallel auxiliary/deceleration lane can slightly increase the speed by approximately 5 percent.

4.4.3 Capacity

- For weaving segments, capacity of the segments can be significantly enhanced by adding an auxiliary lane. Over 40 percent capacity enhancement can be expected when an auxiliary lane is added where a freeway has three mainline lanes in the studied direction. An additional ramp lane on either the entrance ramp or the exit ramp can further enhance the capacity of the weaving segments.
- For isolated ramp influence areas (entrance/exit), providing a parallel auxiliary lane does not have significant impacts on the capacity of the ramp influence area. This is generally consistent with the findings in the Highway Capacity Manual (2010).

4.5 REFERENCES

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CHAPTER 5: OPERATIONAL IMPACTS OF AUXILIARY LANES AT THE CORRIDOR LEVEL

The purpose of this chapter is to describe the micro-simulation studies performed to identify the level and scope of impacts of auxiliary lanes at corridors where successive ramps are available. To this end, field data were collected at three selected study locations in Houston, Texas, and traffic operations at the study sites were modeled using VISSIM. The level and scope of impacts of auxiliary lanes were investigated by comparing operational performance of corridors with various auxiliary lane designs.

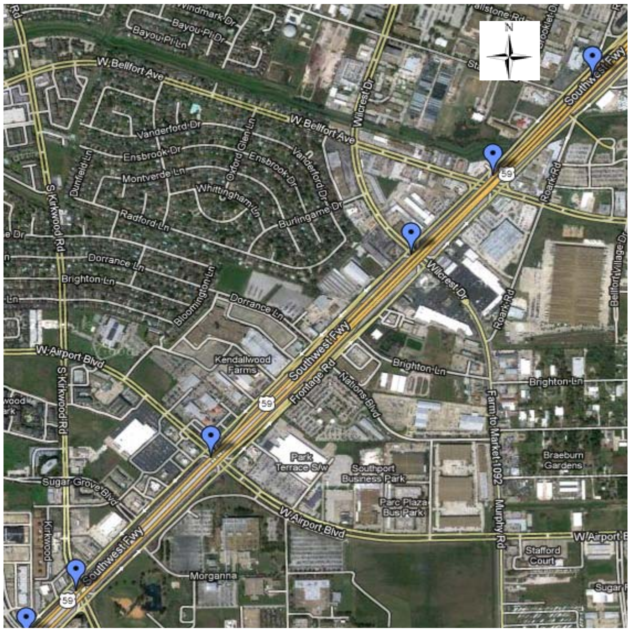
5.1 FIELD DATA COLLECTION

5.1.1 Study Locations

To prepare field data for the simulation-based studies, field data at selected study locations were collected. The collected data included traffic volumes and travel times, which were key inputs to the simulation modeling. The selected study locations were freeway corridors with successive ramps and weaving sections. With approval from the Project Monitoring Committee (PMC), three study locations were selected, as shown in Table 5-1. In Figure 5-1 through Figure 5-3, the blue pins on the Google Maps are either the ending points of the studied freeway segments or the locations of the TranStar surveillance cameras.

Table 5-1. Description of Selected Study Locations.

Location 1 (Figure 5-1, Southbound) US 59 & W. Airport Blvd.	Location 2 (Figure 5-2, Eastbound) I-610 & Stella Link Rd.	Location 3 (Figure 5-3 Westbound) I-610 & Kirby Dr.
• The length of this segment is approximately 1.82 miles. • Three to four lanes on southbound freeway mainline. • Three entrance ramps and two exit ramps. • Posted speed limit is 65 mph. • Advisory speed for exit ramp is 45 mph. • Two full auxiliary lanes provided. The spacing between entrance ramp and exit ramp is 3,090 ft and 3,161 ft, respectively.	• The length of this segment is approximately 1.68 miles. • Five lanes on freeway mainline eastbound. • Posted speed limit is 60 mph. • Advisory speed for exit ramp is 35 mph. • Two entrance ramps and three exit ramps. • Two full auxiliary lanes provided along this segment and the lengths are approximately 1,840 ft and 1,760 ft, respectively.	• The length of this segment is about 4,030 ft. • Five lanes on freeway mainline eastbound. • Posted speed limit is 60 mph. • Advisory speed for exit ramp is 35 mph. • Two entrance ramps and two exit ramps. • Two full auxiliary lanes provided along this segment and the lengths are approximately 864 ft and 832 ft, respectively.



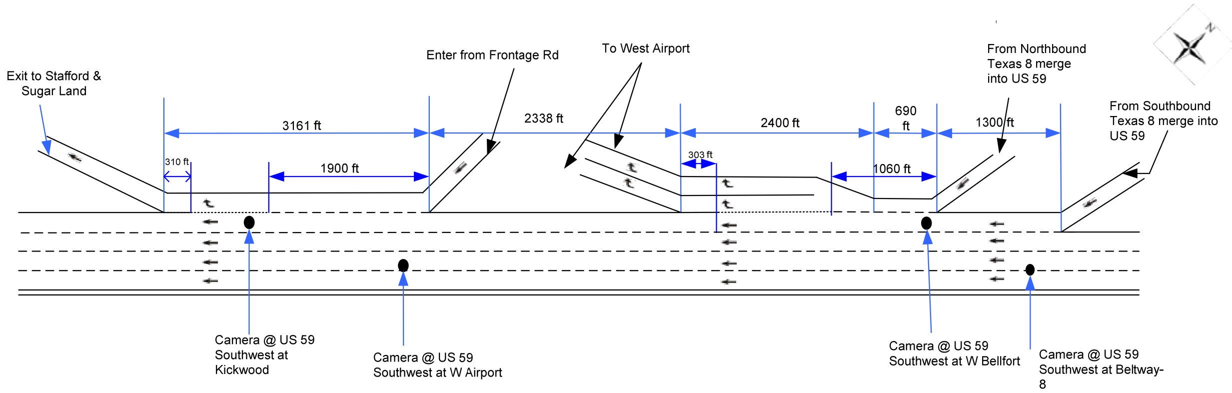


Figure 5-1. US 59 Southwest Freeway and W. Airport Blvd (Southbound).

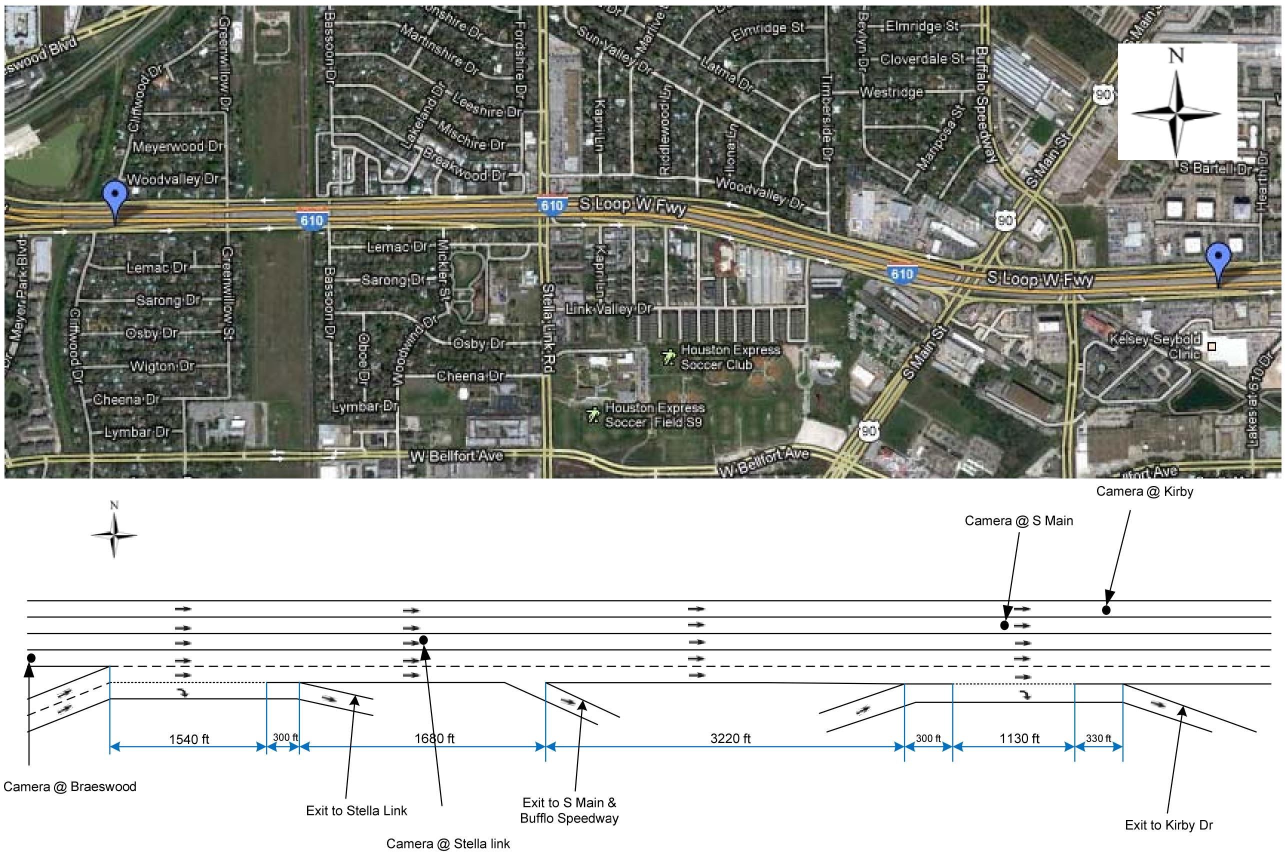


Figure 5-2. I-610 Freeway and Stella Link Rd (Eastbound).

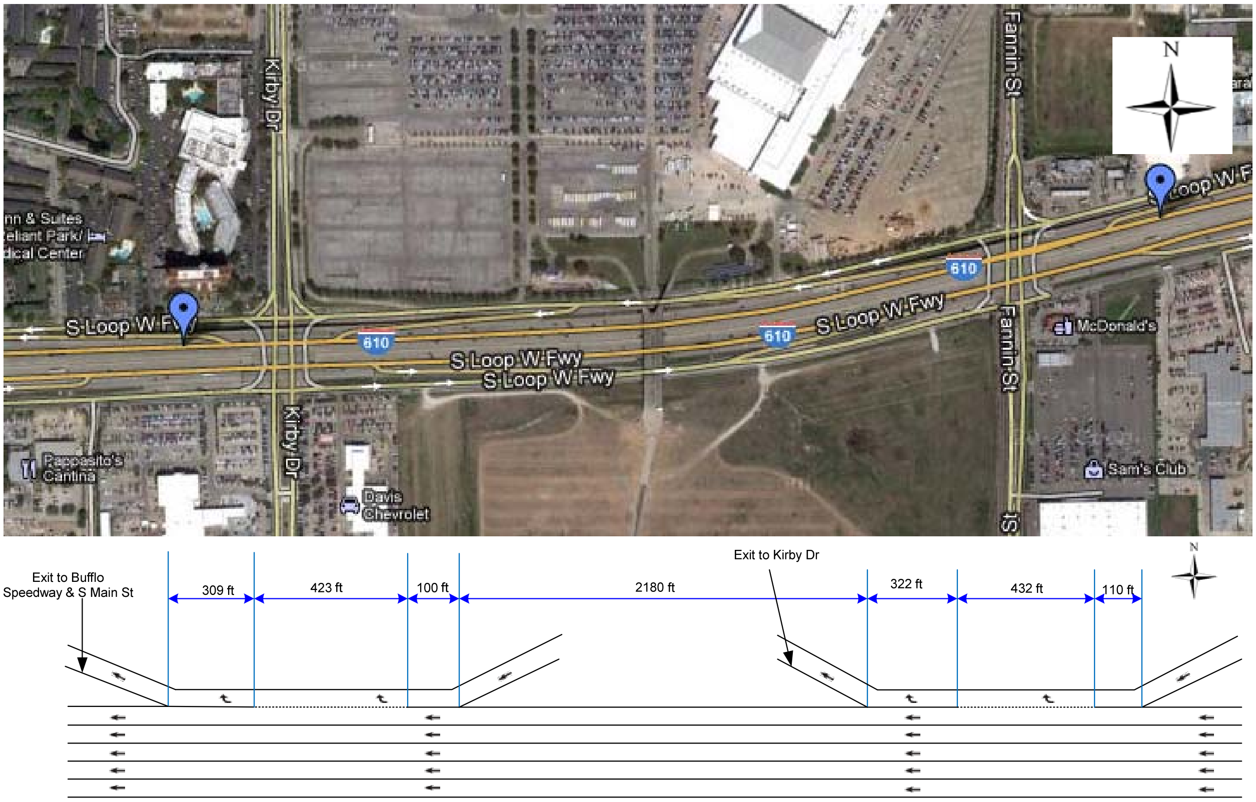


Figure 5-3. I-610 Freeway and Kirby Dr (Westbound).

5.1.2 Field Data Collection

5.1.2.1 Time Periods for the Observation

- Location 1—US 59 Southwest Freeway and W. Airport Blvd: 1.5 hours during 7:00-8:30 a.m. and 1.5 hours during 5:00-6:30 p.m. on June 18, 2012 (weekday).
- Location 2—I-610 Freeway and Stella Link Rd: 1.5 hours during 5:00–6:30 p.m. on June 19, 2012 (weekday) and 1.5 hours during 8:00–9:30 a.m. on June 20, 2012 (weekday).
- Location 3—I-610 Freeway and Kirby Dr: 1.5 hours during hours during 7:00–8:30 a.m. and 1.5 hours during 5:00–6:30 p.m. on June 14, 2012 (weekday).

5.1.2.2 Observation Methods

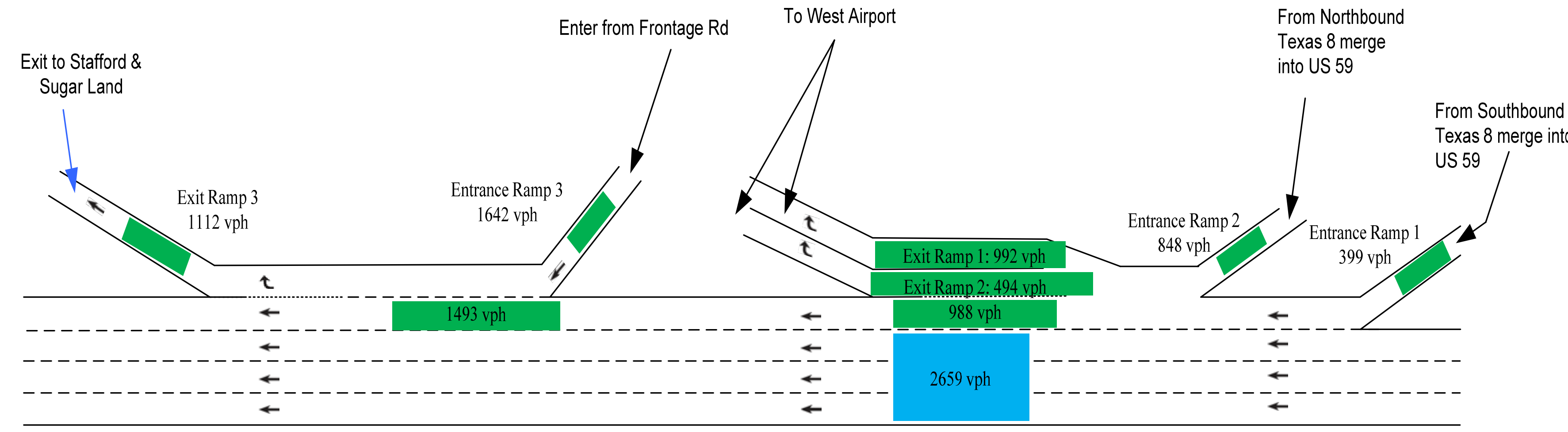
An Excel-based vehicle counter was developed to facilitate the data counting. The recorded videos were replayed in the laboratory to collect traffic data.

5.1.3 Traffic Data Observed

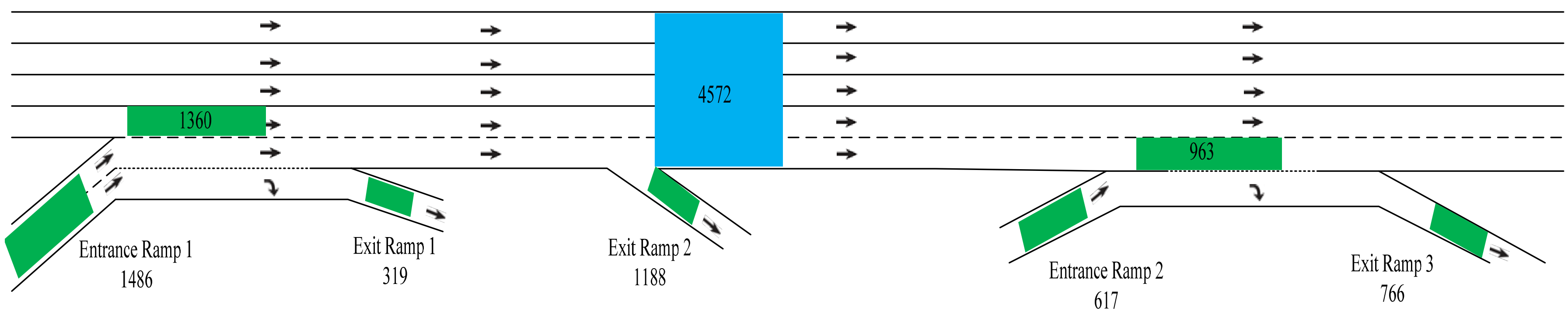
5.1.3.1 Traffic Volumes

Traffic volumes were observed during the observational periods and averaged for both the morning and afternoon peak periods, respectively.

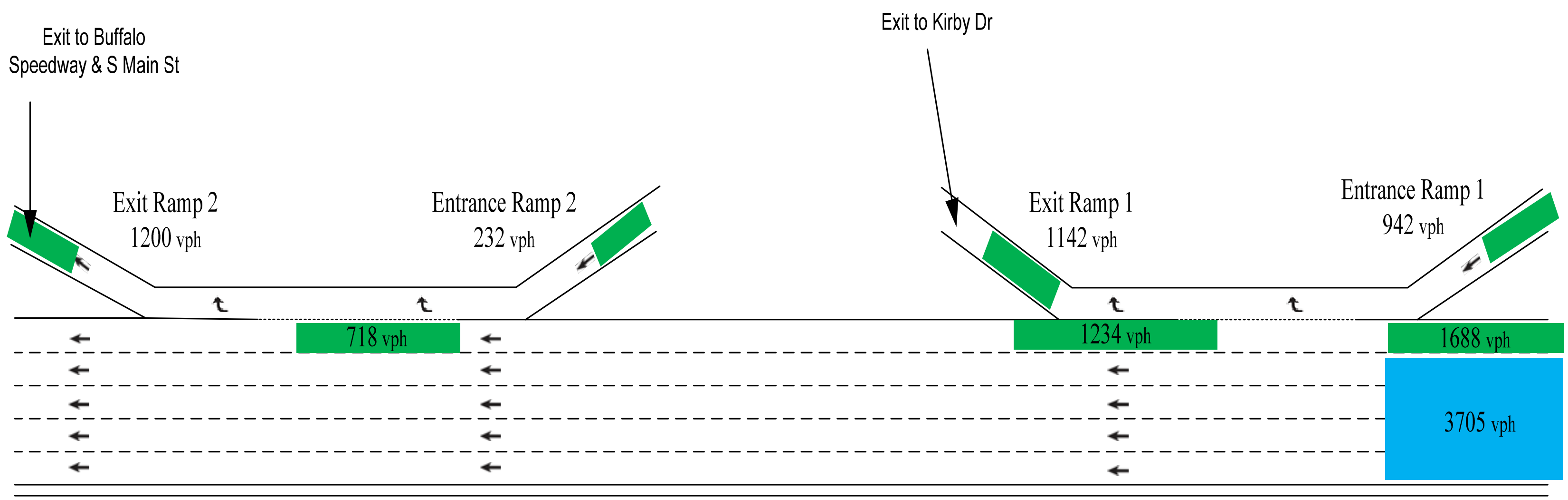
The observed volumes are shown in Figure 5-4. Note that ramp volumes were lane specific, and lane-based volumes were also collected for the auxiliary lanes and one mainline lane adjacent to the auxiliary lanes. The total volumes for other inside mainline lanes were also collected.



(a) Location 1: US 59 and W. Airport



(b) Location 2: I-610 and Stella Link



(c) Location 3: I-610 and Kirby

Figure 5-4. Traffic Volumes Observed (in vph).

5.1.3.2 Travel Times

Travel times were collected using a floating-car method based on the recorded videos. The data were then used to calibrate the simulation models, as described in the following section. Vehicles were randomly selected and time stamped when they passed the reference lines. Then, the travel time of each sampled vehicle between the reference lines was acquired.

Location 1—US 59 and W Airport in Houston: the researchers set up two reference points (A and B) and measured the travel time between them. The selection of reference lines depended on availability of good quality surveillance videos.

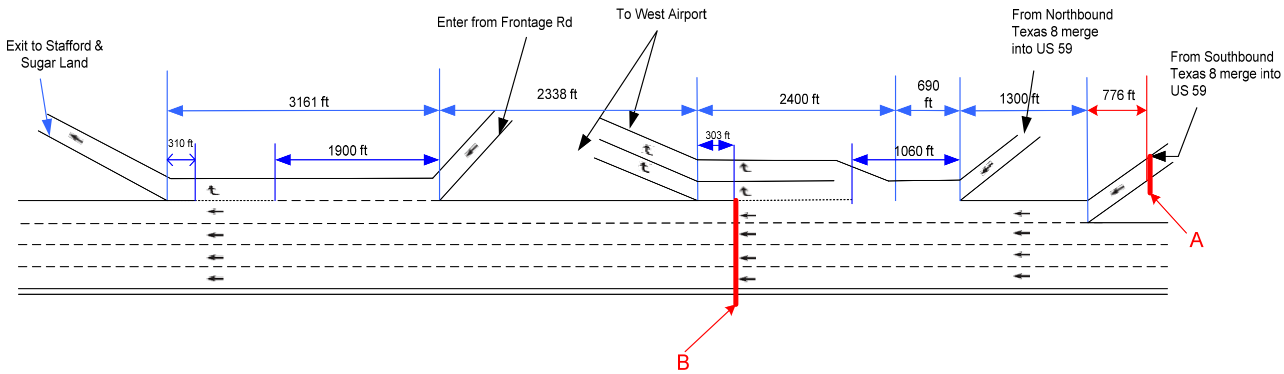


Figure 5-5. Reference Lines for Measuring Travel Times at Location 1: US 59 and W. Airport Blvd.

The collected travel times between the reference lines are presented in Table 5-2.

Table 5-2. Average Travel Times Observed at Location 1 (in Seconds).

	Morning Peak	Afternoon Peak
Average Travel Time	52.4	91.6
Sample Size	16	16
Standard Deviation	6.5	25.4

Location 2—I-610 and Stella Link: the researchers set up three reference lines of A, B, and C and measured the travel time between them.

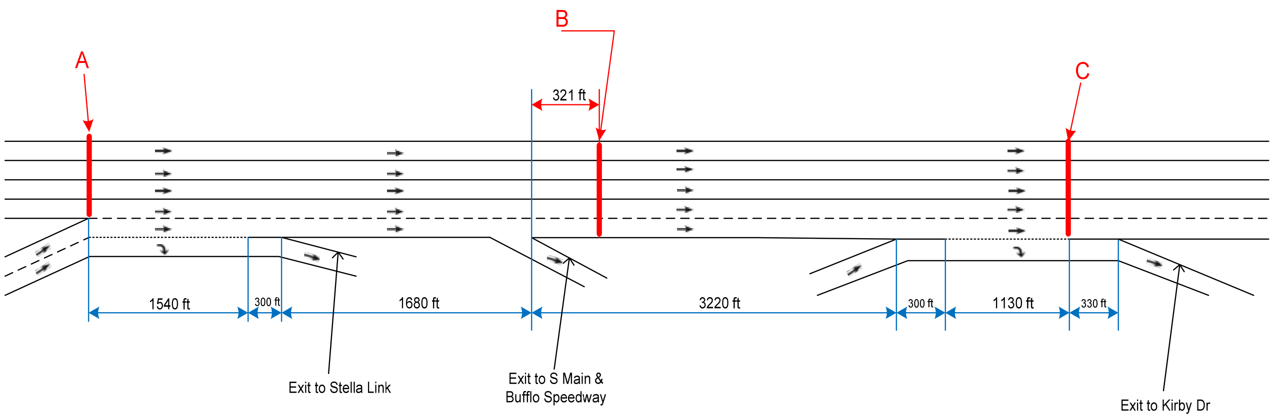


Figure 5-6. Reference Lines for Measuring Travel Times at Location 2: I-610 and Stella Link.

