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Investigation Into The Operation And Safety Of Freeway Auxiliary Lanes: Towards Uniform Design Guidelines

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INVESTIGATION INTO THE OPERATION AND SAFETY OF FREEWAY AUXILIARY LANES: TOWARDS UNIFORM DESIGN GUIDELINES

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Abstract

Freeways operate closest to the purest form of uninterrupted traffic flow. There is no constant interruption to traffic flow (such as stop sign and traffic signal), and access is limited to ramp locations. Therefore, at freeways, bottlenecks, if exist, are usually caused by merging and diverging traffic at ramp locations. Bottleneck removal at freeway ramp areas can reduce average freeway commuter delay. Currently, engineers may add auxiliary lanes at ramp areas to mitigate or remove bottlenecks.

The American Association of State Highway Transportation Officials (AASHTO) publication A Policy on Geometric Design of Highways and Streets, commonly known as the "Green Book", 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 either the added lane between an upstream on-ramp and a downstream off-ramp, the acceleration lane immediately downstream of an isolated on-ramp, or the deceleration lane immediately upstream of an off-ramp.

While auxiliary lanes are widely used in urban freeway interchanges, broader understanding is necessary for the design and impacts of auxiliary lanes. The objective of this research is to first analyze the operational and safety impacts of adding auxiliary lanes, and then to develop guidelines on when and how auxiliary lanes should be implemented. In addition, look-up charts and tables have been developed to provide better quantitative understanding on how auxiliary lane improves operations and safety at freeway ramp areas. These guidelines and look-up tables developed in this dissertation help decision makers to better understand the

expected benefits of auxiliary-lane use, including how auxiliary lanes address both congestion concerns in the proximity of freeway ramps.

For the operational impacts of auxiliary lanes, the study results showed that, after adding an auxiliary lane, the density reduced and level of service improved. At weaving segments, adding an auxiliary lane reduces density by 1.6 to 19.5 pc/mi/ln. At on-ramp junctions, after the addition of an auxiliary lane, the density in the merge influence area reduces by 3.0 to 9.4 pc/mi/ln. At off-ramp junctions, after the addition of an auxiliary lane, the density in the diverge influence area reduces by 4.5 to 13.5 pc/mi/h for L_D=500 ft, and up to 13.5 pc/mi/ln.

For the safety impacts of auxiliary lane, the study results showed that, on-ramp junctions with auxiliary lanes have significantly lower average crash rate (in terms of number of crashes per MEV). However, there is no significant change in the average crash severity (i.e., portion of crashes that are fatal or result in injuries). With regards to crash types, sites with auxiliary lanes are observed to have significantly lower proportion of rear-end crashes and higher proportion of objected related crashes. In addition, the results also showed that, that crash frequency at on-ramp junctions with auxiliary lanes is negatively influenced by the length of the auxiliary lane, the percentage of heavy vehicles on the freeway. Nonetheless, it is positively influenced by the number of lanes on the freeway and the average daily traffic per lane on the freeway.

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Chapter 1

Introduction

1.1 Problem Background

Freeways operate closest to the purest form of uninterrupted traffic flow. There is no constant interruption to traffic flow (such as stop sign and traffic signal), and access is limited to ramp locations. Therefore, at freeways, bottlenecks, if exist, are usually caused by merging and diverging traffic at ramp locations. The Highway Management Handbook (Carvell el al.,1997) views bottleneck analysis and removal a key element of congestion relief at freeway. Bottleneck removal at freeway ramp areas can reduce average freeway commuter delay. Currently, engineers may add auxiliary lanes at ramp areas to mitigate or remove bottlenecks.

The American Association of State Highway Transportation Officials (AASHTO) publication A Policy on Geometric Design of Highways and Streets, commonly known as the "Green Book", 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" (AASHTO, 2004). In freeway design, an auxiliary lane typically refers to either the added lane between an upstream on-ramp and a downstream off-ramp, the acceleration lane immediately downstream of an isolated on-ramp, or the deceleration lane immediately upstream of an off-ramp.

Figure 1.1 shows a typical Freeway Weaving Segment (FWS) with three main lanes and an auxiliary lane. The auxiliary lane added between the on-ramp and off-ramp can provide an improved weaving environment, rather than a forced or direct merge or diverge, for vehicles entering and departing the freeway facility. In other words, the auxiliary lane provides additional longitudinal space for a vehicle to travel while seeking a gap to execute a mandatory

lane change while entering or exiting the freeway. Although the length of the weaving segment (and the length of the auxiliary lane) may be taken as the distance between the upstream on-ramp and the downstream off-ramp, the 2010 edition of Highway Capacity Manual (HCM2010) (TRB, 2010) defines it as the distance between the end points of barrier markings (solid white lines) that prohibit or discourage lane-changing. The length of a weaving segment, according to this definition, is denoted by L_S in Figure 1.1. The terms weaving segment and auxiliary lane appear throughout this dissertation. It is important to note that a FWS refers to the freeway facility as shown in Figure 1.1, and in the context of this research, an auxiliary lane is the travel lane next to the right shoulder that connects an upstream on-ramp and a downstream off-ramp, as highlighted in shade in Figure 1.1.