The collected travel times between the reference lines are presented in Table 5-3.

Table 5-3. Average Travel Times Observed at Location 2 (in Seconds).

	A to B		B to C	
	Morning Peak	Afternoon Peak	Morning Peak	Afternoon Peak
Average Travel Time	49.2	50.3	50.4	239.0
Sample Size	30	30	30	29
Standard Deviation	3.4	5.2	6.7	185.9

Location 3—I-610 and Kirby: the researchers used two reference lines, A and B, and measured the travel times between them. The collected travel times are presented in Table 5-4.

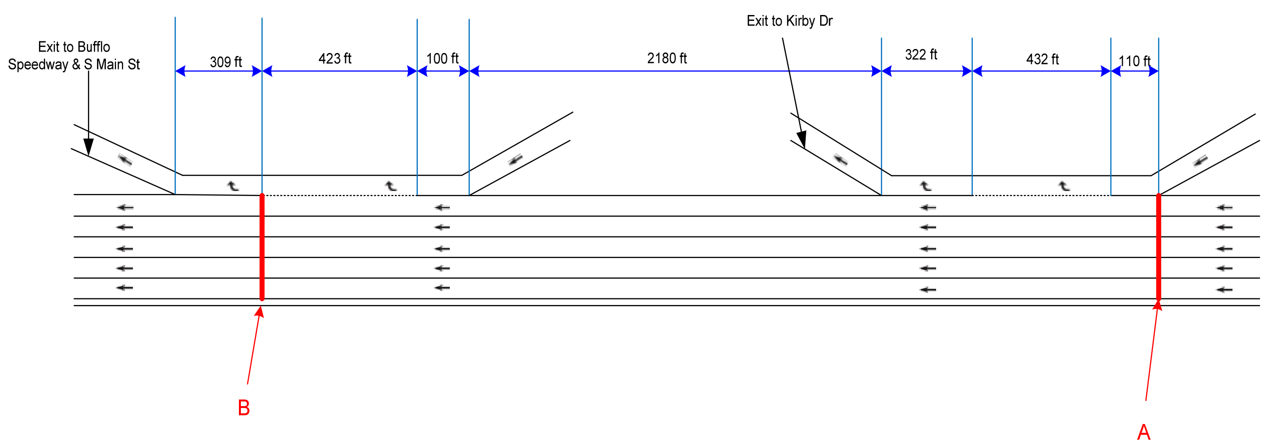


Figure 5-7. Reference Lines for Measuring Travel Times at Location 3: I-610 and Kirby.

Table 5-4. Average Travel Times Observed at Location 3 (in Seconds).

	Morning Peak	Afternoon Peak
Average Travel Time	45.2	48.2
Sample Size	30	30
Standard Deviation	3.5	3.5

5.2 DEVELOPING AND CALIBRATING BASE-CASE MODELS

Calibration is a process of adjusting model parameters so that the simulated response agrees with the measured field conditions. For this study, the objective of model calibration was to obtain the best possible matches between model estimated performance measurements and the observed measurements at the study locations. Travel time was selected as the measurement for calibrating the base-case models.

The models were calibrated by comparing simulated travel times against field observations. The results of the calibration are summarized in Table 5-5. The simulated travel times highly match with the observed travel time with errors of less than 10 percent.

Table 5-5. Effectiveness of Calibrated Micro-Simulation Models.

	Travel Time (Second, for morning peak period)			
	Location 1	Location 2		Location 3
Reference Points	Point A-B	Point A-B	Point B-C	Point A-B
VISSIM Simulated	54.9	48.2	53.1	45.3
Observed	52.4	49.2	50.4	45.2
Absolute Error	0.5	-1.0	2.7	0.1
Relative Error	4.9%	2.0%	5.4%	0.4%

In addition, the simulated traffic conditions (in simulation animations) were also visually compared to the recorded traffic videos. As shown in the following figures, they were consistent.

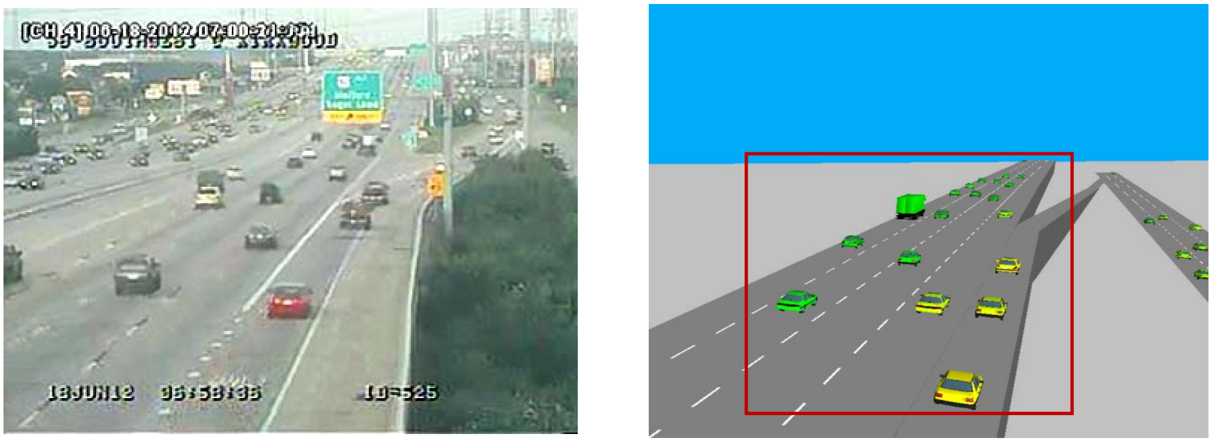


Figure 5-8. Exit Ramp at Kirkwood Blvd, Southbound (Location 1).

Figure 5-9. Entrance Ramp at Braeswood Blvd, Eastbound (Location 2).

Figure 5-10. Entrance Ramp at Main St, Eastbound (Location 2).

Figure 5-11. Exit Ramp at Kirby St, Westbound (Location 3).

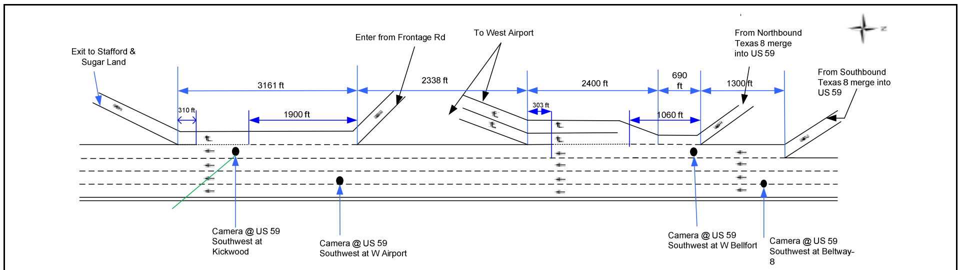
Overall, the calibrated models were in good agreement with the observed data sets.

5.3 IDENTIFYING IMPACTS AND SCOPE OF AUXILIARY LANES

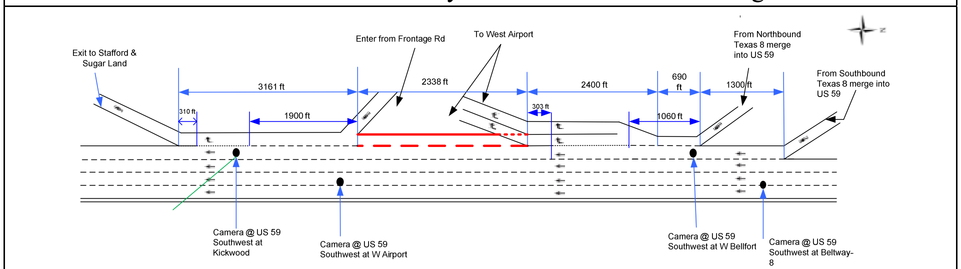
Based on the calibrated base cases, comparative scenarios were also designed and simulated to understand the operational impacts of auxiliary lanes at a corridor level through VISSIM simulation. The traffic patterns were assumed to be the same as the base cases among all the comparative scenarios. Each scenario covered 60 minutes of simulation after a warm-up period of 60 minutes of simulation, and the simulation was conducted with 10 different random number seeds. The experimental results are presented below.

5.3.1 Location 1—Experimental Scenarios, Results, and Discussion

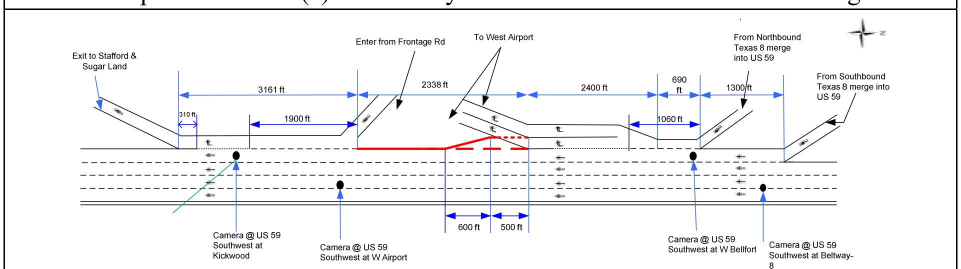
For Location 1, three comparative scenarios were hypothesized and simulated along with the base case (Figure 5-12).



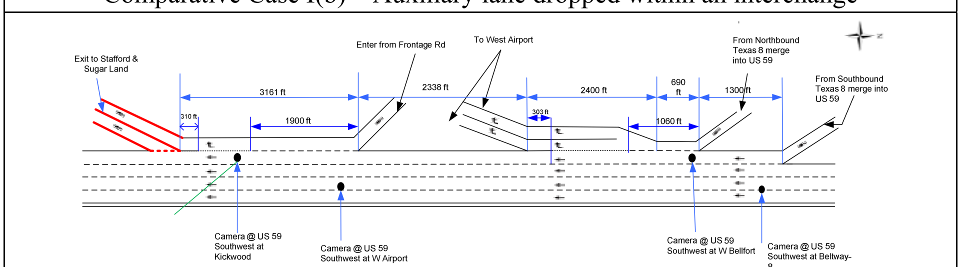
Base Case I—No auxiliary lane between the interchanges



Comparative Case I(a)—Auxiliary lane continued to the next interchange



Comparative Case I(b)—Auxiliary lane dropped within an interchange



Comparative Case I(c)—Double-lane exit for exit ramp to Stafford

Figure 5-12. Base Case and Comparative Cases (Location 1).

Three focus areas were defined to study the impacts of changes in auxiliary lane settings on the corridor, as shown in Figure 5-13. The operational performances of the same areas were analyzed for both the base and comparative cases.

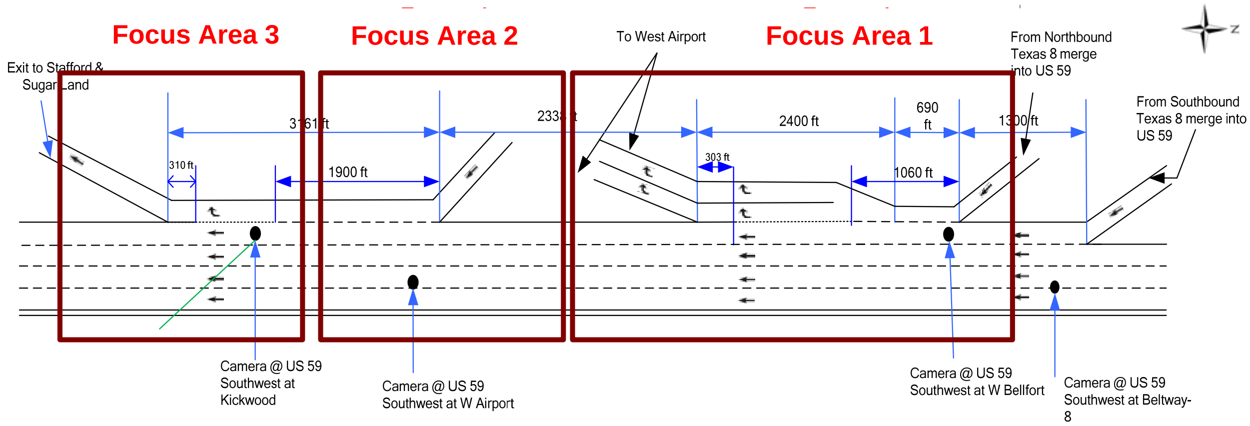


Figure 5-13. Focus Areas Analyzed at Location 1.

5.3.1.1 Focus Area 1 (Major Weaving Segment)

Based on color-coded maps outputted from VISSIM, the number of lanes with speeds lower than 45 or 50 miles was collected from the simulation results, which represented how many lanes were affected due to the presence of the interchanges. The impacts of various designs of auxiliary lanes were investigated by comparing the longitudinal lengths and cross-sectional width of the influence area due to the presence of the interchanges.

Overall, the geometric changes of auxiliary lanes had no significant impacts on Focus Area 1, as shown in Table 5-6.

Table 5-6. Comparison of Effects of Geometric Changes on Location 1—Focus Area 1.

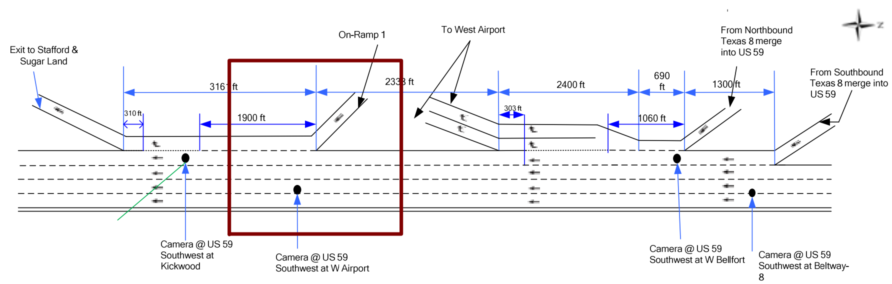
Case	No. of lanes with speed < 45 mph conditions (cross-sectional)	Length of influence area due to interchange (longitudinal, speed < 45 mph)		No. of lanes with speed < 50 mph conditions (cross-sectional)	Length of influence area due to interchange (longitudinal, speed < 50 mph)	
		Relative length	Actual length		Relative length	Actual length
Base I	2-3	Base	640 ft	2-3	Base	1075 ft
I(a)	2-3	+0 ft	640 ft	2-3	+0 ft	1075 ft
I(b)	2-3	+0 ft	640 ft	2-3	+0 ft	1075 ft
I(c)	2-3	+0 ft	640 ft	2-3	+0 ft	1075 ft

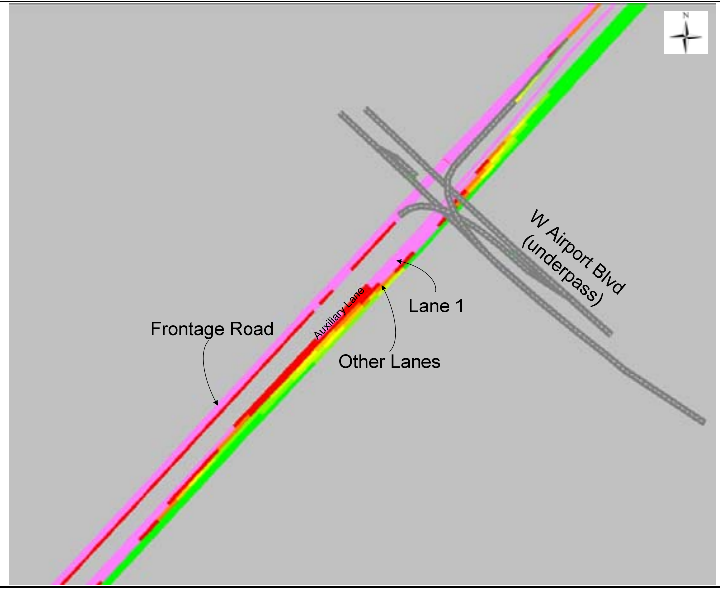
5.3.1.2 Focus Area 2 (Downstream of the Major Weaving Segment)

Table 5-7 shows the effects of the geometric changes on Focus Area 2 at Location 1. The simulated average speed is depicted on the maps, with warm colors (e.g., red and pink) representing low speeds and cold colors (e.g., green) representing higher speeds.

Overall, Case I(b) represented the best case in terms of traffic operations, while the auxiliary lane extension in Case I(a) also provided operational benefits. In Case I(c), simply providing a double-lane exit did not exhibit significant impacts on the traffic operations in Focus Area 2.

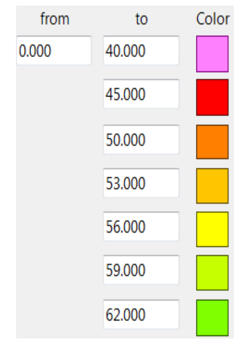
Table 5-7. Base Case and Comparative Cases (Location 1—Focus Area 2).

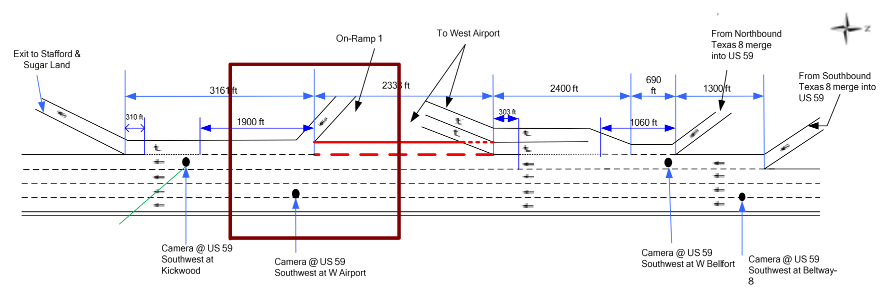


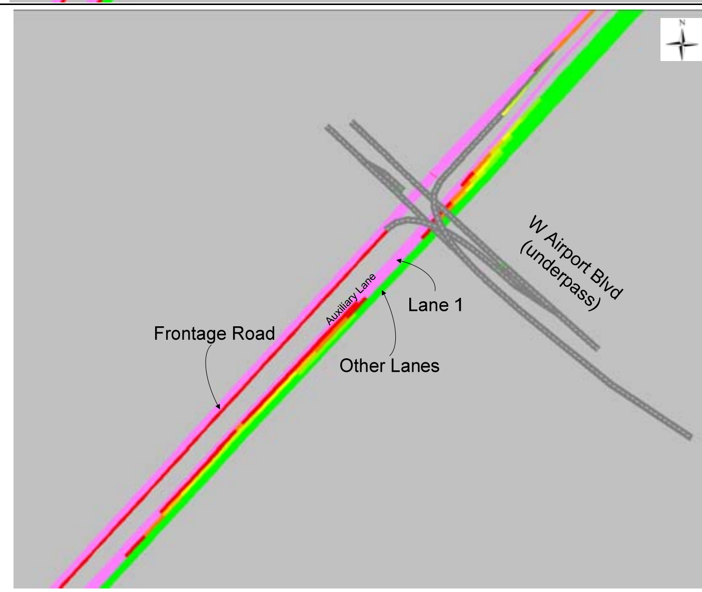


Base Case—No auxiliary lane between the interchanges

Legend
Speed (mph)

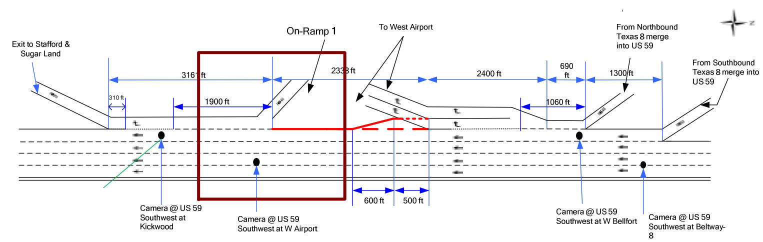




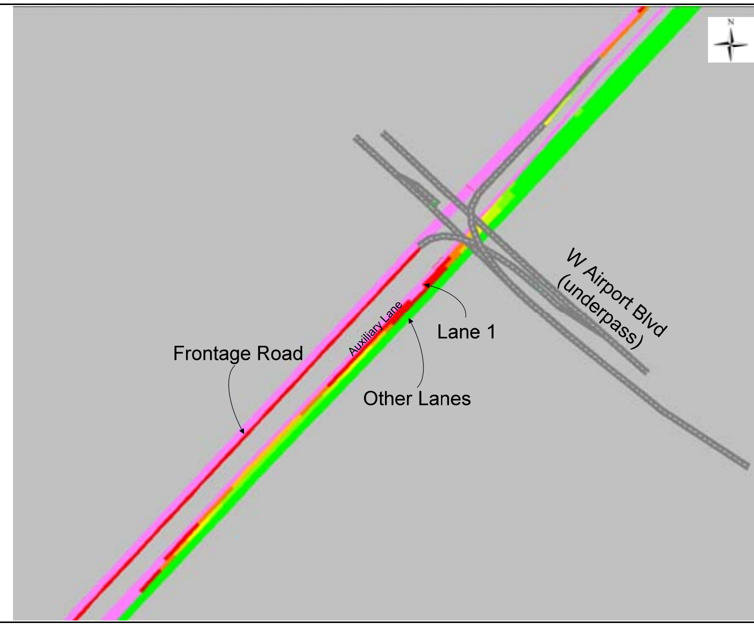


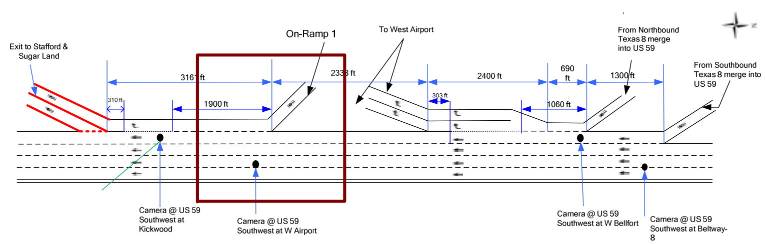
Comparative Case I(a)—Auxiliary lane continued to the next interchange

Table 5-7. Base Case and Comparative Cases (Location 1—Focus Area 2) (Continued).

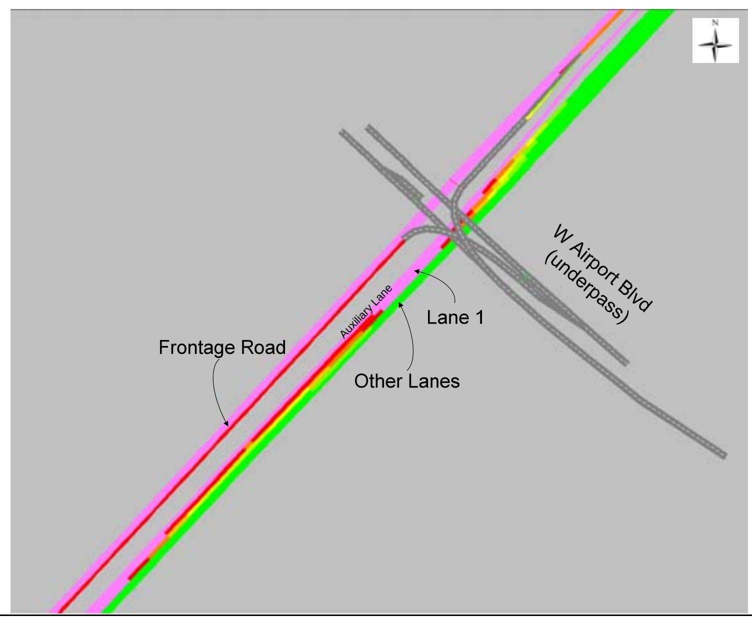


Comparative Case I(b)—Auxiliary lane dropped within an interchange





Comparative Case I(c)—Double-lane exit for exit ramp to Stafford



Legend
Speed (mph)

from	to	Color
0.000	40.000	pink
	45.000	red
	50.000	orange
	53.000	amber
	56.000	yellow
	59.000	yellow-green
	62.000	green

For Focus Area 2 at Location 1, based on color-coded maps outputted from VISSIM, Table 5-8 presents the impacts of the geometric changes in auxiliary lanes in terms of the longitudinal lengths and cross-sectional width of the influence area due to the presence of the interchanges.

Table 5-8. Comparison of Effects of Geometric Changes on Location 1—Focus Area 2.

Case	No. of lanes with speed < 45 mph (cross-sectional)	Length of influence area due to interchange (longitudinal, speed < 45 mph)		No. of lanes with speed < 50 mph (cross-sectional)	Length of influence area due to interchange (longitudinal, speed < 50 mph)	
		Relative	Actual		Relative	Actual
Base I	4	Base	1395 ft	4	Base	1620 ft
I(a)	3	+0 ft	1395 ft	3	+0 ft	1620 ft
I(b)	3	-200 ft	1195 ft	3	-300 ft	1320 ft
I(c)	4	+0 ft	1395 ft	4	+0 ft	1620 ft

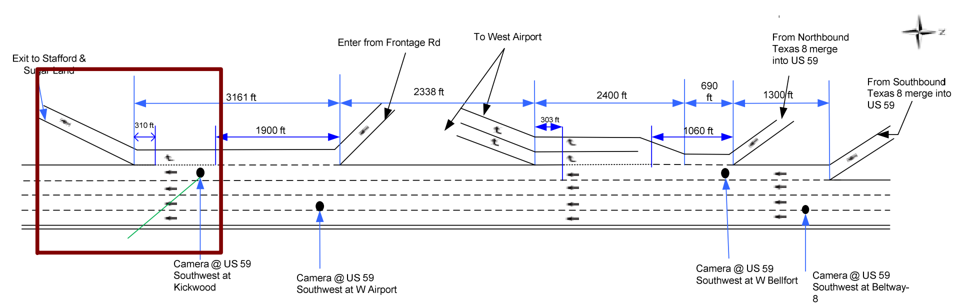
Cross-Sectional: in Base Case I and Case I(c), there were four lanes with speeds less than 45 (or 50) mph; in contrast, Case I(a) and (b), in which the auxiliary lanes were extended, led to one more lane with an improved speed of greater than 45 (or 50) mph.

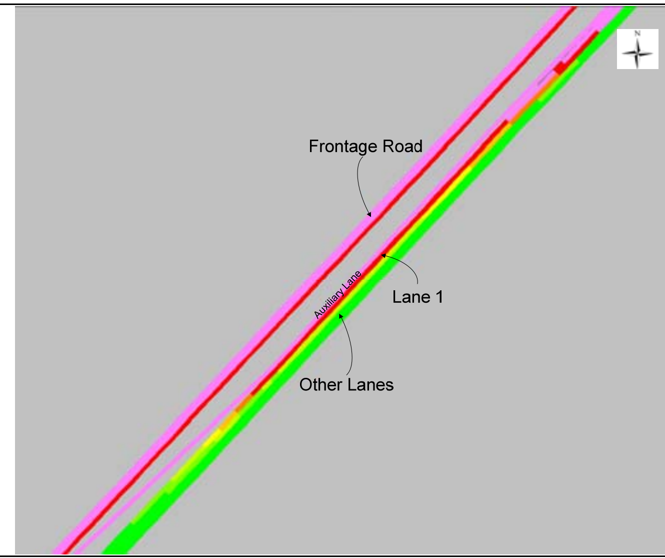
Longitudinally: in Case I(b), the lengths of influence areas due to the interchange at the W. Airport Blvd were reduced compared to the other cases. In this case, the auxiliary lane was extended and dropped before reaching the next entrance-ramp location. The operation of Case I(b) was better than that of Case I(a), where the auxiliary lane was extended to the next entrance-ramp location, because in Case I(a), the continuous auxiliary lane carried more vehicles to the downstream merging point, which caused direct conflicts between the vehicles on the auxiliary lane and the merging vehicles. Note that the merging demand from Entrance Ramp 1 was quite high (i.e., 1642 vph).

5.3.1.3 Focus Area 3 (Downstream)

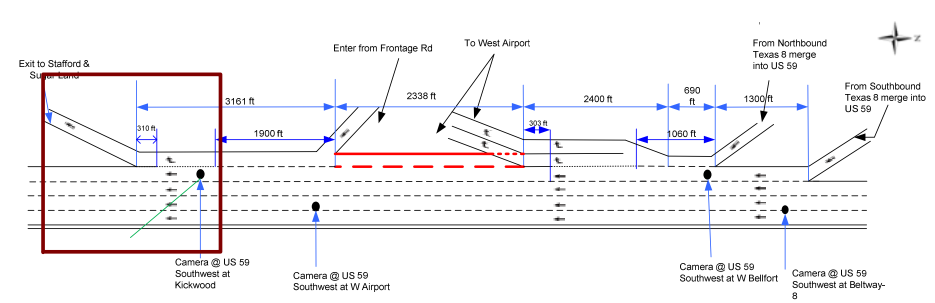
Table 5-9 shows the operational impacts of the geometric changes in auxiliary lanes for Focus Area 3 at Location 1.

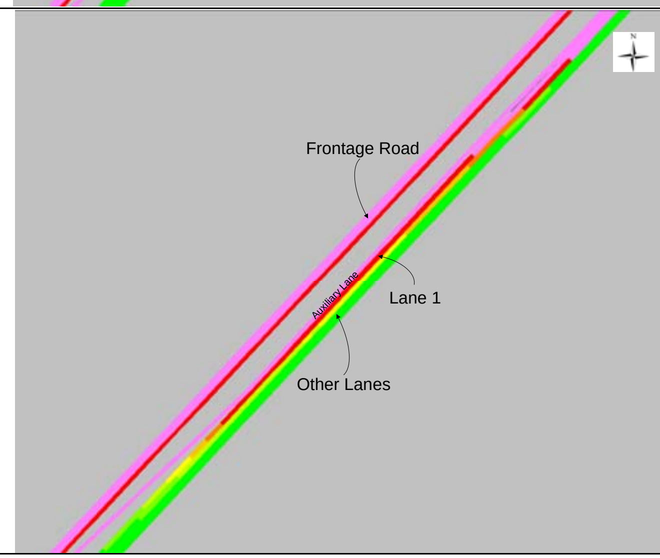
Table 5-9. Base Case and Comparative Cases (Location 1—Focus Area 3).





Base Case—No auxiliary lane between the interchanges

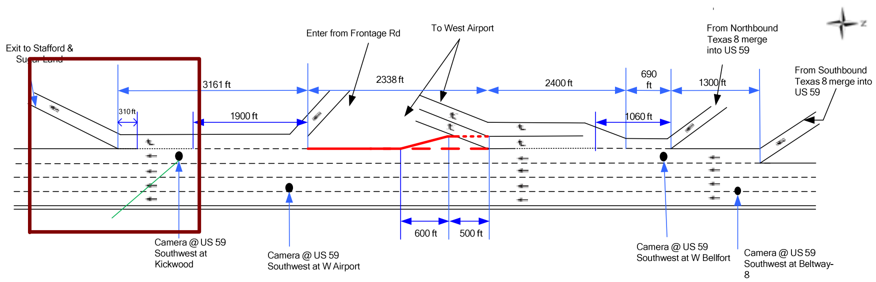


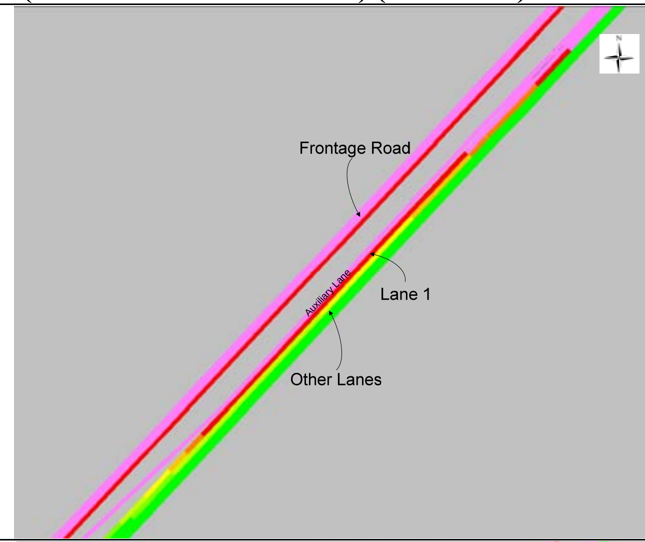


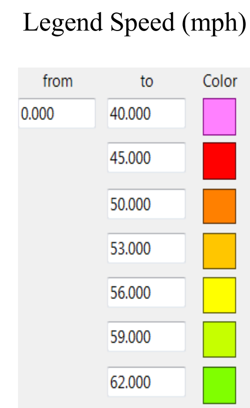
Comparative Case I(a)—Auxiliary lane continued to the next interchange

from	to	Color
0.000	40.000	
	45.000	
	50.000	
	53.000	
	56.000	
	59.000	
	62.000	

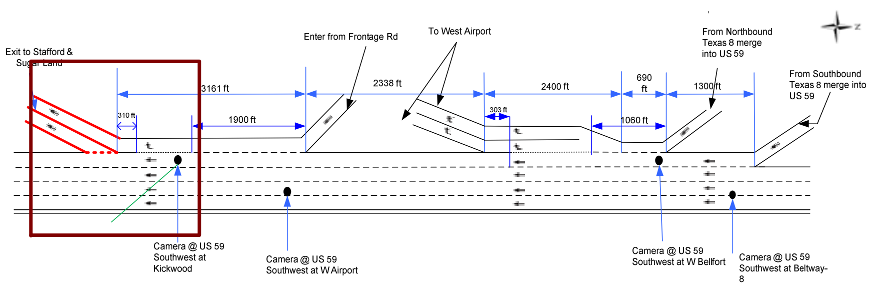
Table 5-9. Base Case and Comparative Cases (Location 1—Focus Area 3) (Continued).

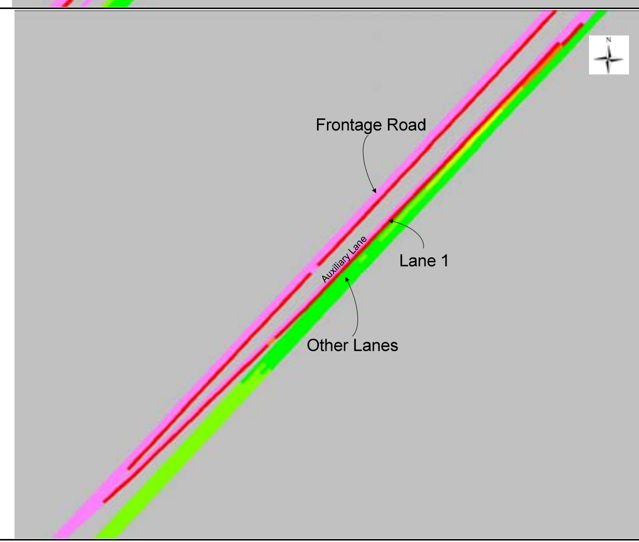






Comparative Case I(b)—Auxiliary lane dropped within an interchange





Comparative Case I(c)—Double-lane exit for exit ramp to Stafford

For Focus Area 3, there were no significant differences between the base case, Case I(a), and Case I(b). In Case I(c), the influence area due to the presence of the interchange at the downstream was shorter than in the other scenarios because the double-lane exit provided an easier and direct exit for the diverging vehicles, one that did not force diverging vehicles to change to the auxiliary lane to be able to exit.

Table 5-10. Comparison of Effects of Geometric Changes on Location 1—Focus Area 3.

Case	No. of lanes with speed < 45 mph conditions (cross-sectional)	Length of influence area due to interchange (longitudinal, speed < 45 mph)		No. of lanes with speed < 50 mph conditions (cross-sectional)	Length of influence area due to interchange (longitudinal, speed < 50 mph)	
		Relative	Actual		Relative	Actual
Base I	3	Base	1460 ft	3	Base	1510 ft
I(a)	3	+0 ft	1460 ft	3	+0 ft	1510 ft
I(b)	3	+0 ft	1460 ft	3	+0 ft	1510 ft
I(c)	2	-40 ft	1420 ft	2	-90 ft	1420 ft

5.3.1.4 Overall Corridor Performance (Location 1)

For Location 1, the overall corridor average speeds for different scenarios were also compared, as shown in Table 5-11. The results showed that Case I(b)—auxiliary lane dropped within an interchange—had the best performance.

Table 5-11. Comparison of Corridor Average Speed at Location 1.

Case	Corridor average speed, mph
Base I	43.9
I(a)	44.3
I(b)	44.6
I(c)	44.1

5.3.1.5 Implications of Operational Analysis for Location 1

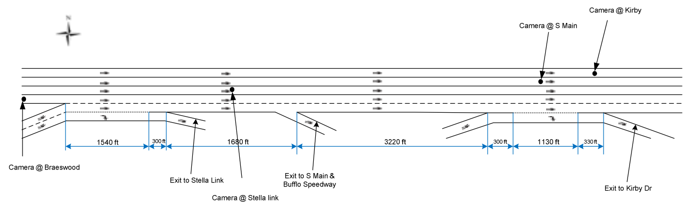
Based on the results analysis for Focus Areas 1 and 2, the following implications can be drawn:

- For Focus Area 2 at Location 1, the competing traffic from Entrance Ramp 1 was as high as 1642 vph; therefore, dropping the auxiliary lane within the interchange at the upstream could be a better option than extending it to the next entrance ramp with heavy traffic volume.
- The double-lane exit provided an easier and direct exit for the diverging vehicles, one that did not force these vehicles to change to the auxiliary lane (the shoulder

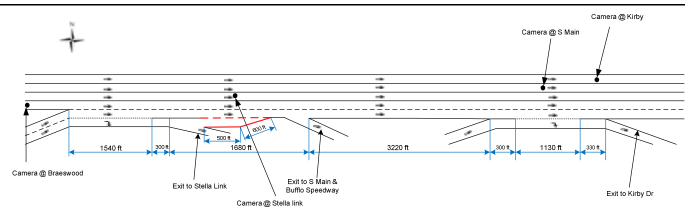
lane). Where operational problems are caused by high exit ramp demand, a double-lane exit may be a solution to reduce the number of lane changes mandated for the diverging vehicles.

5.3.2 Location 2—Experimental Scenarios, Results, and Discussion

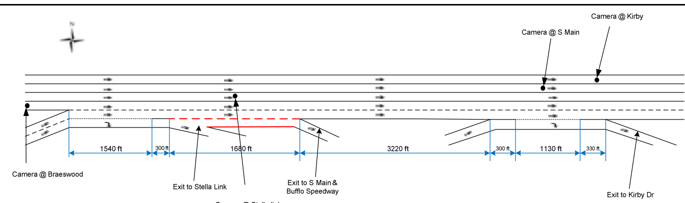
For Location 2, three comparative scenarios were hypothesized and simulated along with the base case.



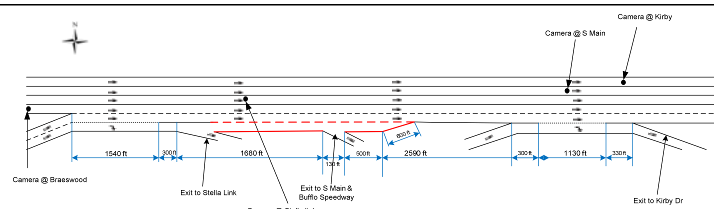
Base Case II—Continuous auxiliary lane along the corridor studied



Comparative Case II(a)—Auxiliary lane dropped within an interchange



Comparative Case II(b)—Auxiliary lane continued to the next interchange



Comparative Case II(c)—Auxiliary lane continued to the next interchange and dropped within the interchange downstream

Figure 5-14. Base Case and Comparative Cases (Location 2).

Two focus areas were defined to study the impacts of changes in auxiliary lane settings on the operation of this corridor, as shown in Figure 5-15. The operational performances of the same areas were analyzed for both the base and comparative cases.

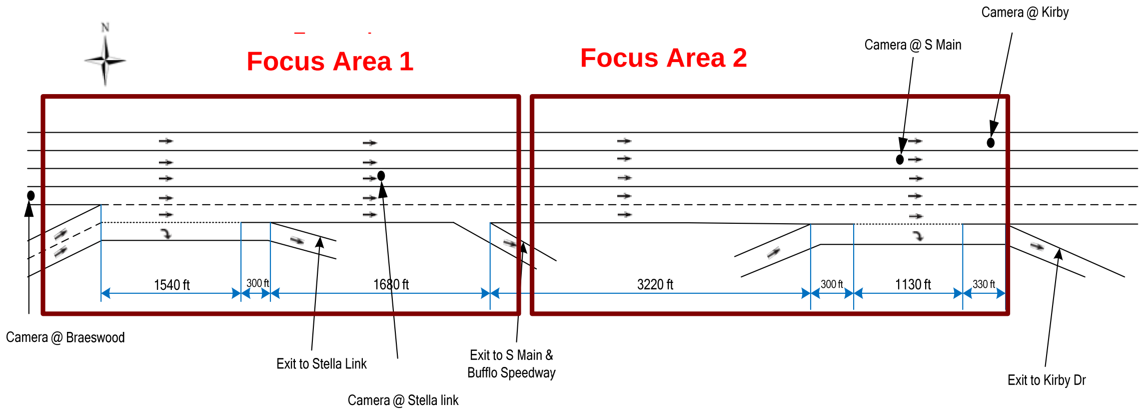


Figure 5-15. Focus Areas Analyzed at Location 2.

5.3.2.1 Focus Area 1

Table 5-12 shows the effects of the geometric changes on Focus Area 1, Location 2: I-610 Freeway and Stella Link Rd.

The simulated average speed is depicted on the maps, with warm colors (e.g., red and pink) representing low speeds and cold colors (e.g., green) representing higher operating speeds.

Table 5-12. Base-Case and Comparative Cases (Location 2—Focus Area 1).

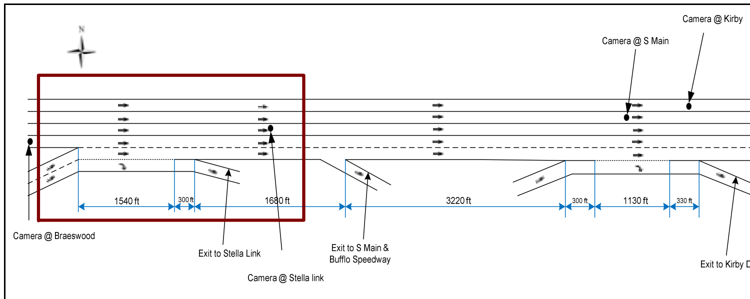
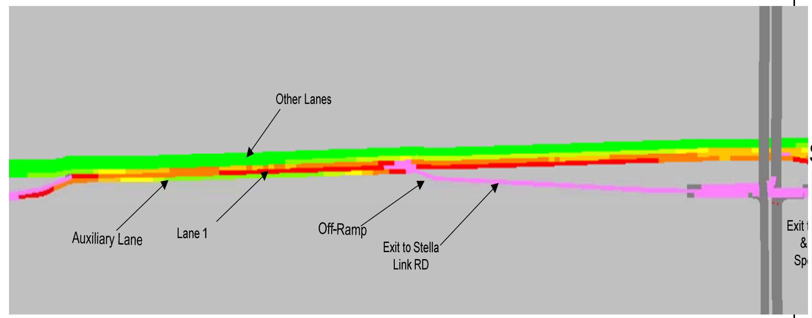
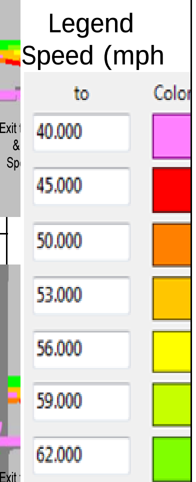
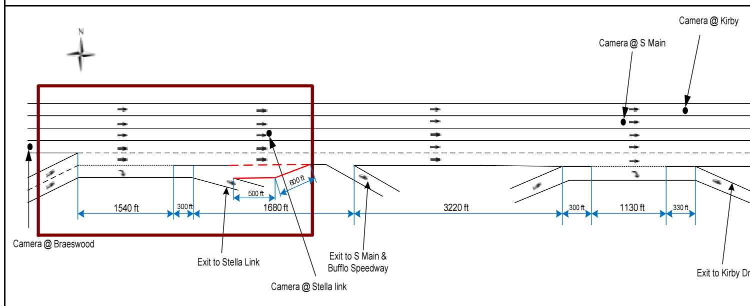
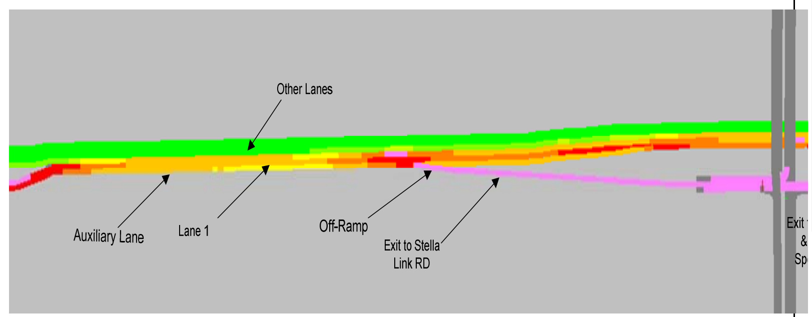
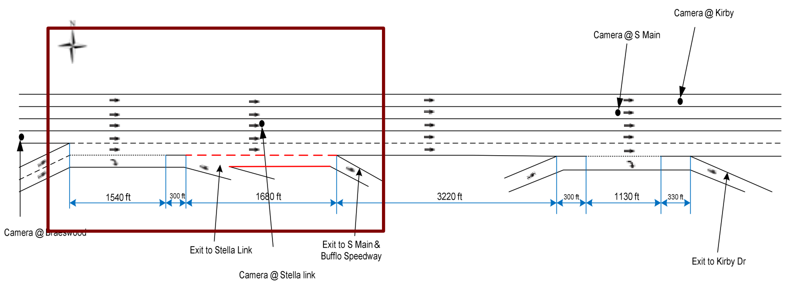
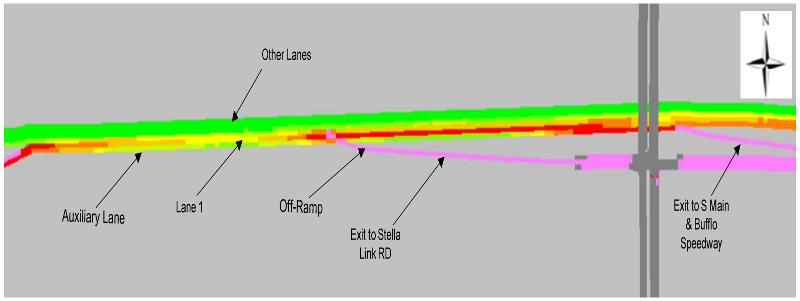
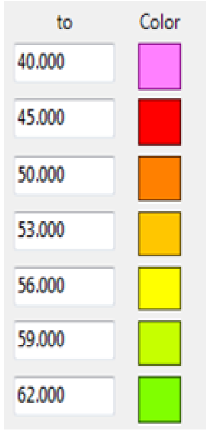
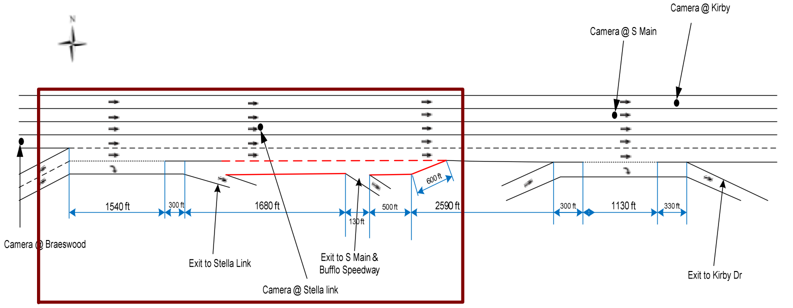
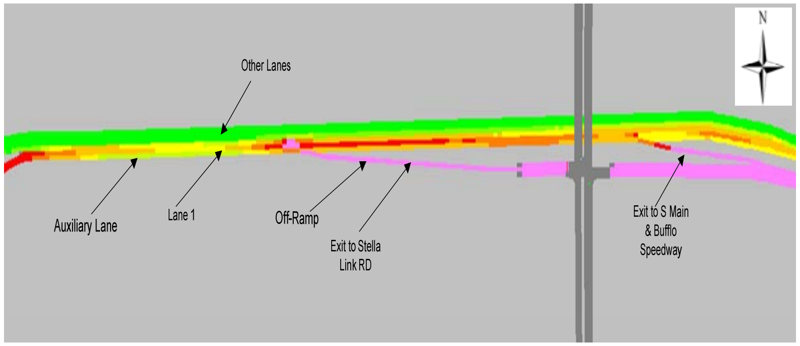
		
Base Case II—Continuous auxiliary lane along the corridor studied		
		
Comparative Case II(a)—Auxiliary lane dropped within an interchange		

Table 5-12. Base-Case and Comparative Cases (Location 2—Focus Area 1) (Continued).

		Legend Speed (mph 
Comparative Case II(b)—Auxiliary lane continued to the next interchange		
		
Comparative Case II(c)—Auxiliary lane continued to the next interchange and dropped within the interchange downstream		

Based on color-coded maps outputted from VISSIM, Table 5-13 lists the impacts of the changes in auxiliary lanes on Focus Area 1 at Location 2.

Case II(c) presented the best operations for the two-lane entrance ramp area compared to the other scenarios. By extending the auxiliary lane to different lengths, the operational performance was improved and the number of lanes impacted by the interchange (lanes with speeds lower than 45 or 50 mph) was reduced.

Table 5-13. Comparison of Effects of Geometric Changes on Location 2.

Case	No. of lanes with speed < 45 mph (cross-sectional)	Length of influence area due to interchange (longitudinal, speed < 45 mph)		No. of lanes with speed lower than 50 mph (cross-sectional)	Length of influence area due to interchange (longitudinal, speed < 50 mph)	
		Relative length	Actual length		Relative length	Actual length
Base Case II	3	Base	1960 ft	3	Base	2955 ft
Case II(a)	2-3	-1010 ft	950 ft	3	-155 ft	2800 ft
Case II(b)	2	-240 ft	1720 ft	2-3	-155 ft	2800 ft
Case II(c)	1-2	-1110 ft	850 ft	2-3	-955 ft	2000 ft

For Case II(c), on the auxiliary lane and Lane 1 (next to the auxiliary lane), the vehicle speeds in the weaving area were considerably increased compared to the base case and Case II(a). For the area between the exit to Stella Link Rd and the exit to S Main/Buffalo Speedway, Case II(c) was slightly better than the base case and Case II(b).

It was noted that in Case II(b), extending the auxiliary lane to the exit ramp (to S Main and Buffalo Speedway) required exiting vehicles to change two lanes to access the exit ramp. In contrast, the base case and Case II(a) required only one lane change, which is why Case II(b) had a longer auxiliary lane than Case II(a) but still yielded operational performance similar to Case II(a). At this location, the exit ramp to S Main and Buffalo Speedway had a relative high volume of 1188 vph. This traffic condition made it less preferable to terminate the auxiliary lane at this exit-ramp location, which would increase the traffic density at the diverge area.

5.3.2.2 Focus Area 2

The simulations showed that overall, the geometric changes among the scenarios had no significant impacts on Focus Area 2 (the areas downstream of the geometric changes).

5.3.2.3 Overall Corridor Performance (Location 2)

For Location 2, the corridor average speeds were simulated and shown as follows. The comparative Case II(c)—auxiliary lane continued to the next interchange and dropped within the interchange downstream—had a slightly better performance than others. While the local congestion at the two-lane entrance ramp could be alleviated by extending the auxiliary lane, the scenarios presented no significant differences in average travel speeds at the corridor level.

Table 5-14. Comparison of Corridor Average Speed at Location 2.

Case	Corridor average speed, mph
Base II	50.0
II(a)	51.0
II(b)	51.0
II(c)	51.1

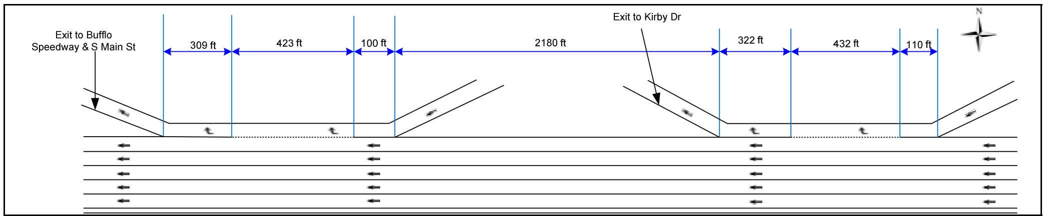
5.3.2.4 Implications of Operational Analysis for Location 2

Based on the analysis results from Location 2, the following findings were obtained:

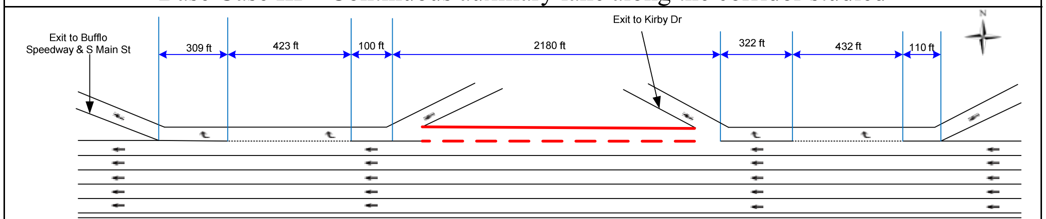
- For a two-lane entrance ramp, the merging traffic demand is normally high; therefore, additional operational benefits can be achieved by extending the auxiliary lane that originated from the two-lane entrance ramp.
- Where a weaving auxiliary lane is followed by an exit ramp, if the exit ramp has a high traffic volume, it can be less operationally favorable to terminate the extended auxiliary lane at the exit ramp location. Instead, further extending it and dropping it within the exit ramp interchange represents a more operationally effective option.

5.3.3 Location 3—Experimental Scenarios, Results, and Discussion

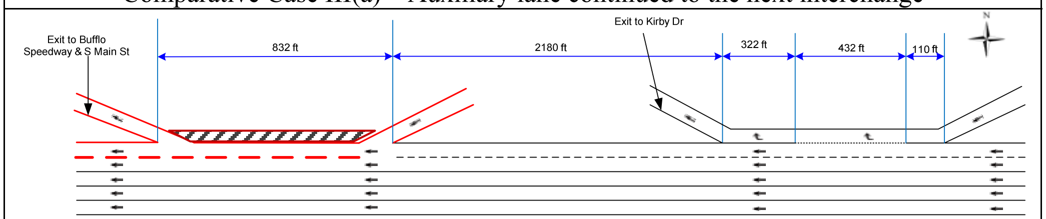
For Location 3, two comparative scenarios were hypothesized and simulated along with the base case.



Base Case III—Continuous auxiliary lane along the corridor studied



Comparative Case III(a)—Auxiliary lane continued to the next interchange



Comparative Case III(b)—Auxiliary lane eliminated at the weaving area downstream

Figure 5-16. Base Case and Comparative Cases (Location 3).

Two focus areas were defined to study the impacts of changes in auxiliary lane settings on this corridor, as shown in Figure 5-17. The operational performances of the same areas were analyzed for both the base and comparative cases.

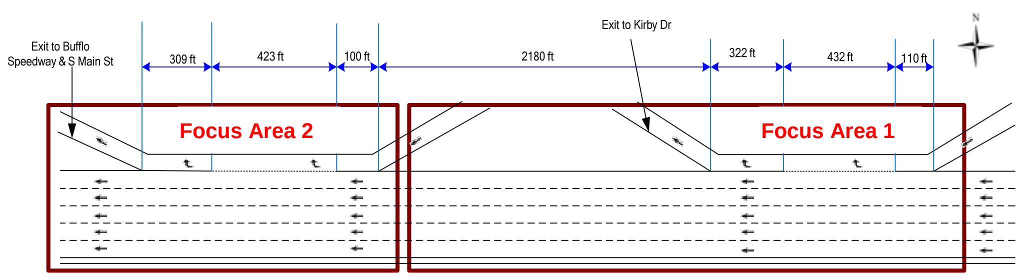
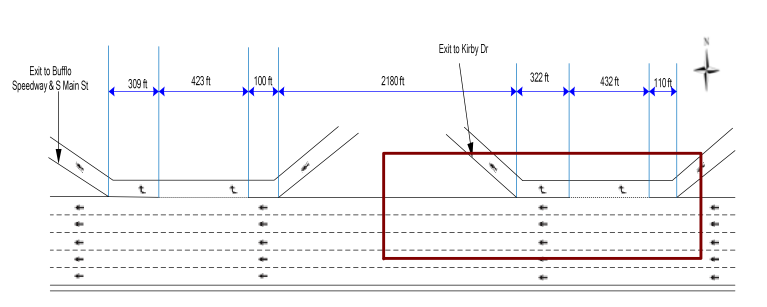


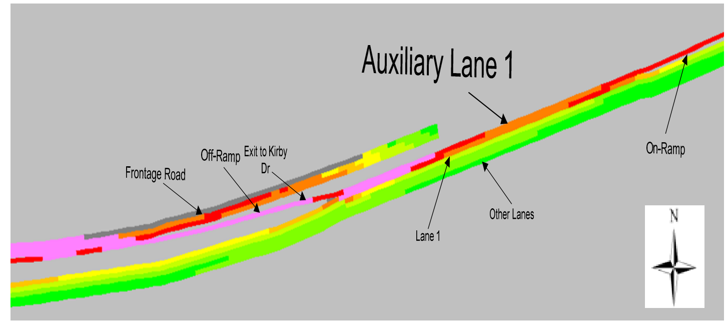
Figure 5-17. Focus Areas Analyzed at Location 3.

5.3.3.1 Focus Area 1 (Upstream Weaving Section)

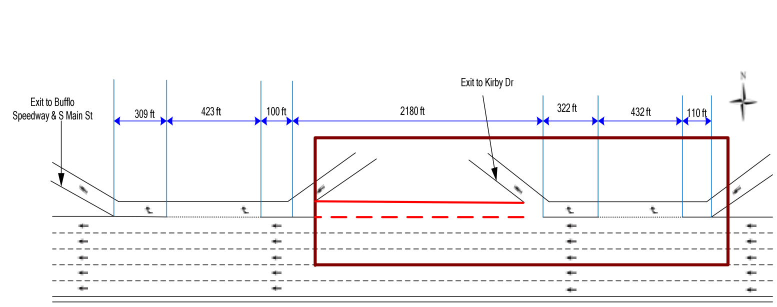
Table 5-15 shows the effects of the geometric changes on Focus Area 1 at Location 3.

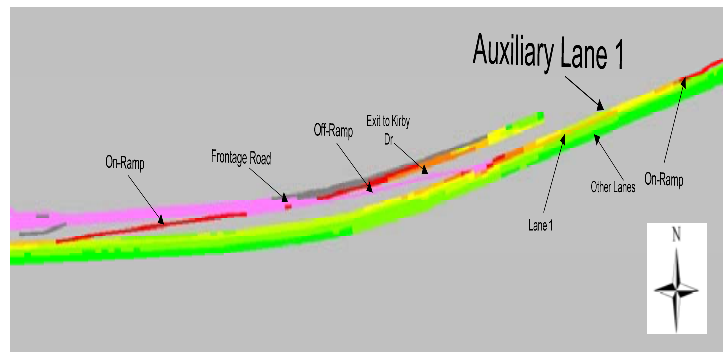
Table 5-15. Base Case and Comparative Cases (Location 3—Focus Area 1).



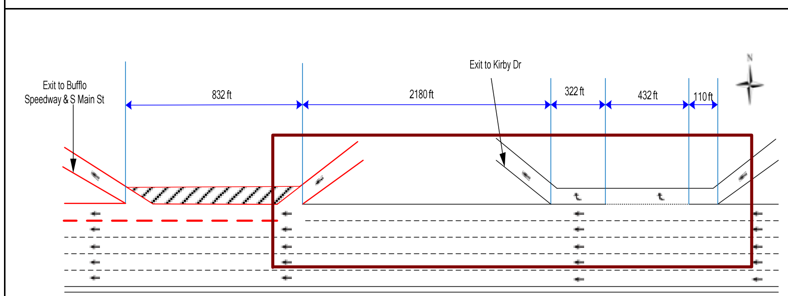


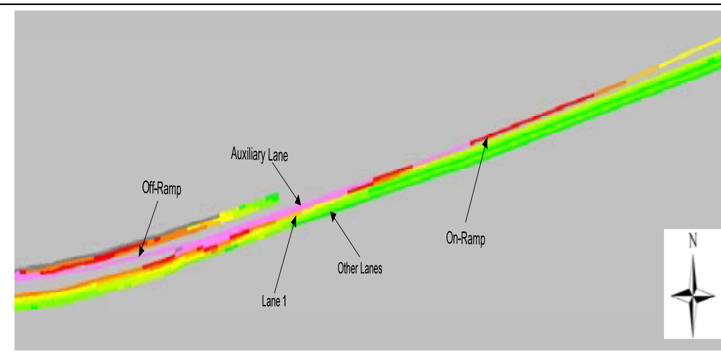
Base Case III





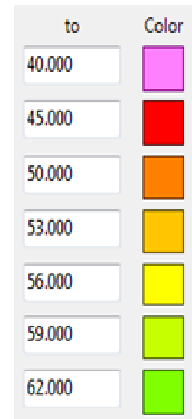
Case III(a)—Auxiliary lane continued to the next interchange





Case III(b)—Auxiliary lane eliminated at the weaving area downstream

Legend
Speed (mph)



Overall, for Focus Area 1, Case III(a) presented the best operations for this exit-ramp area compared to the other scenarios. Case III(a) had the minimum number of lanes with an average speed lower than 45 or 50 mph, as well as the shortest length of influence area due to the interchange.

Table 5-16. Comparison of Effects of Geometric Changes on Location 3—Focus Area 1.

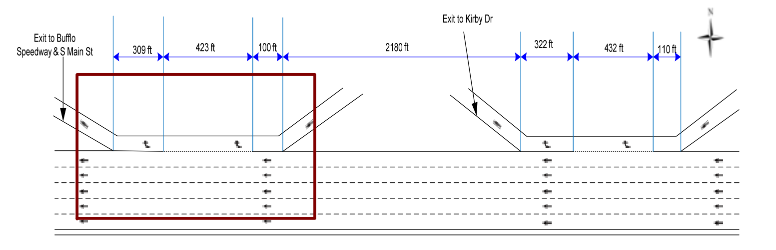
Case	No. of lanes with speed < 45 mph (cross-sectional)	Length of influence area due to interchange (longitudinal, speed < 45 mph)		No. of lanes with speed < 50 mph (cross-sectional)	Length of influence area due to interchange (longitudinal, speed < 50 mph)	
		Relative length	Actual length		Relative length	Actual length
Base III	2	Base	1030 ft	3	Base	1400 ft
III(a)	2	-630	400 ft	2	-800	600 ft
III(b)	4	+720	1750 ft	4	+900	2300 ft

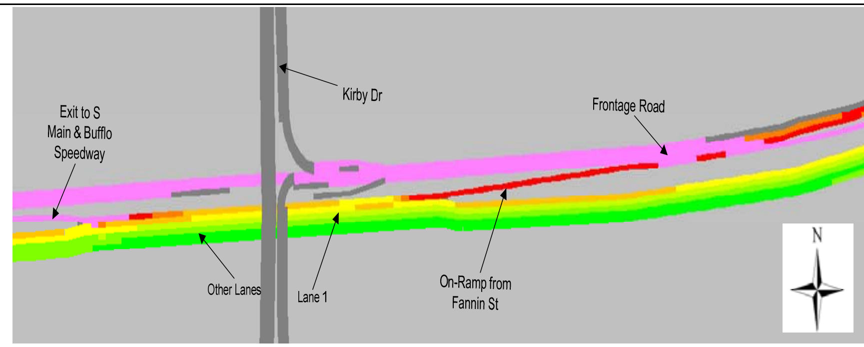
For Case III(a), the auxiliary lane continued to the next entrance-ramp location, which provided more distance for vehicles traveling on the auxiliary lane to merge into mainline traffic. In addition, since the merging traffic volume from the next entrance ramp was relatively low (232 vph in the AM peak and 486 vph in the PM peak), the extension of the auxiliary lane to this location did not cause significant traffic conflicts between the through traffic on the auxiliary lane and the merging traffic from the entrance ramp. Thus, Case III(a) had relative good performance. Compared to the base case, the area of influence was shortened and the traffic operation was considerably improved in Focus Area 1.

5.3.3.2 Focus Area 2 (Downstream Weaving Section)

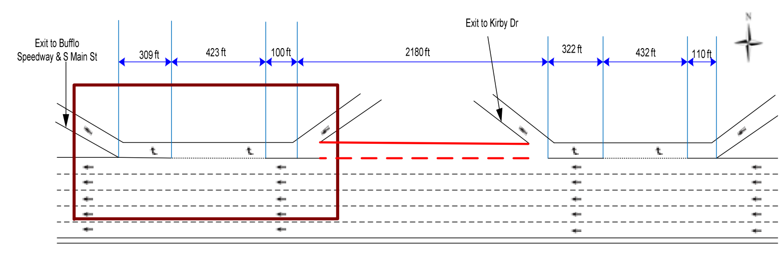
Table 5-17 shows the effects of the geometric changes on Focus Area 2 at Location 3. The simulated average speed is depicted on the maps, with warm colors (e.g., red and pink) representing low speeds and cold colors (e.g., green) representing higher operating speeds.

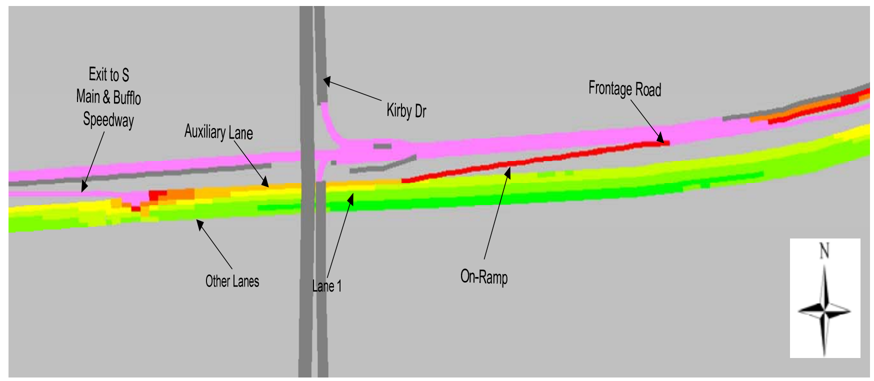
Table 5-17. Base Case and Comparative Cases (Location 3—Focus Area 2).



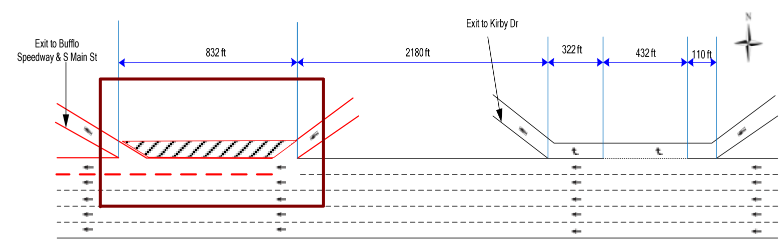


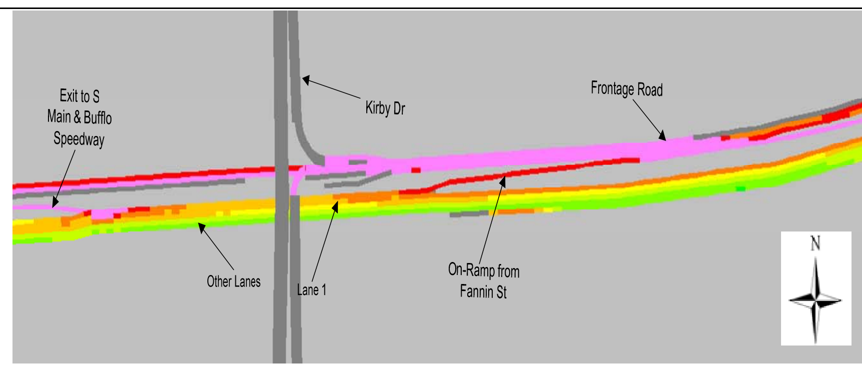
Base Case III





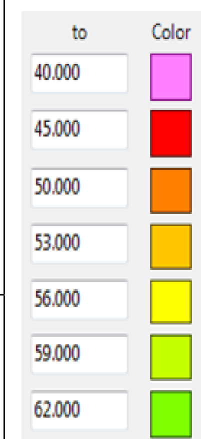
Case III(a)—Auxiliary lane continued to the next interchange





Case III(b)—Auxiliary lane eliminated at the weaving area downstream

Legend
Speed (mph)



For Focus Area 2, Case III(a) presented the best operations for this weaving area compared to the other two scenarios. In Case III(a), an auxiliary lane was added from the upstream interchange to Focus Area 2. This change greatly improved operational performance of upstream traffic. The length of influence due to the interchange was shortened. However, the number of affected lanes (lanes with speeds slower than 45 mph or 50 mph) increased in Case III(a) because more vehicles merging from the previous entrance ramp continually traveled on the auxiliary lane to the next exit-ramp location, where the auxiliary lane was terminated. Therefore, intensive lane changes occurred at this location, and more lanes were affected in a short distance. For Case III(b), the auxiliary lane at Focus Area 2 was eliminated; the performance at the auxiliary lane area was extremely deteriorated compared to the other two cases. Additionally, the impact of speed reduction traced back to the upstream interchange. Thus, the total length of influence area was significantly longer than in the other two cases.

Table 5-18. Comparison of Effects of Geometric Changes on Location 3—Focus Area 2.

Case	No. of lanes with speed < 45 mph (cross-sectional)	Length of influence area due to interchange (longitudinal, speed < 45 mph)		No. of lanes with speed < 50 mph (cross-sectional)	Length of influence area due to interchange (longitudinal, speed < 50 mph)	
		Relative length	Actual length		Relative length	Actual length
Base III	2	Base	460 ft	2	Base	600 ft
III(a)	4	-230 ft	230 ft	3-4	-220 ft	380 ft
III(b)	2	+10 ft	470 ft	3	+2500 ft	3100 ft

5.3.3.3 Overall Corridor Performance (Location 3)

For Location 3, the overall corridor average speeds were also calculated and are shown in Table 5-19. Case III(a)—auxiliary lane continued to the next interchange—had the best performance, a finding that is generally consistent with the analysis of the focus areas.

Table 5-19. Comparison of Corridor Average Speed at Location 3.

Case	Corridor average speed, mph
Base III	55.1
III(a)	57.7
III(b)	54.5

5.3.3.4 Implications of Operational Analysis for Location 3

Collectively, based on the analysis results for Location 3, the following findings were obtained:

- Where a weaving auxiliary lane is followed by an entrance ramp, extending the auxiliary lane in the weaving area to the next entrance ramp can lead to improved operation at the area of the weaving section.
- Providing an auxiliary lane normally increases the average speed and reduces the traffic congestion at the upstream of the auxiliary lane.

5.4 SUMMARY

In the project objective described in this chapter, micro-simulation studies were conducted to identify the level and scope of impacts of auxiliary lanes at the corridor level. To this end, the researchers collected field data at three selected study locations in Houston, Texas. One of the locations was selected from freeway US 59, and the other two were from freeway I-610. Each of the studied corridors has multiple entrance and exit ramps consisting of successive freeway interchanges. Videos were recorded via Houston TranStar and were used to collect traffic volume and travel time data by observing the traffic video on a frame-by-frame basis.

Using VISSIM, the geometric and observed traffic conditions were replicated in the micro-simulation models. The base-case models, which represented the real-world conditions, were well calibrated using travel times as benchmarks. The simulated travel times along the corridor had very low error rates (less than 10 percent). A total of eight comparative scenarios were developed with hypothesized geometric treatments related to the auxiliary lanes, including extending auxiliary lanes, adding auxiliary lanes, and deleting auxiliary lanes. Based on the results of the simulation studies, the following conclusions were reached:

- Where a freeway weaving section with auxiliary lanes is followed by an entrance ramp, if the traffic volume at the entrance ramp is low to moderate (e.g., Case III[a]), extending the weaving auxiliary lane to the entrance ramp can lead to improved traffic operation at the weaving section. On the other hand, if the traffic volume at the entrance ramp is high (e.g., Case I[a]), extending the auxiliary lane to the entrance ramp may result in increased congestion at the downstream entrance ramp. This is a result of more vehicles traveling on the extended auxiliary lane, which thereafter conflict with the vehicles merging from the entrance ramp. Alternatively, to avoid such impacts, the auxiliary lane can be terminated at a location upstream of the following entrance ramp (e.g., Case I[b]).
- Where a weaving auxiliary lane is followed by an exit ramp, if the traffic volume at this exit ramp is high (e.g., Case II[c]), it can be less operationally favorable to terminate the auxiliary lane at the exit ramp. Instead, further extending it and dropping it at some point beyond the exit ramp represents a more operationally effective option.

- A double-lane exit ramp provides an easier and direct exit for diverging vehicles that usually reduces the number of lane changes required for vehicles to exit the freeway. Thus, where operational problems are caused by high exit-ramp demand, a double-lane exit may be a solution to increase the ramp capacity and reduce the number of lane changes mandated for the diverging vehicles.

CHAPTER 6: SAFETY IMPACTS OF AUXILIARY LANES

The purpose of the objective described in this chapter was to analyze traffic safety performance, with and without auxiliary lanes, under various traffic and geometric conditions. To achieve this goal, the following tasks were performed:

- The key results from the AASHTO HSM (HSM, 2010) were synthesized and discussed.
- To supplement the existing literature, simulation studies were performed using VISSIM in conjunction with SSAM, developed by FHWA. The output of simulation studies was the frequency of traffic conflicts as a surrogate safety measure. A series of traffic conflict modification factors (TCMFs) was calculated based on the simulation studies. The TCMF factors were provided for estimating the expected changes of traffic conflicts at a location after implementing specific geometric changes associated with auxiliary lanes.
- Historical crash data analysis was conducted for the selected freeway weaving sections with various auxiliary lane settings.

6.1 RESULTS OF THE AASHTO HIGHWAY SAFETY MANUAL

According to the HSM, previous research investigates the safety performances of freeway segments with the presence of auxiliary lanes. These researches focused on major interchanges, e.g., trumpet, one quadrant, diamond, single point urban, partial cloverleaf, full cloverleaf, and so forth.

A crash modification factor (CMF) is used for the safety assessment method presented in the HSM. A CMF is a multiplicative factor used to compute the expected number of crashes at a location after implementing a specific countermeasure. CMFs are normally developed for evaluating and quantifying the effectiveness of certain safety countermeasures.

As to a freeway merge/diverge segment, the following sections discuss the results related to the safety impacts of auxiliary lanes.

6.1.1 Parallel Acceleration Lane at Merge Area

According to the HSM, the length of an auxiliary lane at a merge area has significant effects on the occurrence of crashes. For total crashes:

$$CMF = 1.296 \times e^{(-2.59 \times L)}$$

where L = length of acceleration lane (mi), which is measured from the nose of the gore area to the end of the lane-drop taper. The base condition for the CMFs in the above equation is a 0.1-mile-long (528-ft) acceleration lane, and:

$$CMF = 1.296 \times e^{(-2.59 \times 0.1)} = 1$$

The variability of the CMFs is unknown according to the HSM.

As an example, if an auxiliary lane with a length of 0.12 mile were lengthened to 0.20 mile, the applicable CMF for total crashes could be calculated using the following CMF equation:

$$CMF = \frac{1.296 \times e^{(-2.59 \times 0.20)}}{1.296 \times e^{(-2.59 \times 0.12)}} = 0.81$$

This CMF result indicates that the traffic safety could be improved by lengthening the auxiliary lanes in a merge area. After the treatment, the projected number of crashes would reduce to 81 percent of that before the treatment.

For fatal and injury crashes, the CMF is expressed as:

$$CMF = 1.576 \times e^{(-4.55 \times L)}$$

6.1.2 Parallel Deceleration at Diverge Area

According to the HSM, extending deceleration lane length may potentially affect safety performance (Table 6-1).

Table 6-1. Potential Crash Effects of Extending Deceleration Lanes.

Treatment	Setting	Traffic Volume	Crash Type	CMF	Std. Error
Extend deceleration lane by 100 ft	Unspecific	Unspecific	All	0.93	0.06
Base Condition: Maintain existing deceleration lane that is less than 690 ft in length					

In using this CMF, an example is presented in the HSM regarding extending a 650-ft-long deceleration lane by 100 ft, and 15 crashes/year is the crash frequency before the treatment. The applicable CMF is 0.93. The 95th percentile confidence interval estimation of crashes after the treatment is equal to [0.93 ± (2*0.06)]*15 crashes/year=12.2 to 15.8 crashes/year.

6.1.3 Limitations in Current AASHTO HSM and Research Needs

Other than the above results, many treatments related to auxiliary lanes still have unknown crash effects, such as:

- Parallel versus taper in weaving and merge/diverge areas (with and without auxiliary lanes).
- Additional lanes on the entrance/exit ramps.

In addition, existing crash prediction tools, such as the Interactive Highway Safety Design Model (IHSDM) or Interchange Safety Analysis Tool (ISAT) developed by FHWA, are not sensitive enough to these factors involved in auxiliary lane design.

6.2 SIMULATION STUDIES IN DEVELOPING TRAFFIC CONFLICT MODIFICATION FACTORS

To supplement the existing studies, simulation studies were performed by the researchers using VISSIM in conjunction with SSAM.

6.2.1 Definition of Traffic Conflict Modification Factor

TCMFs were developed in this study. Similar to the CMFs presented in the AASHTO HSM, the TCMFs were provided for estimating the expected changes of traffic conflict frequency at a location after implementing specific geometric treatments associated with an auxiliary lane. The TCMFs were calculated as follows:

$$\text{TCMF} = \frac{\text{Traffic Conflict Frequency after Treatment}}{\text{Traffic Conflict Frequency before Treatment}} \times 100\%$$

A TCMF with a value less than 1.0 means the treatment can potentially reduce the occurrence of traffic conflicts and improve the safety performance, while a TCMF with a value greater than 1.0 means the treatment can potentially increase the occurrence of traffic conflicts and compromise the safety performance.

6.2.2 Method for Estimating Traffic Conflict Frequency

The traditional way of assessing safety impacts is to analyze historical crash data at the study sites. Recognizing the fact that crashes are rare events and subject to randomness inherent in small numbers, the crashes are normally observed over a relatively long period, such as 1-6 years. This process is relatively slow to reveal the need for remediation and is not applicable to conduct safety assessments for roadway designs that have not been built or operational strategies that have not been applied in the field.

An available alternative to assess safety impacts of roadway designs is to use microscopic traffic simulation models to obtain useful safety surrogate measures that can reflect their safety impacts. A typical procedure for applying such methods is the following: First, microscopic traffic simulation scenarios are developed by incorporating designated roadway designs—in this context, the varying auxiliary lane designs. Then, together with operational measures, safety surrogate measures, which can be derived from the results of the microscopic traffic simulation, are computed, extracted, and analyzed to estimate the conflict frequency and the safety risk. In this study, the SSAM developed by FHWA was used for assessing the safety impacts of various design options. By directly processing vehicle trajectory data obtained from the results of microscopic traffic simulation, researchers were able to estimate the traffic conflict frequencies.

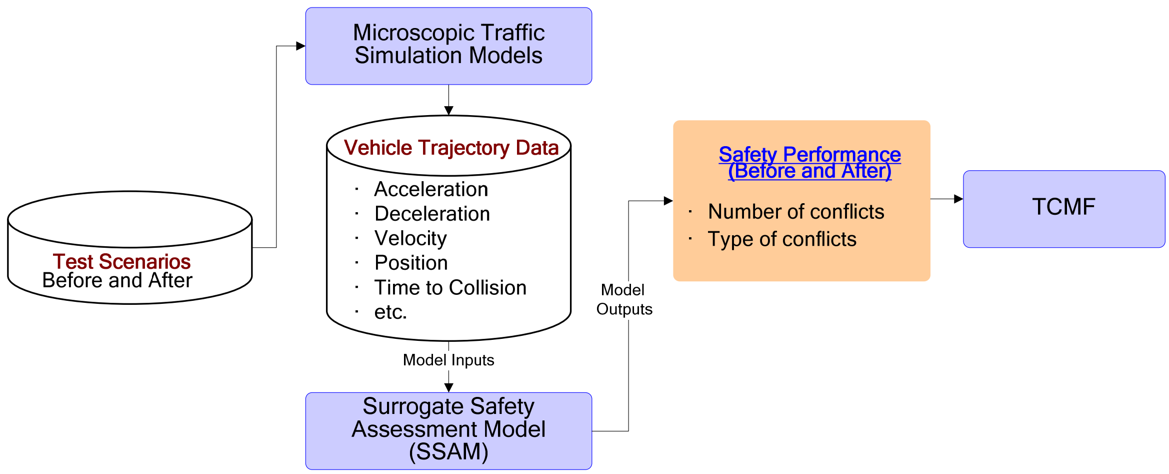


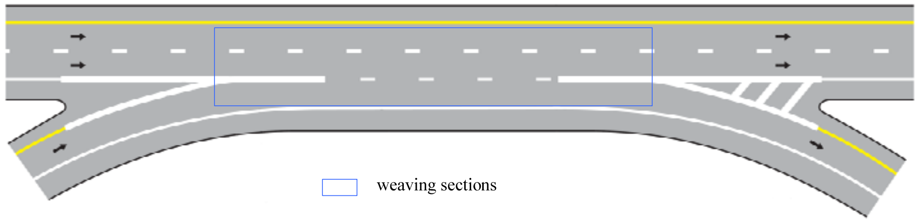
Figure 6-1. Method of Estimating Traffic Conflict Frequency.

6.2.3 Scenario Design and Experimental Results

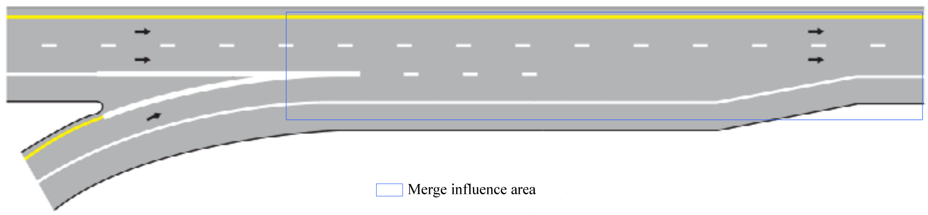
In developing the TCMFs, researchers designed the scenarios in the following groups, which had varying conditions, such as weaving/merge/diverge lengths, weaving volume, and ramp volumes. The scenarios included five groups of experiments:

- Weaving segments with one-lane entrance and one-lane exit, 24 scenarios (12 different geometric and traffic conditions, with and without auxiliary lanes).
- Weaving segments with one-lane entrance and two-lane exit, 24 scenarios (12 different geometric and traffic conditions, with and without auxiliary lanes).
- Weaving segments with two-lane entrance and one-lane exit, 24 scenarios (12 different geometric and traffic conditions, with and without auxiliary lanes).
- Merge segments with a one-lane entrance, 24 scenarios (12 different geometric and traffic conditions, with and without auxiliary lanes).
- Diverge segments with a one-lane exit, 24 scenarios (12 different geometric and traffic conditions, with and without auxiliary lanes).
- Diverge segments with a two-lane exit, 24 scenarios (12 different geometric and traffic conditions, with and without auxiliary lanes).

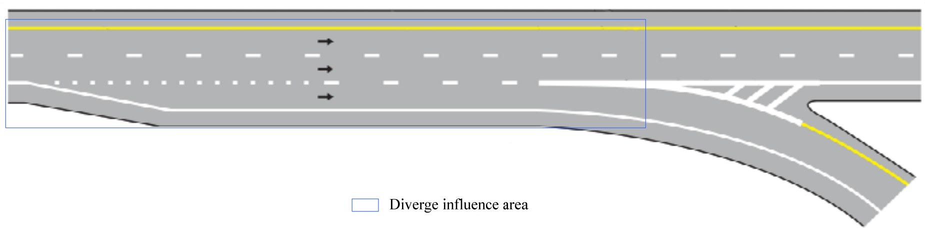
Overall, there were 144 simulation experiments. For each simulation scenario, the simulation period was 120 minutes and the simulation was conducted with 10 different random number seeds. Each run generated one trajectory file, which was input into SSAM for processing. The traffic conflict frequency was calculated as the average of the 10 simulation runs. Figure 6-2 shows the focus areas where the traffic conflicts were collected.



(a) Continuous auxiliary lane at paired entrance and exit ramps (depending on the noses of the gore area)



(b) Auxiliary lane as parallel acceleration lane (with a length of 1500 ft)



(c) Auxiliary lane as parallel deceleration lane (with a length of 1500 ft)

Figure 6-2. Focus Areas Where the Traffic Conflicts Were Collected.

Tables 6-2 to 6-7 show the simulated traffic conflict frequency and the TCMFs calculated for each group of the experiments.

Table 6-2. TCMFs for Weaving Segments (One-Lane Entrance Ramp and One-Lane Exit Ramp).

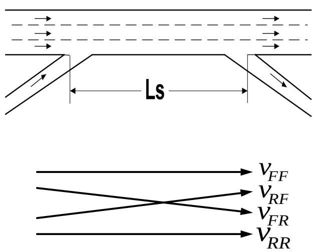
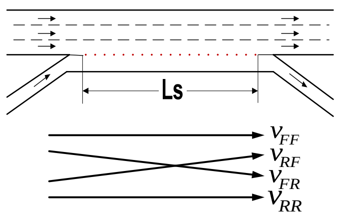
Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Ramp Spacing (ft), L_S	Traffic Volume: Freeway-to-Freeway Volume (pc/h/ln), v_{FF}	Traffic Volume: Weaving Volume (pc/h), $v_{RF}+v_{FR}$	Traffic Volume: Ramp-to-Ramp Volume (pc/h), v_{RR}	Conflict Count Before (conflicts/h/ 500 ft)	Conflict Count After (conflicts/h/ 500 ft)	TCMF
		750	500	500	10	10.00	0.10	0.01
				1500	10	41.37	3.83	0.09
			1500	500	10	27.03	1.10	0.04
				1500	10	152.97	28.23	0.18
		1500	500	500	10	8.88	0.10	0.01
				1500	10	12.02	0.47	0.04
			1500	500	10	20.68	0.10	0.00
				1500	10	77.75	2.60	0.03
		2250	500	500	10	4.28	0.00	0.00
				1500	10	8.58	0.01	0.00
			1500	500	10	11.02	0.51	0.05
				1500	10	15.37	0.59	0.04
							Average	0.04

Table 6-3. TCMFs for Weaving Segments (One-Lane Entrance Ramp and Two-Lane Exit Ramp).

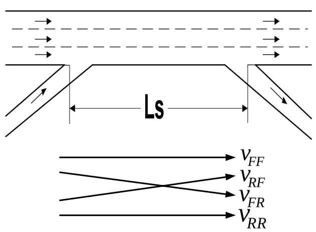
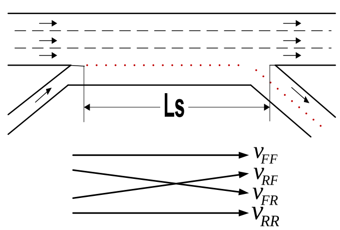
Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Ramp Spacing (ft), L_S	Traffic Volume			Conflict Count Before (conflicts/h/500 ft)	Conflict Count After (conflicts/h/500 ft)	TCMF
			Freeway-to-Freeway volume (pc/h/ln), v_{FF}	Weaving Volume (pc/h), $v_{RF}+v_{FR}$	Ramp-to-Ramp volume (pc/h), v_{RR}			
		750	500	500	10	10.00	0.00	0.00
				1500	10	41.37	0.08	0.00
			1500	500	10	27.03	0.96	0.04
				1500	10	152.97	13.40	0.09
		1500	500	500	10	8.88	0.05	0.01
				1500	10	12.02	0.14	0.01
			1500	500	10	20.68	1.09	0.05
				1500	10	77.75	1.91	0.02
		2500	500	500	10	4.28	0.05	0.01
				1500	10	8.58	0.00	0.00
			1500	500	10	11.02	2.50	0.23
				1500	10	15.37	2.35	0.15
							Average	0.05

Table 6-4. TCMFs for Weaving Segments (Two-Lane Entrance Ramp and One-Lane Exit Ramp).

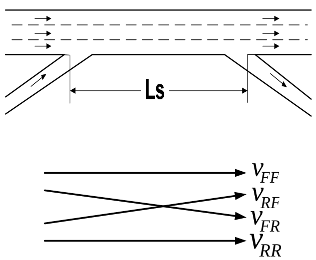
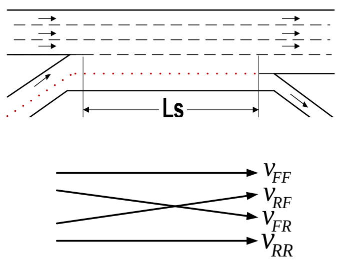
Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Ramp Spacing (ft), L_S	Traffic Volume: Freeway-to-Freeway volume (pc/h/ln), v_{FF}	Traffic Volume: Weaving Volume (pc/h), $v_{RF}+v_{FR}$	Traffic Volume: Ramp-to-Ramp volume (pc/h), v_{RR}	Conflict Count Before (conflicts/h/ 500 ft)	Conflict Count After (conflicts/h/ 500 ft)	TCMF
		750	500	500	10	10.00	0	0.00
				1500	10	41.37	3.05	0.07
			1500	500	10	27.03	0.65	0.02
				1500	10	152.97	22	0.14
		1500	500	500	10	8.88	0.05	0.01
				1500	10	12.02	0.8	0.07
			1500	500	10	20.68	2.6	0.13
				1500	10	77.75	6.7	0.09
		2250	500	500	10	4.28	0.05	0.01
				1500	10	8.58	0.65	0.08
			1500	500	10	11.02	2	0.18
				1500	10	15.37	4.95	0.32
							Average	0.09

Table 6-5. TCMFs for Merge Segments with a One-Lane Entrance Ramp.

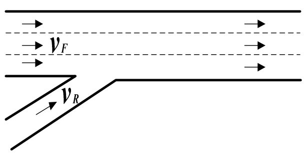
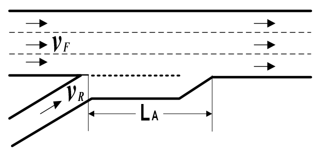
Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Parallel Acceleration Length (ft), L_A	Traffic Volume		Conflict Count Before (conflicts/h/ 500 ft)	Conflict Count After (conflicts/h/ 500 ft)	TCMF
			Freeway Volume (pc/h/ln), v_F	Ramp Volume (pc/h), v_R			
		500	500	250	20.15	0.05	0.00
				750	58.95	0.2	0.00
			1500	250	55.30	3.25	0.06
				750	180.35	31.1	0.17
		1000	500	250	10.20	0.08	0.01
				750	30.90	0.13	0.00
			1500	250	26.53	0.73	0.03
				750	91.78	2.70	0.03
		1500	500	250	4.27	0.02	0.00
				750	13.85	0.03	0.00
			1500	250	15.08	0.37	0.02
				750	45.90	1.03	0.02
						Average	0.03

Table 6-6. TCMFs for Diverge Segments with a One-Lane Exit Ramp.

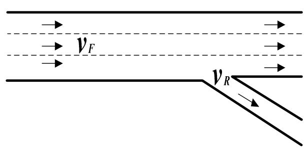
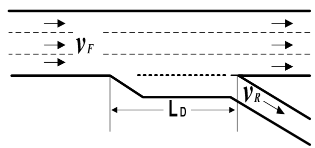
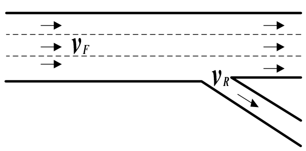
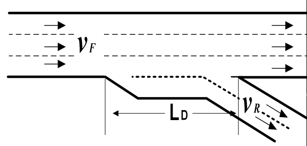
Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Parallel Deceleration Length (ft), L_D	Traffic Volume		Conflict Count Before (conflicts/h/ 500 ft)	Conflict Count After (conflicts/h/ 500 ft)	TCMF
			Freeway Volume (pc/h/ln), v_F	Ramp Volume (pc/h), v_R			
		500	500	250	0.05	0.00	0.00
				750	0.00	0.00	N/A
			1500	250	2.10	1.30	0.62
				750	2.50	1.25	0.50
		1000	500	250	0.03	0.00	0.00
				750	0.00	0.00	N/A
			1500	250	1.05	0.60	0.57
				750	1.25	1.00	0.80
		1500	500	250	0.02	0.00	0.00
				750	0.00	0.00	N/A
			1500	250	0.70	0.37	0.52
				750	0.83	0.65	0.78
						Average	0.42

Table 6-7. TCMFs for Diverge Segments with a Two-Lane Exit Ramp.

Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Parallel Deceleration Lane Length (ft), L_D	Traffic Volume: Freeway Volume (pc/h/ln), v_F	Traffic Volume: Ramp Volume (pc/h/ln), v_R	Conflict Count Before (conflicts/h)	Conflict Count After (conflicts/h)	TCMF
		500	500	250	0.05	0.00	0.00
				750	0.00	0.00	N/A
			1500	250	2.10	0.90	0.43
				750	2.50	0.60	0.24
		1000	500	250	0.03	0.00	0.00
				750	0.00	0.00	N/A
			1500	250	1.05	0.40	0.38
				750	1.25	0.30	0.24
		1500	500	250	0.02	0.00	0.00
				750	0.00	0.00	N/A
			1500	250	0.70	0.28	0.40
				750	0.83	0.35	0.42
						Average	0.23

6.2.4 Summary for Simulation Studies

The developed TCMFs can be used to project the safety performance of a freeway segment when auxiliary-lane-related geometric treatments are made under the given traffic conditions. Overall, installing auxiliary lanes at weaving/merge/diverge areas can significantly reduce the frequency of traffic conflicts as opposed to the cases without auxiliary lanes.

Several key findings are summarized as follows:

- For typical weaving segments:
  - Auxiliary lanes with a one-lane entrance and one-lane exit ramp (Table 6-2) considerably reduced frequency of traffic conflicts, compared to no auxiliary lanes. The reduction of traffic conflicts could be especially significant when high weaving volumes were present (e.g., with a weaving volume of 1500 vph).
  - Installing auxiliary lanes with a one-lane entrance and two-lane exit (Table 6-3) eliminated the majority of traffic conflicts (average TCMF=0.02). Likewise, installing auxiliary lanes with a two-lane entrance and one-lane exit (Table 6-4) eliminated the majority of traffic conflicts (average TCMF=0.03).
- For typical merge areas:
  - Adding a parallel auxiliary/acceleration lane reduced the frequency of the traffic conflicts by more than 80 percent as opposed to a tapered merge area, which was measured within a 1500-ft-long influence area. Longer parallel auxiliary/acceleration lanes led to more considerable safety benefits (Table 6-5).
- For typical diverge areas:
  - Likewise, a parallel auxiliary/deceleration lane reduced the frequency of the traffic conflicts by 3 percent to 100 percent within a 1500-ft-long influence area as opposed to a tapered diverge area (Tables 6-6 and 6-7).

6.3 HISTORICAL CRASH DATA ANALYSIS

To investigate the impacts of auxiliary lanes and ramp arrangements on safety at weaving segments, crash data of 15 weaving segments with various auxiliary lane settings were collected over a four-year period from 2007 to 2011.

6.3.1 Method for Collecting Crash Data

The Crash Record Information System (CRIS) was established in June 2001 in a joint initiative between TxDOT and the Texas Department of Public Safety. The crash history from 2007 to 2011 was utilized in the crash data comparison study. What follows is a description of the data mining process.

6.3.1.1 Step 1: Filter Crash Data at the Selected Study Sites

Each data sample contained longitude and latitude of crash locations, which enabled a spatial distribution analysis. Using ArcMap software, the locations of crashes were displayed on Tiger Line format maps of cities where the candidate study sites were located, as shown in Figure 6-3.

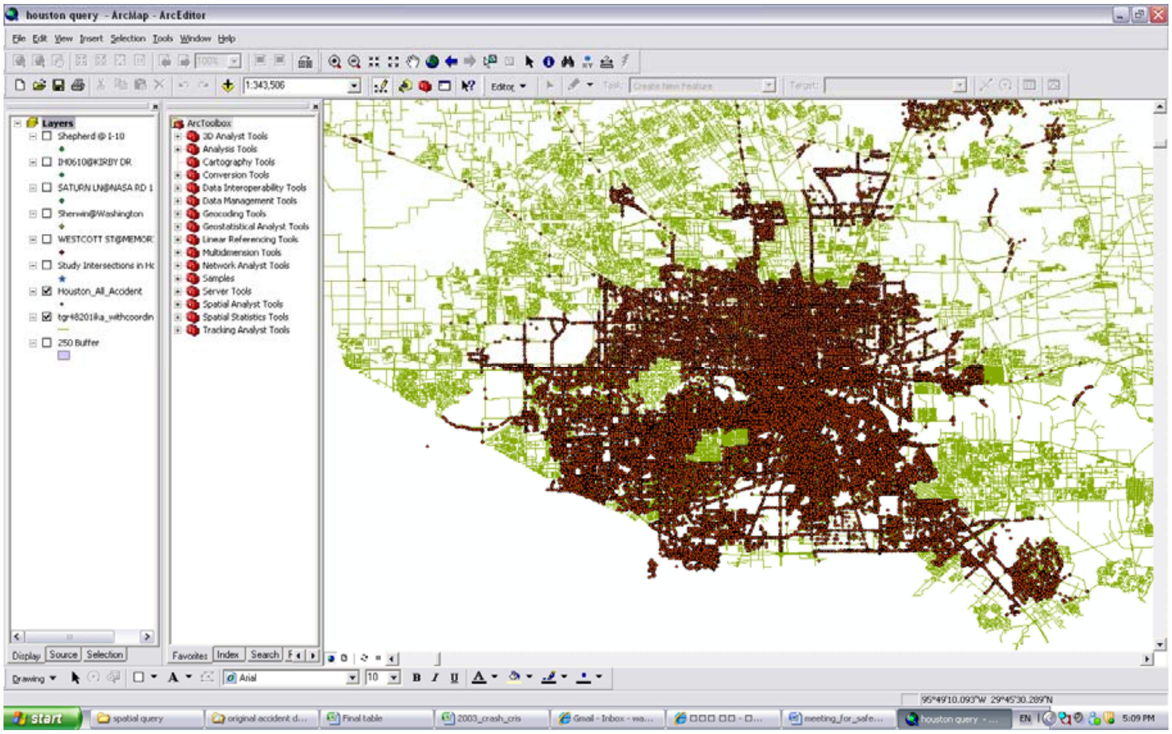


Figure 6-3. Crash Map in Houston as a Sample.

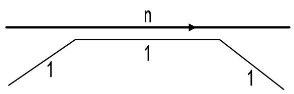
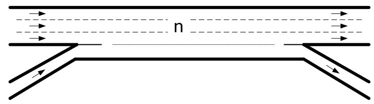
6.3.1.2 Step 2: Identify Crashes Involving Weaving Segments Under Study

Through a geographical information system (GIS) and additional crash information in the CRIS, researchers were able to select the crashes that occurred within the area of the study segments by eliminating the crashes that happened on crossroads and frontage roads.

6.3.2 Results and Discussion

In all, 112 crashes at the study locations during the study period of 2007-2011 were identified. The studied freeway weaving segments were categorized into three types, as shown in Table 6-8.

Table 6-8. Category of Auxiliary Lanes for Crash Experience Analysis.

<table>
<tr><th>Type</th><th>Number of Lanes</th><th>Varying Lane Arrangement</th><th>Number of Locations</th></tr>
<tr><td rowspan="2">A</td><td rowspan="2">
</td><td>
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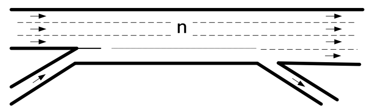
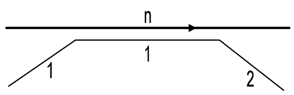
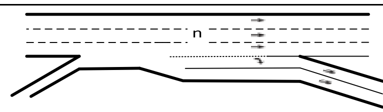
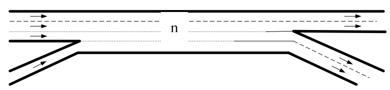
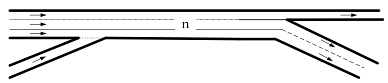
<tr><td>
</td><td>1</td></tr>
<tr><td rowspan="4">B</td><td rowspan="4">
</td><td>
</td><td>1</td></tr>
<tr><td>
</td><td>3</td></tr>
<tr><td>
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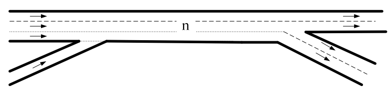
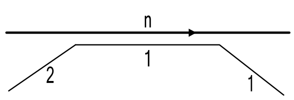
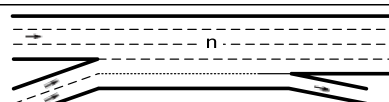
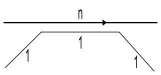
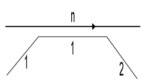
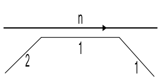
<tr><td>
</td><td>1</td></tr>
<tr><td>C</td><td>
</td><td>
</td><td>4</td></tr>
<tr><td colspan="3">Total</td><td>15</td></tr>
</table>

As shown in Table 6-9, among three typical weaving segments with auxiliary lanes, Type A design (one-lane entrance and one-lane exit) generally presented the best safety performance, followed by Type B design (one-lane entrance and two-lane exit). Type C (two-lane entrance and one-lane exit) was associated with the highest crash frequency among the three types of weaving auxiliary lane settings.

Table 6-9. Crash Rates at Studied Locations.

Type of Lane Arrangement	Studied Freeway	Weaving Segment Exits	Number of Crashes	Crash Frequency (crash/year)	ADT	Length (ft)	Crash Rate[1]	Average Crash Rate
A 	US 59 SB	Tidwell	2	0.4	57,230	2370	4.266	27.58
	US 59 SB	Stafford/Sugar Land	5	1.2	57,725	2851	8.790	
	I-610 EB	Kirby Dr.	1	0.4	56,355	1130	4.543	
	I-610 WB	Kirby Dr.	4	0.8	60,880	432	44.002	
	I-610 WB	Buffalo Speedway	6	1.2	53,800	423	76.278	
B 	US 59 SB	W. Airport	7	1.4	64,865	2787	11.203	29.81
	I-610 WB	S Oak Post Rd	5	1	70,940	1325	15.390	
	I-610 EB	US 288	31	6.2	72,000	2160	57.670	
	I-610 WB	US 288	1	0.2	72,900	808	4.912	
	I-610 SB	I-10	11	2.2	49,940	1315	48.461	
	I-610 WB	I-45 North Dallas	12	2.4	65,550	1285	41.217	
C 	I-610 EB	Stella Link	5	1	64,795	1540	14.497	31.72
	I-610 NB	Wallisville Rd	5	1	53,420	957	28.296	
	US 288 NB	Yellowston Blvd	4	0.8	60,677	2662	7.165	
	US 59 NB	Lyons Ave & Quitman St	13	2.6	24,200	2020	76.939	

Note: [1] The crash rate was measured in crashes per 100 million vehicle miles traveled. The formula for calculating the crash rate for a roadway segment is:

$$R = \frac{A*100{,}000{,}000}{L*ADT*365}$$

where:
A = Average number of crashes along the study segments per year
L = Length of roadway segment in mile
ADT = Average daily traffic volume along the roadway

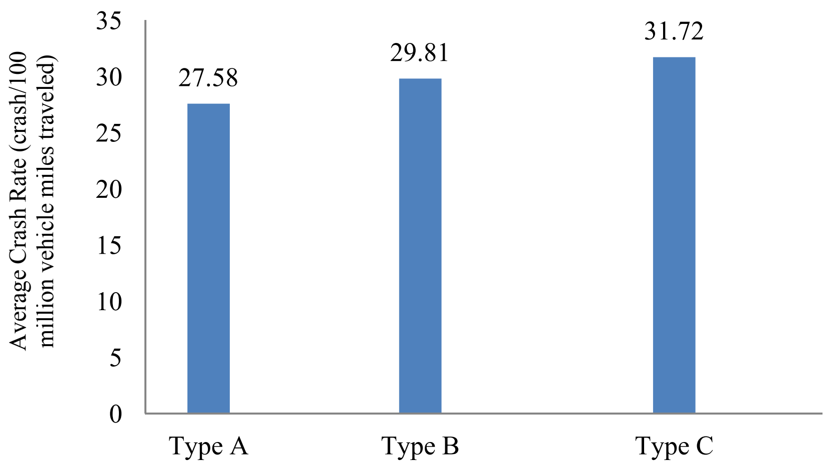


Figure 6-4. Crash Rate of Various Settings of Weaving Segments.

6.4 SUMMARY

In the study objective described in this chapter, traffic safety performance with and without auxiliary lanes was analyzed for various traffic and geometric conditions. The major findings are summarized as follows:

- As to the freeway merge/diverge segments, the HSM provides results for estimating the impacts of parallel acceleration/deceleration lanes on crash rates at freeway merge/diverge segments.
- TCMFs were calculated based on the simulation studies, which showed that considerable safety benefits in terms of mitigating traffic conflicts were achieved by installing auxiliary lanes compared to the case without auxiliary lanes.
- Among three typical weaving segments with auxiliary lanes, Type A design (one-lane entrance and one-lane exit) generally presented the best safety performance, followed by Type B design (one-lane entrance and two-lane exit). Type C (two-lane entrance and one-lane exit) was associated with the highest crash frequency among the three types of weaving auxiliary lane settings.

6.5 REFERENCES

HSM, 2010, *Highway Safety Manual*, First Edition. American Association of State Highway and Transportation Officials. Washington, D.C., 2010.

CHAPTER 7: GUIDELINES FOR DESIGNING AND ASSESSING THE IMPACTS OF FREEWAY AUXILIARY LANES

The purpose of this chapter is to present guidelines for the conditions under which auxiliary lanes should be considered and guidelines for the geometric design of auxiliary lanes. These guidelines were developed based on the results of the literature review, survey of traffic engineers, and traffic simulation and crash data analysis.

7.1 FRAMEWORK OF DEVELOPED GUIDELINES

The proposed guidelines include two parts: (1) general guidelines on the use of auxiliary lanes, and (2) guidelines for design of auxiliary lanes. The recommended guidelines are highlighted in shaded text boxes for easy reference.

7.2 GENERAL GUIDELINES ON THE USE OF AUXILIARY LANES

This part of the guidelines aims to provide general guidelines regarding the conditions under which use of auxiliary lanes is suggested.

<u>Guideline 1—When to Consider the Use of Freeway Auxiliary Lanes:</u>

<u>Auxiliary lane at weaving segments</u>

- If the distance between an entrance ramp and an exit ramp is less than 1500 ft, a continuous auxiliary lane is strongly recommended.
- If an entrance ramp is less than 2400 ft upstream from a two-lane exit ramp, a continuous auxiliary lane between the entrance and the exit should be provided.
- If an exit ramp is less than 2500 ft downstream from a two-lane entrance ramp, a continuous auxiliary lane between the entrance and the exit should be provided.
- If a local frontage road does not exist, a continuous auxiliary lane is strongly recommended.

<u>Auxiliary lane as parallel acceleration/deceleration lane</u>

If interchanges are widely spaced (e.g., greater than 2,500 ft in length), a continuous auxiliary lane between them might not be practical or necessary. In this case, parallel acceleration/deceleration should be considered when:

- Turbulence in the traffic flow that is caused by vehicles attempting to recover and proceed on the through lanes is significant.
- Safety issues arise because of the forced merges at an entrance ramp.
- Traffic volumes on freeway mainline and entrance ramp meet the conditions provided in Table 7-1.

Generally, traffic volumes, speed, grade, and safety/operational issues should be analyzed to determine the need for auxiliary lanes. Engineering studies are desirable on a case-by-case basis in determining the need for an auxiliary lane.

7.2.1 Auxiliary Lane at Weaving Segments

Generally, according to the AASHTO Green Book (2011), operations may be improved by using a continuous auxiliary lane between the entrance and exit ramps where (1) interchanges are closed spaced, (2) the distance between the end of the taper on the entrance terminal taper and the beginning of the taper on the exit terminal taper is short, and/or (3) a local frontage road does not exist. Note that the first two conditions are related to the weaving distance. Several state DOT designs provide more specific guidelines regarding the desired weaving distance for the use of auxiliary lanes as follows.

- According to the TxDOT Roadway Design Manual (2010), the provision regarding auxiliary lanes is a major determinant of the spacing required between an entrance ramp and a following exit ramp. It suggests the minimum spacing shall be 2000 ft (600 m) without an auxiliary lane and 1,500 ft (450 m) with an auxiliary lane. Therefore, an auxiliary lane is desirable for a spacing of 1,500 ft.

- Arizona DOT Roadway Design Guidelines (2007) suggest that within metropolitan areas and all other urban/suburban areas throughout the state, mainline auxiliary lanes should be provided on controlled-access highways between ramp entrances and exits of nominally one mile (5,280 ft).
- According to the California DOT Highway Design Manual (2001), auxiliary lanes should be provided in all cases when the weaving distance is less than 2000 ft (600 m).
- The Illinois DOT Bureau of Design and Environment Manual (2010), Ohio DOT Location and Design Manual (2011), and Minnesota DOT Roadway Design Manual (2001) suggest an auxiliary lane should be provided where the distance between the taper end of the entrance terminal and beginning taper of the exit taper is less than 1500 ft.
- According to the Montana DOT Road Design Manual (2007), an auxiliary lane should be provided where the distance between the end of the entrance terminal and the beginning of an exit terminal is less than 1600 ft.

Based on the literature, it is strongly recommended that if the distance between a one-lane entrance ramp and a one-lane exit ramp is less than 1500 ft, an auxiliary lane be used.

In addition, according to the TxDOT Roadway Design Manual (2010), if an entrance ramp is less than 2400 ft upstream from a two-lane exit ramp, an auxiliary lane should be continuous between the entrance and the exit. If an exit ramp is less than 2500 ft downstream from a two-lane entrance ramp, an auxiliary lane should be continuous between the entrance and the exit.

Moreover, according to the design manuals of some state DOTs, several other factors, including traffic volume, grade, speed, etc., should be analyzed to determine the need for auxiliary lanes. The Illinois DOT Bureau of Design and Environment Manual (2010), Indiana DOT Design Manual (2011), and Montana DOT Road Design Manual (2007) recommend traffic volumes be analyzed to determine the need for auxiliary lanes. The California DOT Highway Design Manual (2001) requires analyzing grade when considering auxiliary lanes.

Furthermore, in the nationwide survey performed in this project, other factors that should be involved in the decision on use of auxiliary lanes were identified. They included traffic density, safety or operational issues, percentage of trucks, and LOS.

7.2.2 Auxiliary Lane as Parallel Acceleration/Deceleration Lane

When interchanges are widely spaced (e.g., greater than 2,500 ft in length), it might not be practical or necessary to extend the auxiliary lane from one interchange to the next. Under such circumstances, parallel acceleration/deceleration lanes are needed if turbulence is significant in the traffic flow due to vehicles attempting to recover and proceed on the through lanes (AASHTO Green Book, 2011).

In addition, the AASHTO Highway Safety Manual (2010) indicated that the installation of parallel acceleration lanes at an entrance ramp could improve safety performance. Therefore, a parallel acceleration lane is preferable when there are traffic safety issues because of forced merges that already exist at an entrance ramp. Furthermore, newly published literature (Wang et al., 2013) defined traffic volume conditions for adding an auxiliary lane (parallel acceleration lane) with a minimum required length at an entrance ramp, as shown in Table 7-1. In this table, the row index v_F is the traffic volume on freeway mainline (pc/h/ln) and the column index v_R is the traffic volume on the entrance ramp (pc/h/ln). The cells correspondent to these two indexes indicate, under the given traffic volume conditions, whether an auxiliary lane (a parallel acceleration lane) is needed and how long it should be. A cell with the actual number indicates that an auxiliary lane is needed, and the value of this number is the minimum required length of this auxiliary lane (parallel acceleration lane) at this ramp.

Table 7-1. Traffic Volume Conditions for Adding an Auxiliary Lane with Minimum Required Length.

Minimum L_A (ft) for $N_F = 2$ lanes										
v_F (pc/h/ln)	v_R (pc/h/ln)									
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
500	-	-	-	-	-	-	-	-	-	-
750	-	-	-	-	-	-	-	-	-	-
1000	-	-	-	-	-	-	-	-	-	100
1250	-	-	-	-	200	300	400	500	600	700
1500	300	400	500	700	800	900	1000	1100	1200	1400
1750	900	1000	1200	1300	1400	1500	-	-	-	-
2000	-	-	-	-	-	-	-	-	-	-
Minimum L_A (ft) for $N_F = 3$ lanes										
v_F (pc/h/ln)	v_R (pc/h/ln)									
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
500	-	-	-	-	-	-	-	-	-	-
750	-	-	-	-	-	-	-	-	-	-
1000	-	-	-	-	-	-	-	-	-	-
1250	-	-	-	-	-	-	-	100	200	400
1500	-	-	-	200	300	500	600	700	900	1000
1750	400	600	700	800	1000	1100	1300	1400	-	-
2000	1100	1300	1400	1500	-	-	-	-	-	-
Minimum L_A (ft) for $N_F = 4$ lanes										
v_F (pc/h/ln)	v_R (pc/h/ln)									
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
500	-	-	-	-	-	-	-	-	-	-
750	-	-	-	-	-	-	-	-	-	-
1000	-	-	-	-	-	-	-	-	-	-
1250	-	-	-	-	-	-	-	-	-	100
1500	-	-	-	-	-	100	300	400	500	600
1750	100	200	300	400	500	600	800	900	1000	1100
2000	600	700	800	900	1000	1100	1300	1400	1500	-

Note: N_F: Number of lanes on freeway (mainline); L_A: length of auxiliary lane; v_F: volume on freeway (mainline); v_R: volume on on-ramp.

Generally, these guidelines are a useful rule of thumb to trigger the consideration of an auxiliary lane. For a specific application, engineering studies are desirable on a case-by-case basis in making the final decision on the use of auxiliary lanes.

Guideline 2—Assessment of Operational and Safety Benefits of Adding an Auxiliary Lane:

Look-up tables, as presented in Table 7-2 to Table 7-7, can be used to preliminarily analyze the operational and safety impacts of adding an auxiliary lane.

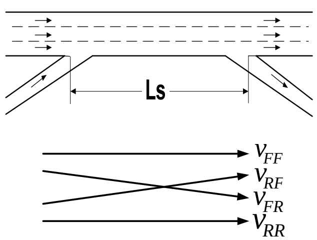
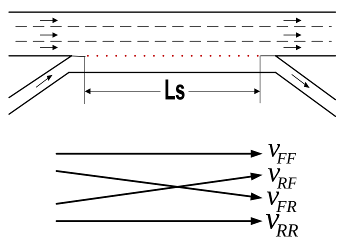
To facilitate analysis performed by engineers, a set of look-up tables were developed in this project. The tables covered a wide range of combinations of typical geometric and traffic conditions. They allow users to perform a preliminary analysis without having to conduct a complex calculation (such as HCM procedures) or a detailed traffic simulation-based analysis.

Note that the results of this study showed that the HCM methods might be limited in analyzing a weaving segment without an auxiliary lane for the following two reasons:

- The HCM model for weaving segments is only for the segments with an auxiliary lane, and it yields results (e.g., density and speed) for all lanes within the weaving segment (please see Figure 4-2[[b]). For the weaving segments without auxiliary lanes, the HCM suggests modeling them as two joint ramp influence areas (please see Figure 4-2[a]). However, this approach yields results (e.g., density and speed) only for the two mainline lanes next to the shoulder (i.e., two ramp influence areas). Thus, the modeling results of these two cases cannot be compared directly.
- The results (e.g., density and speed) of Case A (without auxiliary lanes, modeled as two joint ramp influence areas) sometimes were better than those of Case B (with auxiliary lanes, modeled by HCM standard method), which is not reasonable because installing an auxiliary lane should not make the segment performance become worse, and the two outer lanes next to the shoulder should be affected more by the diverging and merging traffic than the inner lanes.

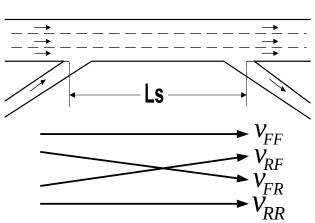
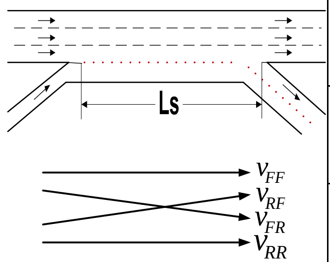
Therefore, in this study, the traffic simulation-based approach was used to develop the look-up tables for analyzing the operational and safety impacts of adding an auxiliary lane. Please note that for developing the proposed look-up tables, researchers implicitly used several assumptions in the simulation studies besides the traffic and geometric conditions shown in Tables 7-2 to 7-7. Consideration should be given to adjust the estimates of the performance measures listed in the look-up tables for a specific case that deviates from these assumptions. These assumptions include peak-hour factor = 1.0; percentage for heavy vehicle = 0 percent; lane width and auxiliary lane width = 12 ft; grade = 0; and driver population = regular commuters.

Table 7-2. Look-Up Table for Weaving Segments (One-Lane Entrance Ramp and One-Lane Exit Ramp).

Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Ramp Spacing (ft), L_s	Freeway to Freeway volume (pc/h/ln), v_{FF}	Weaving Volume (pc/h), $v_{FR}+v_{RF}$	Density-Before (vpm)	Density-After (vpm)	% of Change in Density	Speed-Before (mph)	Speed-After (mph)	% of Change in Speed	Capacity - Before (veh/h)	Capacity - After (veh/h)	% of Change in Capacity	Conflict Count-Before (conflicts/h/500ft)	Conflict Count-After (conflicts/h/500ft)	TCMF	LOS Before	LOS After
		750	500	500	9.5	7.0	-26.32%	61.8	63.0	1.94%	5908	8198	38.77%	10.00	0.10	0.01	A	A
				1500	13.3	10.1	-24.06%	56.9	56.1	-1.41%				41.37	3.83	0.09	B	B
			1500	500	26.2	19.1	-27.10%	60.7	62.3	2.64%				27.03	1.10	0.04	C	B
				1500	31.5	24.0	-23.81%	55.7	54.9	-1.44%				152.97	28.23	0.18	D	C
		1500	500	500	9.4	6.9	-26.60%	62.7	63.7	1.59%	5914	8421	42.39%	8.88	0.10	0.01	A	A
				1500	13.1	9.5	-27.48%	57.8	59.7	3.29%				12.02	0.47	0.04	B	A
			1500	500	25.8	19.0	-26.36%	61.6	62.6	1.62%				20.68	0.10	0.00	C	B
				1500	30.4	21.7	-28.62%	57.7	60.6	5.03%				77.75	2.60	0.03	D	C
		2250	500	500	9.3	6.9	-25.81%	62.9	63.8	1.43%	5962	8668	45.39%	4.28	0.00	0.00	A	A
				1500	12.9	9.4	-27.13%	58.0	60.0	3.45%				8.58	0.01	0.00	B	A
			1500	500	25.7	19.0	-26.07%	61.9	62.8	1.45%				11.02	0.51	0.05	C	B
				1500	29.9	21.5	-28.09%	58.6	61.1	4.27%				15.37	0.59	0.04	D	C
					Average :		-26.45%	Average :		1.99%	Average :		42.18%	Average :		0.04		

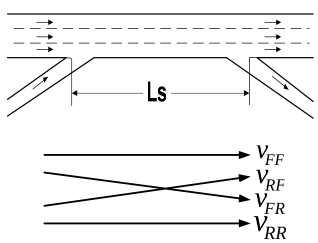
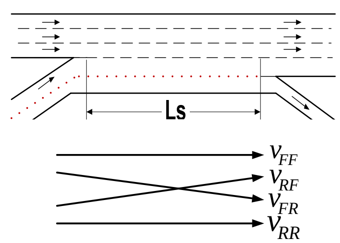
Note: Weaving Volume=Volume of Ramp to Freeway + Volume of Freeway to Ramp

Table 7-3. Look-Up Table for Weaving Segments (One-Lane Entrance Ramp and Two-Lane Exit Ramp).

Before Implementation of Auxiliary lanes	After implementation of Auxiliary lanes	Ramp Spacing (ft)	Freeway-to-freeway volume (pc/h/ln)	Weaving volume (pc/h) $v_{FR}+v_{RF}$	Before Density	After Density	% of Density	Before Speed (mph)	After Speed (mph)	% of Speed	Before Capacity (veh/h)	After Capacity (veh/h)	% of Capacity	Before (conflicts/h/500 ft)	After (conflicts/h/500 ft)	TCMF	LOS Before	LOS After
		750	500	500	9.5	6.9	-27.37%	61.8	63.5	2.75%	5908	8249	39.62%	10.00	0.00	0.00	A	A
				1500	13.3	9.6	-27.82%	56.9	59.3	4.22%				41.37	0.08	0.00	B	A
			1500	500	26.2	19.1	-27.10%	60.7	62.5	2.97%				27.03	0.96	0.04	C	B
				1500	31.5	22.4	-28.89%	55.7	58.9	5.75%				152.97	13.40	0.09	D	C
		1500	500	500	9.4	6.9	-26.60%	62.7	63.8	1.75%	5914	8631	45.94%	8.88	0.05	0.01	A	A
				1500	13.1	9.5	-27.48%	57.8	60.0	3.81%				12.02	0.14	0.01	B	A
			1500	500	25.8	19.0	-26.36%	61.6	62.7	1.79%				20.68	1.09	0.05	C	B
				1500	30.4	21.7	-28.62%	57.7	60.7	5.20%				77.75	1.91	0.02	D	C
		2250	500	500	9.3	6.9	-25.81%	62.9	64.0	1.75%	5962	8665	45.34%	4.28	0.05	0.01	A	A
				1500	12.9	6.9	-46.51%	58.0	63.4	9.31%				8.58	0.00	0.00	B	A
			1500	500	25.7	19.0	-26.07%	61.9	62.8	1.45%				11.02	2.50	0.23	C	B
				1500	29.9	18.9	-36.79%	58.6	62.9	7.34%				15.37	2.35	0.15	D	B
						Average:	-29.62%		Average:	4.01%		Average:	43.63%		Average:	0.05		

Note: Weaving Volume = Volume of Ramp to Freeway + Volume of Freeway to Ramp

Table 7-4. Look-Up Table for Weaving Segments (Two-Lane Entrance Ramp and One-Lane Exit Ramp).

Before Implementation of Auxiliary lanes	After implementation of Auxiliary lanes	Ramp Spacing (ft), L_s	Freeway to Freeway volume (pc/h/ln), v_{FF}	Weaving Volume (pc/h), $v_{FR}+v_{RF}$	Density-Before (vpm)	Density-After (vpm)	% of Change in Density	Speed-Before (mph)	Speed-After (mph)	% of Change in Speed	Capacity - Before (veh/h)	Capacity - After (veh/h)	% of Change in Capacity	Conflict Count-Before (conflicts/h/500ft)	Conflict Count-After (conflicts/h500ft)	TCMF	LOS Before	LOS After
		750	500	500	9.5	5.5	-42.11%	61.8	63.5	2.75%	5908	8767	48.39%	10.00	0	0.00	A	A
				1500	13.3	7.9	-40.60%	56.9	57.1	0.35%				41.37	3.05	0.07	B	A
			1500	500	26.2	15.1	-42.37%	60.7	63.0	3.79%				27.03	0.65	0.02	C	B
				1500	31.5	17.7	-43.81%	55.7	59.6	7.00%				152.97	22	0.14	D	B
		1500	500	500	9.4	5.5	-41.49%	62.7	63.6	1.44%	5914	9441	59.64%	8.88	0.05	0.01	A	A
				1500	13.1	7.5	-42.75%	57.8	60.2	4.15%				12.02	0.8	0.07	B	A
			1500	500	25.8	15.1	-41.47%	61.6	63.3	2.76%				20.68	2.6	0.13	C	B
				1500	30.4	17.0	-44.08%	57.7	62.0	7.45%				77.75	6.7	0.09	D	B
		2250	500	500	9.3	5.5	-40.86%	62.9	64.0	1.75%	5962	9539	60.00%	4.28	0.05	0.01	A	A
				1500	12.9	7.4	-42.64%	58.0	61.1	5.34%				8.58	0.65	0.08	B	A
			1500	500	25.7	14.9	-42.02%	61.9	63.8	3.07%				11.02	2	0.18	C	B
				1500	29.9	16.8	-43.81%	58.6	62.6	6.83%				15.37	4.95	0.32	D	B
						Average :	-42.33%		Average :	3.89%		Average :	56.01%		Average :	0.09		

Note: Weaving Volume=Volume of Ramp to Freeway + Volume of Freeway to Ramp

Table 7-5. Look-Up Table for Merge Segments with a One-Lane Entrance Ramp.

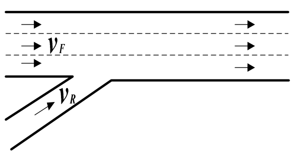
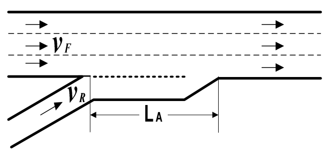
Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Parallel Acceleration Length (ft), L_A	Freeway-to-Freeway volume (pc/h/ln), v_F	Merging Volume (pc/h), v_R	Density Before(vpm)	Density After (vpm)	% of Change in Density	Speed Before (mph)	Speed After (mph)	% of Change in Speed	Capacity Before (veh/h)	Capacity After (veh/h)	% of Change in Capacity	Conflict Count Before (conflicts/h/500 ft)	Conflict Count After (conflicts/h/500 ft)	TCMF	LOS Before	LOS After
		500	500	250	9.2	7.1	-22.83%	63.8	62.5	-2.04%	6892	6970	1.13%	20.15	0.05	0.00	A	A
				750	12.5	9.5	-24.00%	60.5	59.8	-1.16%				58.95	0.2	0.00	B	A
			1500	250	25.9	19.6	-24.32%	61.5	61.0	-0.81%				55.30	3.25	0.06	C	B
				750	30.4	24.4	-19.74%	57.7	53.9	-6.59%				180.35	31.1	0.17	D	C
		1000	500	250	9.2	6.9	-25.00%	63.8	63.9	0.16%	6892	7055	2.37%	10.20	0.08	0.01	A	A
				750	12.5	9.3	-25.60%	60.5	60.9	0.66%				30.90	0.13	0.00	B	A
			1500	250	25.9	19.1	-26.25%	61.5	62.4	1.46%				26.53	0.73	0.03	C	B
				750	30.4	21.9	-27.96%	57.7	60.2	4.33%				91.78	2.70	0.03	D	C
		1500	500	250	9.2	6.9	-25.00%	63.8	63.9	0.16%	6892	7059	2.42%	4.27	0.02	0.00	A	A
				750	12.5	9.3	-25.60%	60.5	61.1	0.99%				13.85	0.03	0.00	B	A
			1500	250	25.9	19.1	-26.25%	61.5	62.4	1.46%				15.08	0.37	0.02	C	B
				750	30.4	21.8	-28.29%	57.7	60.4	4.68%				45.90	1.03	0.02	D	C
						Average:	-25.07%		Average:	-0.28%		Average:	1.97%		Average:	0.03		

Table 7-6. Look-Up Table for Diverge Segments with a One-Lane Exit Ramp.

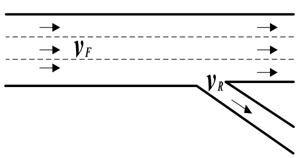
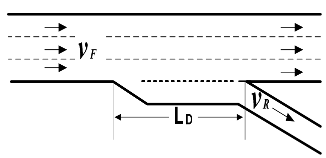
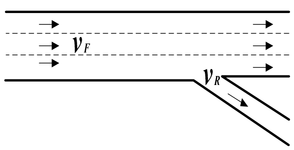
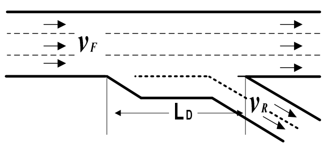
Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Parallel Deceleration Length (ft), L_D	Freeway-to-Freeway volume (pc/h/ln), v_F	Diverging Volume (pc/h), v_R	Density Before(vpm)	Density After (vpm)	% of Change in Density	Speed Before (mph)	Speed After (mph)	% of Change in Speed	Capacity Before (veh/h)	Capacity After (veh/h)	% of Change in Capacity	Conflict Count Before (conflicts/h/500 ft)	Conflict Count After (conflicts/h/500 ft)	TCMF	LOS Before	LOS After
		500	500	250	8.1	6.0	-25.93%	62.0	63.4	2.26%	6584	6636	0.79%	0.05	0.00	0.00	A	A
				750	8.4	6.3	-25.00%	59.6	59.7	0.17%				0.00	0.00	N/A	A	A
			1500	250	26.3	18.0	-31.56%	60.5	62.6	3.47%				2.10	1.30	0.62	C	B
				750	29.7	18.3	-38.38%	59.4	61.6	3.70%				2.50	1.25	0.50	C	B
		1000	500	250	8.1	5.8	-28.40%	62.0	65.3	5.32%	6584	6637	0.80%	0.03	0.00	0.00	A	A
				750	8.4	5.9	-29.76%	59.6	64.3	7.89%				0.00	0.00	N/A	A	A
			1500	250	26.3	17.6	-33.08%	60.5	64.0	5.79%				1.05	0.60	0.57	C	B
				750	29.7	17.8	-40.07%	59.4	63.5	6.90%				1.25	1.00	0.80	C	B
		1500	500	250	8.1	5.8	-28.40%	62.0	65.6	5.81%	6584	6640	0.85%	0.02	0.00	0.00	A	A
				750	8.4	5.9	-29.76%	59.6	63.6	6.71%				0.00	0.00	N/A	A	A
			1500	250	26.3	17.7	-32.70%	60.5	63.9	5.62%				0.70	0.37	0.52	C	B
				750	29.7	17.7	-40.40%	59.4	63.9	7.58%				0.83	0.65	0.78	C	B
						Average :	-31.95%		Average :	5.10%		Average :	0.82%		Average :	0.42		

Table 7-7. Look-Up Table for Diverge Segments with a Two-Lane Exit Ramp.

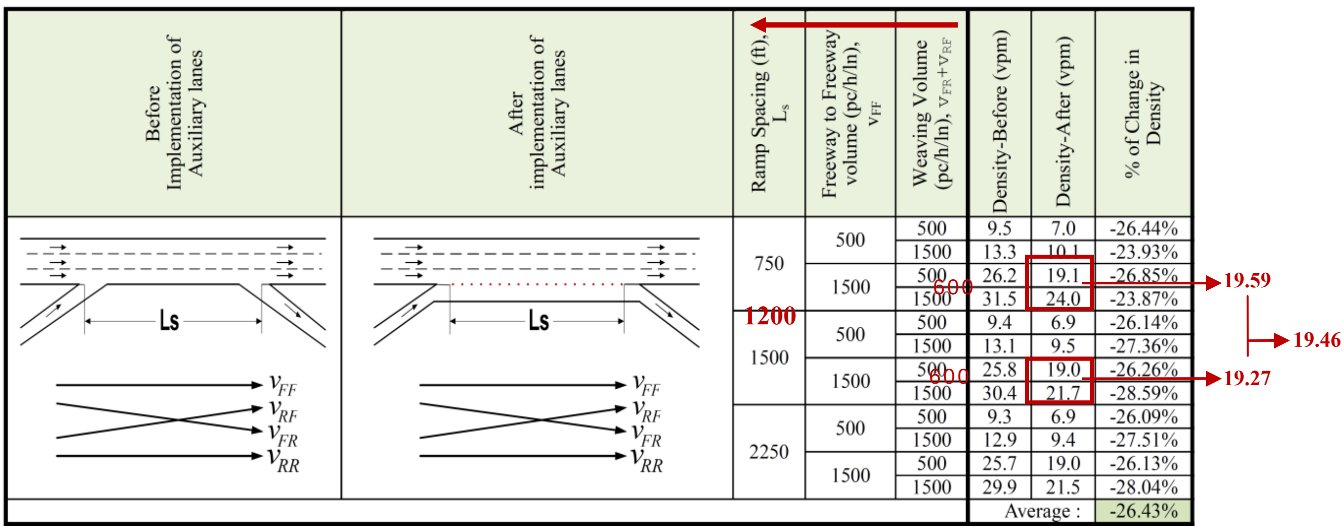
Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Parallel Deceleration Length (ft), L_D	Freeway-to-Freeway volume (pc/h/ln), v_F	Diverging Volume (pc/h), v_R	Density Before(vpm)	Density After (vpm)	% of Change in Density	Speed Before (mph)	Speed After (mph)	% of Change in Speed	Capacity Before (veh/h)	Capacity After (veh/h)	% of Change in Capacity	Conflict Count Before (conflicts/h/500 ft)	Conflict Count After (conflicts/h/500 ft)	TCMF	LOS Before	LOS After
		500	500	250	8.1	5.9	-27.16%	62.0	64.2	3.55%	6584	6995	6.24%	0.05	0.00	0.00	A	A
				750	8.4	6.0	-28.57%	59.6	63.4	6.38%				0.00	0.00	N/A	A	A
			1500	250	26.3	17.9	-31.94%	60.5	62.9	3.97%				2.10	0.90	0.43	C	B
				750	29.7	18.1	-39.06%	59.4	62.5	5.22%				2.50	0.60	0.24	C	B
		1000	500	250	8.1	5.7	-29.63%	62.0	65.7	5.97%	6584	6995	6.24%	0.03	0.00	0.00	A	A
				750	8.4	5.8	-30.95%	59.6	65.0	9.06%				0.00	0.00	N/A	A	A
			1500	250	26.3	17.7	-32.70%	60.5	63.7	5.29%				1.05	0.40	0.38	C	B
				750	29.7	17.7	-40.40%	59.4	63.7	7.24%				1.25	0.30	0.24	C	B
		1500	500	250	8.1	5.7	-29.63%	62.0	66.0	6.45%	6584	6995	6.24%	0.02	0.00	0.00	A	A
				750	8.4	5.8	-30.95%	59.6	65.4	9.73%				0.00	0.00	N/A	A	A
			1500	250	26.3	17.7	-32.70%	60.5	63.9	5.62%				0.70	0.28	0.40	C	B
				750	29.7	17.6	-40.74%	59.4	64.0	7.74%				0.83	0.35	0.42	C	B
						Average:	-32.87%		Average:	6.35%		Average:	6.24%		Average:	0.23		

7.2.3 Example for Using the Look-Up Tables

Interpolated values may be used for a rough estimation based on the tables. For the following instance:

- Ramp spacing (L_S) = 1200 ft.
- Freeway-to-freeway volume (V_{FF}) = 1500 vph.
- Weaving volume (V_{FR}+V_{RF}) = 600 vph.

Assuming an analyst needs to estimate the traffic density after the auxiliary lane is installed at a weaving segment with a one-lane entrance ramp and one-lane exit ramp, Table 7-2 can be used as shown in Figure 7-1.



Before Implementation of Auxiliary lanes	After implementation of Auxiliary lanes	Ramp Spacing (ft), L_s	Freeway to Freeway volume (pc/h/ln), v_{FF}	Weaving Volume (pc/h/ln), $v_{FR}+v_{RF}$	Density-Before (vpm)	Density-After (vpm)	% of Change in Density
		750	500	500	9.5	7.0	-26.44%
				1500	13.3	10.1	-23.93%
			1500	500	26.2	19.1	-26.85%
				1500	31.5	24.0	-23.87%
		1500	500	500	9.4	6.9	-26.14%
				1500	13.1	9.5	-27.36%
			1500	500	25.8	19.0	-26.26%
				1500	30.4	21.7	-28.59%
		2250	500	500	9.3	6.9	-26.09%
				1500	12.9	9.4	-27.51%
			1500	500	25.7	19.0	-26.13%
				1500	29.9	21.5	-28.04%
					Average :		-26.43%

Figure 7-1. Demo of Analyzing the Weaving Segment Performance without and with an Auxiliary Lane Based on the Look-Up Tables.

Since the ramp spacing is given as 1200 ft, the freeway-to-freeway volume is given as 1500 vph, and the weaving volume is 600 vph, the analyst should look at the two red-outlined areas. The interpolated values of the percentage of changes should be calculated using the following equation:

$$y = y_0 + (x - x_0)\frac{y_1 - y_0}{x_1 - x_0}$$

Where: y_1 is the upper bound performance measure (e.g., density, speed, capacity, or conflicts).

y_0 is the lower bound performance measure.

x_1 is the upper bound input variable (e.g., L_S, V_{FF} or V_{FR}+V_{RF}).

x_0 is the lower bound input variable.

The interpolated value is calculated based on the values of the input variables listed from the right to left in the look-up table. Therefore, for a case where the weaving volume (V_{FR}+V_{RF}) = 600 vph, freeway-to-freeway volume (V_{FF}) = 1500 vph, and ramp spacing (L_S) = 750 ft, the interpolated traffic density after installing an auxiliary lane is equal to:

$$19.1+ (600-500)*(24-19.1)/(1500-500) = 19.59 \text{ vpm}$$

Likewise, if the weaving volume (V_{FR}+V_{RF}) = 600 vph, freeway-to-freeway volume (V_{FF}) = 1500 vph, and ramp spacing (L_S) = 1500 ft, the interpolated traffic density after installing an auxiliary lane is equal to:

$$19+ (600-500)*(21.7-19.0)/(1500-500) = 19.27 \text{ vpm}$$

Finally, if the weaving volume (V_{FR}+V_{RF}) = 600 vph, freeway-to-freeway volume (V_{FF}) = 1500 vph, and ramp spacing (LS) = 1200 ft, the interpolated value can be calculated as follows:

$$19.27+ (1200-750)*(19.59-19.27)/(1500-750) = 19.46 \text{ vpm}$$

7.3 GUIDELINES FOR DESIGN OF AUXILIARY LANES

This part of the guidelines aims to synthesize and recommend guidelines regarding geometric design of auxiliary lanes. For guidelines regarding design of signage and pavement markings, please refer to the latest version of the TXDOT Freeway Signing Handbook (2008) and the Texas Manual on Uniform Traffic Control Devices (TMUTCD; Chapter 3).

Guideline 3—General Principles for Lane Arrangement Where Auxiliary Lanes Are Used:

Two basic principles are generally recommended to balance traffic load and maintain a uniform level of service along a freeway with an auxiliary lane:

- Consistency of basic number of lanes.
- Principles of lane balance.

These two general principles were recommended based on the AASHTO Green Book (2011).

7.3.1 Consistency of Basic Number of Lanes

Basic number of lanes is the minimum number of traffic lanes designated and maintained over a significant length of a freeway. It is often determined based on the traffic demand on freeway mainlines. According to the AASHTO Green Book (2011), the basic number of lanes should be consistent for a substantial length of freeway, irrespective of changes in traffic volume and lane balance needs.

7.3.2 Principles of Lane Balance

To realize efficient traffic operation through and beyond an interchange, the AASHTO Green Book (2011) recommends that there be a balance in the number of lanes on the freeway and ramps. The Roadway Design Manuals of Illinois, Indiana, Massachusetts, Minnesota, Montana, Nevada, Ohio, Utah, and Washington explicitly mention that the principles of lane balance should be followed.

For auxiliary lanes less than 1,500 ft in length (e.g., between closely spaced interchanges or between the loop ramp entrance and the loop ramp exit of a cloverleaf interchange), lane balance principles permit the termination of the auxiliary lane with a one-lane exit ramp, as shown in Figure 7-2.

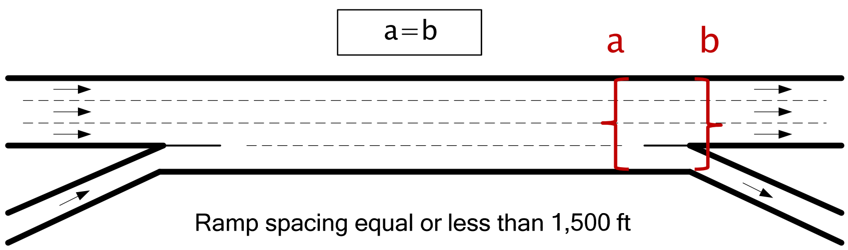
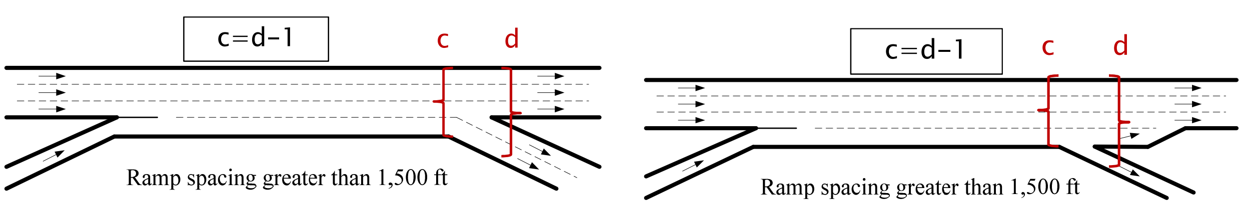


Figure 7-2. Principles of Lane Balance for Ramp Spacing Less than 1,500 ft.

(Source: AASHTO Green Book, 2011)

For auxiliary lanes greater than 1,500 ft in length, lane balance principles state that the number of approach lanes on the freeway must be equal to the number of lanes on the freeway beyond the exit plus the number of lanes on the exit, minus one, as shown in Figure 7-3.

Under the second condition above, the auxiliary lane may be terminated by one of two methods, as shown in Figure 7-3(a) and (b). The first method, shown in Figure 7-3(a), drops the auxiliary lane with a two-lane exit. In this configuration, traffic in the auxiliary lane must exit. Traffic in the basic lane to the left of the auxiliary lane may exit or may proceed along the mainline. The second method, shown in Figure 7-3(b), provides a one-lane exit ramp but carries the auxiliary lane through the exit before it is tapered into the through roadway. This design provides a recovery lane for drivers who inadvertently remain in the discontinued lane.



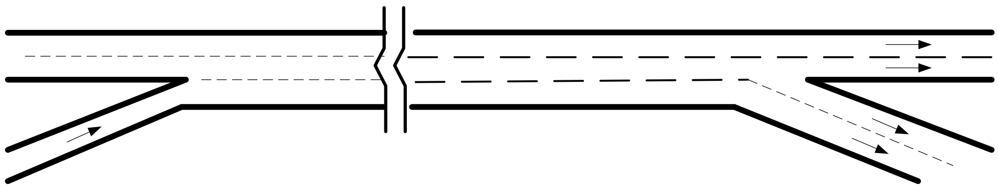
(a) Auxiliary lane terminated with two-lane exit ramp (b) Auxiliary lane terminated with downstream taper

Figure 7-3. Principles of Lane Balance for Ramp Spacing Greater than 1,500 ft.

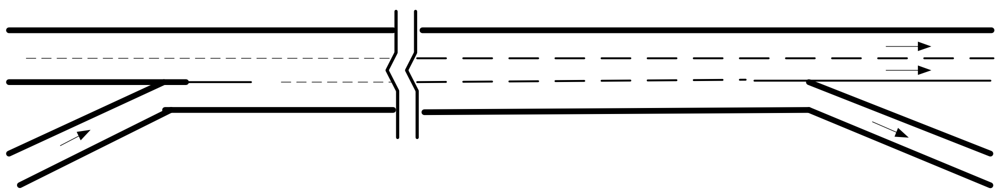
(Source: AASHTO Green Book, 2011)

<u>Guideline 4—Methods for Dropping an Auxiliary Lane from Mainline:</u>

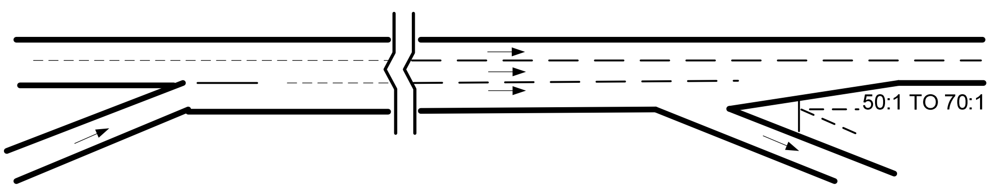
When it is not practical or necessary to extend the auxiliary lane from one interchange to the next, alternative methods can be considered for dropping an auxiliary lane from the mainline, as shown in Figure 7-4.



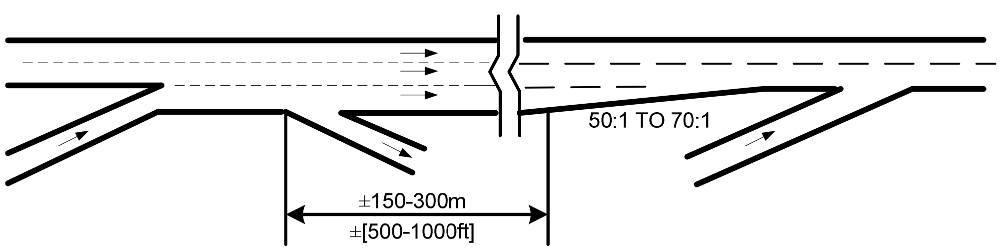
(a) Auxiliary lane dropped on exit ramp



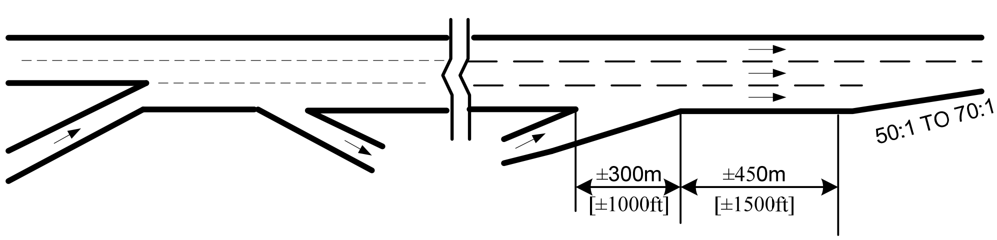
(b) Auxiliary lane between cloverleaf loops or closely spaced interchanges dropped on single exit lane



(c) Auxiliary lane dropped at physical nose



(d) Auxiliary lane dropped within an interchange



(e) Auxiliary lane dropped beyond an interchange

Figure 7-4. Alternative Methods to Drop Auxiliary Lanes.

(Source: AASHTO Green Book, 2011)

Please note that the findings of this project showed that extending the auxiliary lane beyond an interchange (Figure 7-4[e]) is preferable only if the entrance ramp downstream has a low traffic volume or volume of capacity. If the next entrance ramp has a high traffic volume, it is desirable to drop the auxiliary lane before the next entrance, as shown in Figure 7-5.

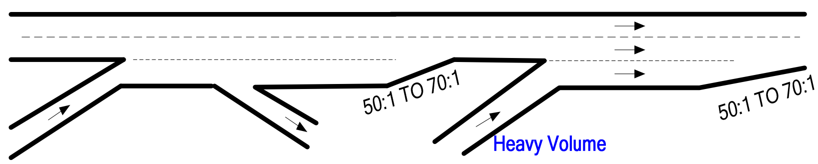
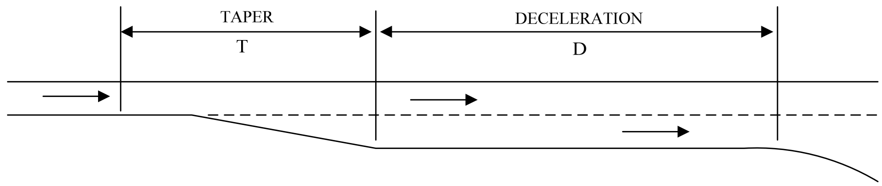


Figure 7-5. Scenario when Auxiliary Lane Dropped within an Interchange Is Preferred.

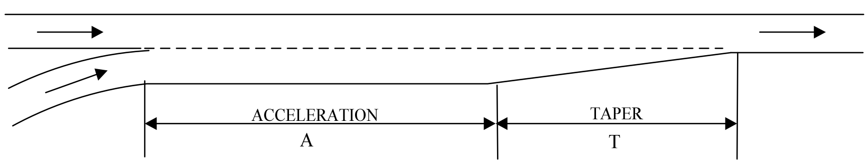
<u>Guideline 5—Length of Parallel Acceleration/Deceleration Auxiliary Lanes at Merge/Diverge Area:</u>

Refer to Figure 7-6 for lengths of taper and parallel acceleration/deceleration lanes, where design speed represents the mainline speed and entrance-curve design speed represents the desired speed at the street-ramp junction.

For parallel acceleration/deceleration lanes, the lengths can be determined based on the provisions (Figure 7-6) in the TxDOT Roadway Design Manual (2010).



HIGHWAY DESIGN SPEED (mph)	MINIMUM LENGTH OF TAPER T (ft)	DECELERATION LENGTH, D (ft) Ramp Speed				
		30	35	40	45	50
50	230	315	285	225	175	-
55	250	380	350	285	235	-
60	265	430	405	350	300	240
65	285	470	440	390	340	280
70	300	520	490	440	390	340
75	330	575	535	490	440	390



HIGHWAY DESIGN SPEED (mph)	MINIMUM LENGTH OF TAPER T (ft)	ACCELERATION LENGTH, A (ft) Entering Speed							
		15	20	25	30	35	40	45	50
50	230	660	610	550	450	350	130	-	-
55	250	900	810	780	670	550	320	150	-
60	265	1140	1100	1020	910	800	550	420	180
65	285	1350	1310	1220	1120	1000	770	600	370
70	300	1560	1520	1420	1350	1230	1000	820	580
75	330	1730	1630	1580	1510	1420	1160	1040	780

Figure 7-6. Lengths of Parallel Acceleration/Deceleration Lanes at Entrance/Exit Ramp.

(Source: TxDOT Roadway Design Manual)

Guideline 6—Design of Auxiliary Lanes at Two-Lane Ramps:

- Where operational problems are caused by high entrance/exit ramp demand, a two-lane entrance/exit ramp is recommended to increase the capacity for the merging/diverging vehicles.
- If a two-lane entrance ramp is installed because of high merging traffic demand and the next ramp is within 2500 ft and has low or moderate traffic volume, it is recommended to extend the auxiliary lane that originated from the two-lane entrance ramp beyond the next ramp.
- The design of parallel acceleration/deceleration lanes at two-lane ramps can follow the TxDOT Roadway Design Manual (2010), as illustrated in Figure 7-7.

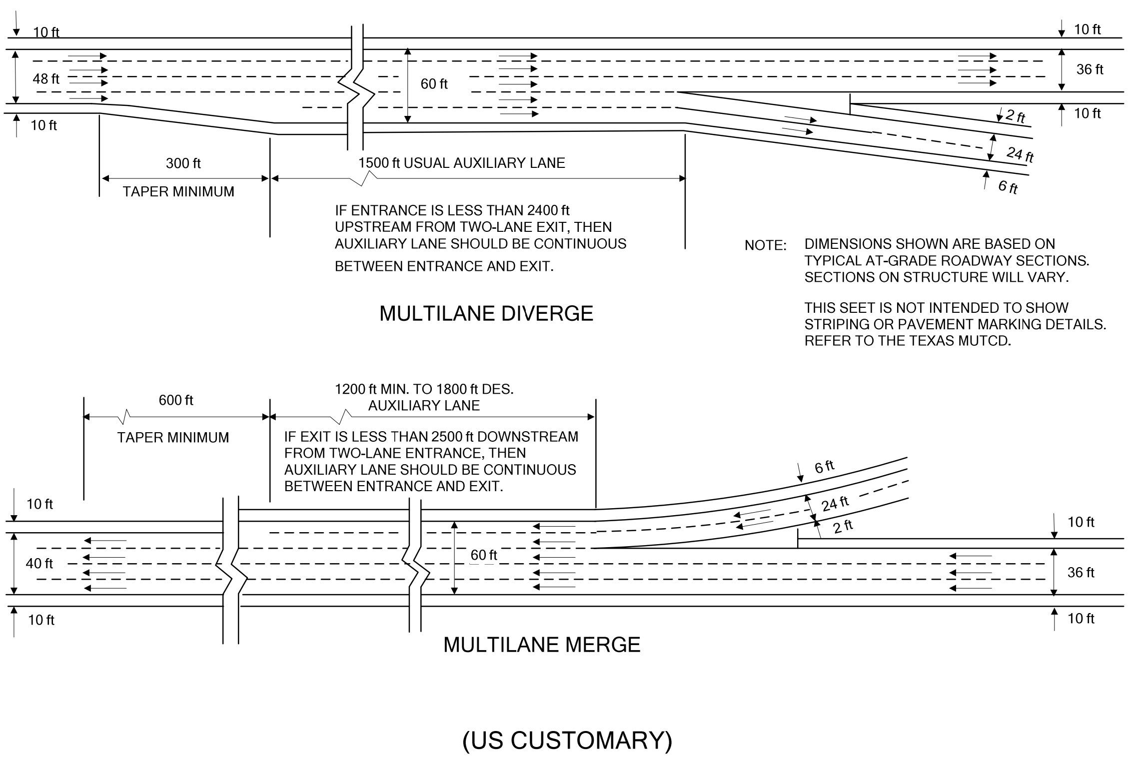


Figure 7-7. Lengths of Parallel Acceleration/Deceleration Lanes at Entrance/Exit Ramp.

(Source: TxDOT Roadway Design Manual)

This guideline is based on the AASHTO Green Book (2011) and the TxDOT Roadway Design Manual (2010)—Chapter 3. In addition, the results of the simulation analysis in this study indicated that operational benefits were achieved by extending two-lane entrance ramps to the next ramp if they are closely spaced. For parallel acceleration/deceleration lanes at two-lane ramps, the design of auxiliary lanes can follow the TxDOT Roadway Design Manual (2010), as shown in Figure 7-7.

<u>Guideline 7—Width of Auxiliary Lanes and Shoulders:</u>

- Desirably, the width of auxiliary lanes should be equal to that of mainline lanes (normally 12 ft).
- Where auxiliary lanes are provided along freeway mainlines, the adjacent shoulder should desirably be 8-12 ft in width or the same width as mainline lanes, with a minimum shoulder width of 6 ft.

This guideline is based on the AASHTO Green Book (2011), as well as the Massachusetts DOT Project Development & Design Guide (2007), Utah DOT Roadway Design Manual of Instruction (2007), and Oregon DOT Highway Design Manual (2003).

According to the AASHTO Green Book (2011), where auxiliary lanes are provided along freeway main lanes, the adjacent shoulder should desirably be 8 ft to 12 ft in width, with a minimum 6-ft-wide shoulder considered.

7.4 REFERENCES

A Policy on Geometric Design of Highways and Streets. American Association of State Highway and Transportation Officials. Washington, D.C., 2011.

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Utah Department of Transportation, Roadway Design Manual of Instruction, 2007.

Wang, Y., R. Cheu, Y. Qi, and X.Chen. Use of Auxiliary Lanes at Isolated Freeway On-ramp Junctions. Journal of Transportation of ITE, volume 5, issue I, 2013.

CHAPTER 8: KEY FINDINGS AND RECOMMENDATIONS

The primary goals of the project were to develop guidelines on the design of freeway auxiliary lanes and to provide methods for assessing the impacts of freeway auxiliary lanes. To fulfill these goals, researchers performed the following key tasks:

- Reviewed and synthesized national and peer states' practices.
- Conducted a survey of traffic engineers.
- Analyzed operational benefits from adding auxiliary lanes at the segment level.
- Used micro-simulation to identify the scope of impacts of auxiliary lanes at the corridor level.
- Analyzed safety impacts of adding auxiliary lanes.
- Developed guidelines and recommended best practices.

This study led to a number of findings, and some key findings are discussed in the following sections.

8.1 LITERATURE REVIEW

Following findings are obtained from the literature review:

- The review of the prior research indicates that the presence of continuous auxiliary lanes generally will improve freeway traffic operations. In addition, a recent study by Wang et al. (2013) presented a set of quantitative guidelines for the use of a parallel acceleration lane for an entrance ramp.
- The existing state DOTs' design manuals provide general guidelines regarding freeway auxiliary lanes that are basically consistent with the provisions in the AASHTO Green Book (2004). These guidelines identify the factors to be considered in the design of auxiliary lanes, including grade, volume, and speed. In addition, quantitative warrants for auxiliary lanes are provided by some states manuals and are mainly based on interchange spacing, space between upstream enter ramp and downstream exit ramp, and existence of frontage roads.

8.2 SURVEY OF TRAFFIC ENGINEERS

From the survey of traffic engineers, it was found that:

- The survey of traffic engineers indicated that for modeling operational performance, the software/tools most commonly used by engineers are HCS and VISSIM.
- The majority of the respondents thought that auxiliary lanes have positive impacts on traffic operations and/or safety at freeway weaving segments and entrance ramp and/or off-ramp junctions.

- The use of a shoulder as an auxiliary lane is not popular and is only used in the Houston, Texas, area and in Kentucky and Illinois. The major concerns are safety and liability.

8.3 OPERATIONAL IMPACTS OF ADDING AUXILIARY LANES

Following are the key findings regarding the operational impacts of adding auxiliary lanes:

- Density, speed, and capacity are representative operational performance measures for freeway auxiliary lanes.
- Generally, adding an auxiliary lane at weaving segment or ramp influence areas can lead to a lower density, which means more freedom of maneuvers from a driver's standpoint.
- For weaving segments, on average, operating speed can be increased slightly (less than 8 percent) by adding an auxiliary lane where a freeway has three mainline lanes. For entrance-ramp influence areas, adding a parallel acceleration lane does not have significant impacts on the speed. For exit-ramp influence areas, adding a parallel auxiliary/deceleration lane can slightly increase the speed by approximately 5 percent.
- For weaving segments, capacity of the segments can be significantly enhanced by adding an auxiliary lane. Over 40 percent capacity enhancement can be expected when an auxiliary lane is added where a freeway has three mainline lanes. An additional ramp lane on either the entrance ramp or the exit ramp can further enhance the capacity of the weaving segments. For isolated ramp influence areas (entrance/exit), providing a parallel auxiliary lane does not have significant impacts on the capacity of the ramp influence area. This is generally consistent with the findings in the Highway Capacity Manual (2010).

For the corridor-level analyses, it was found that:

- Where a freeway weaving section with auxiliary lanes is followed by an entrance ramp, if the traffic volume at the entrance ramp is low to moderate, extending the weaving auxiliary lane to the entrance ramp can lead to improved traffic operation at the weaving section. On the other hand, if the traffic volume at the entrance ramp is high, extending the auxiliary lane to the entrance ramp may result in increased congestion at the downstream entrance ramp. This is a result of more vehicles traveling on the rightmost auxiliary lane that thereafter conflict with the vehicles merging from the entrance ramp. A case-by-case evaluation is preferable to determine where the auxiliary lane should be terminated to better preserve the mobility of the corridor.
- Where a weaving auxiliary lane is followed by an exit ramp, if the traffic volume at this exit ramp is high, it can be less operationally favorable to terminate the auxiliary lane at the exit ramp. Instead, further extending it and dropping it at some point beyond the exit ramp represents a more operationally effective option.

- A double-lane exit ramp provides an easier and direct exit for the diverging vehicles because it usually reduces the number of lane changes required for vehicles to exit the freeway. Thus, where operational problems are caused by high exit ramp demand, a double-lane exit may be a solution to increase the ramp capacity and reduce the number of lane changes mandated for the diverging vehicles.

8.4 SAFETY IMPACTS OF ADDING AUXILIARY LANES

Following are the key findings regarding the safety impacts of adding auxiliary lanes:

- Adding auxiliary lanes can significantly reduce the frequency of traffic conflicts for both weaving segments and ramp influence areas.
- Among three typical weaving segments with auxiliary lanes, Type A design (one-lane entrance and one-lane exit) generally presented the best safety performance, followed by Type B design (one-lane entrance and two-lane exit). Type C (two-lane entrance and one-lane exit) was associated with the highest crash frequency among the three types of weaving auxiliary lane settings.

Finally, guidelines were developed for determining the conditions under which auxiliary lanes should be considered and the methods for assessing their impacts. A set of look-up tables was developed to assess the operational and safety impacts of freeway auxiliary lanes under various geometric conditions (e.g., length of auxiliary lanes, number of ramp lanes, and connectivity of lanes) and traffic conditions (e.g., traffic volume on freeway mainlines and traffic volume on ramps). These tables can be used to preliminarily project changes in density, speed, capacity, and traffic conflict frequency in a freeway section after installing auxiliary lanes. It can allow users to perform a preliminary analysis without having to use the complicated HCM procedures or traffic simulation.

In addition, guidelines were also provided regarding geometric design of auxiliary lanes, including:

- General principles for lane arrangement where auxiliary lanes are used.
- Length of parallel acceleration/deceleration lanes at merge/diverge areas.
- Design of auxiliary lanes at two-lane ramps.
- Width of auxiliary lanes and shoulders.

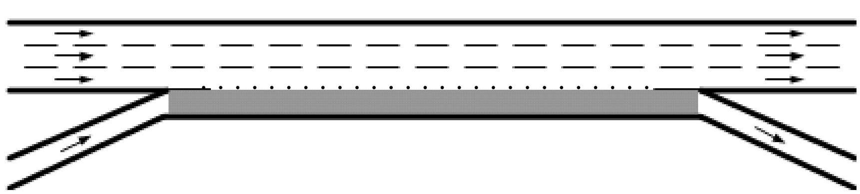
The findings from this research along with the developed guidelines can be used in implementing and designing freeway auxiliary lanes for new construction or retrofit projects. The developed methodologies and outcomes will complement the provisions in current state roadway design manuals/guidelines.

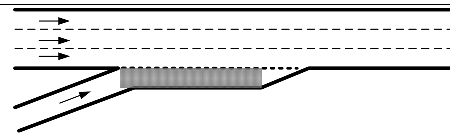
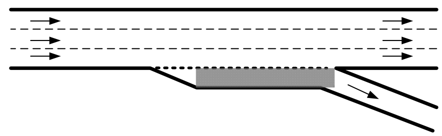
8.5 REFERENCES

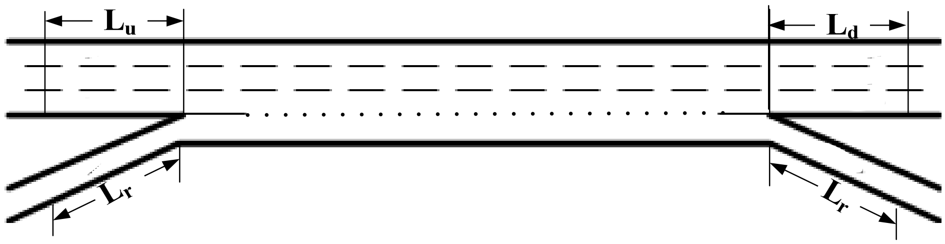
Wang, Y., R. Cheu, Y. Qi, and X.Chen. Use of Auxiliary Lanes at Isolated Freeway On-ramp Junctions. Journal of Transportation of ITE, volume 5, issue I, 2013.

APPENDIX: SURVEY INSTRUMENT

TxDOT Project 0-6706
Chapter 2—DOT Survey Questions

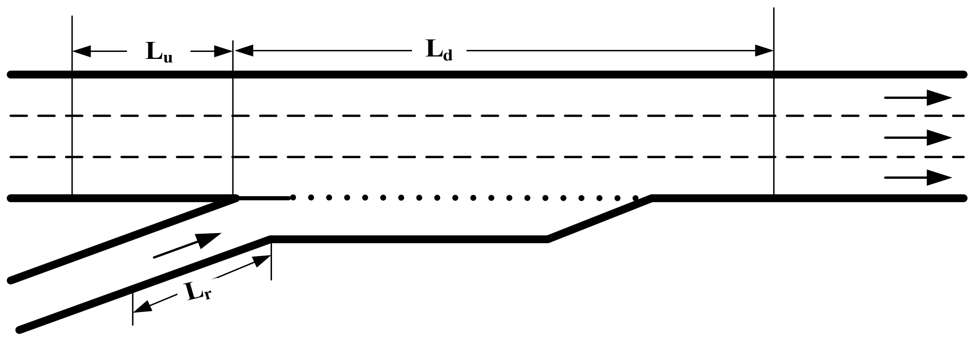
Project background	Texas Department of Transportation (TxDOT) Research Project: Design and Scope of Impact of Auxiliary Lanes (0-6706) Project objective: While auxiliary lanes are widely used in urban freeway interchanges throughout Texas, broader understanding is necessary of the design and impacts of auxiliary lanes, and their role in access-controlled facility function and operations. The goal of this project is to define the conditions under which auxiliary lanes are implemented in design and rehabilitation projects, and to investigate the impacts of auxiliary lanes in a broad scope. About this survey: This survey aims to collect your professional opinions, practical experiences, and concerns regarding the design and use of auxiliary lanes on freeways. Your inputs are the most valuable resources for the project, and your support is greatly appreciated.
Your background	Please share with us your background and contact information: • Name: • Title: • Organization: • City/County/District: • State: • Email: • Phone number:
Definition	As defined by AASHTO, an auxiliary lane is the portion of the roadway adjoining the traveled way for speed change, turning, storage for turning, weaving, truck climbing, and other purposes supplementary to the through traffic movement. On freeways, auxiliary lanes could be used at weaving segments as a supplementary lane to connect an entrance ramp and a closely spaced exit ramp, or it could be used at isolated entrance ramp or exit ramp junctions as a supplemental lane to increase acceleration or deceleration distance. The following figures show examples of weaving and entrance ramp/exit ramp segments with auxiliary lanes.  **Figure A.1. Weaving Segment.**

	 **Figure A.2. Entrance Ramp Junction.**  **Figure A.3. Exit Ramp Junction.**
1	(a) Do you use any of the following manuals when designing auxiliary lanes? (you may select more than one answer) A) AASHTO Green Book B) Highway Capacity Manual (Year:_________) C) MUTCD D) Others (please specify: _____________________________) (b) Does your organization have any local manual/guideline? Yes/No If yes, please provide the name of the manual/guideline
2	What are the performance measures you are using to measure the quality of service at weaving segments and entrance ramp/off ramp junctions? (you may select more than one answer) A) Density B) Weaving demand or entrance ramp/off ramp demand C) Speed D) Others (please specify: _____________________________)
3	What tools and/or software are you using to determine the level of service at weaving segments and entrance ramp/off ramp junctions? Please list all the tools and software: Are these tools/software able to model operational and/or safety impact of adding an auxiliary lane? What kind of impact?
4	What are the operational or safety influencing areas at the upstream and downstream of the weaving segments, entrance ramp and exit ramps? Please give estimates of the influencing distances as shown in following figures based on your experience. 1) For weaving segments



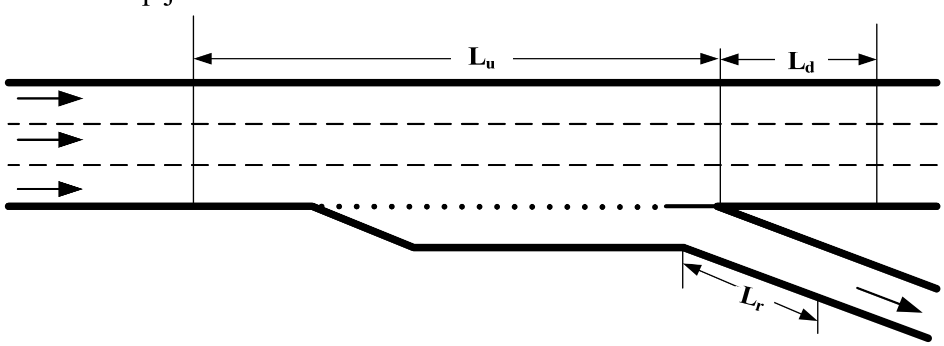
- The distance on the entrance/exit ramp: L_r=_______
- The distance on the upstream of mainline freeway: L_u=____
- The distance on the downstream of mainline freeway: L_d=____

2) For entrance ramp junctions



- The distance on the entrance ramp: L_r=_______
- The distance on the upstream of mainline freeway: L_u=______
- The distance on the downstream of mainline freeway: L_d=______

3) For exit ramp junctions



- The distance on the exit ramp: L_r=_______
- The distance on the upstream of mainline freeway: L_u=______
- The distance on the downstream of mainline freeway: L_d=______

5	Please tell us under which condition you will consider auxiliary lanes in highway design and if so, how do you determine the length of auxiliary lanes?
6	What do you think auxiliary lanes can positively or negatively impact the operations, safety, or other aspects at weaving segments, entrance ramp and/or off ramp junctions?
7	In urban areas, right-of-way is at a premium. Please describe your experience, if any, concerning the use of freeway shoulders to improve performance of weaving/merge/diverge segments (as a form of auxiliary lanes).
8	Can you share some of your experience, lessons, or issues related to the design and use of auxiliary lanes with us?
9	Can we contact you if we need further information? Yes/No If yes, via email and/or via phone?
Our contact	If you have any question regarding this survey, please contact: Dr. Ruey (Kelvin) Cheu Associate Professor, Dept. of Civil Engineering, The University of Texas at El Paso 500 W. University Ave, El Paso, TX 79968-0516 Tel: (915) 747-5717 Fax:(915)747-8037 Email:rcheu@utep.edu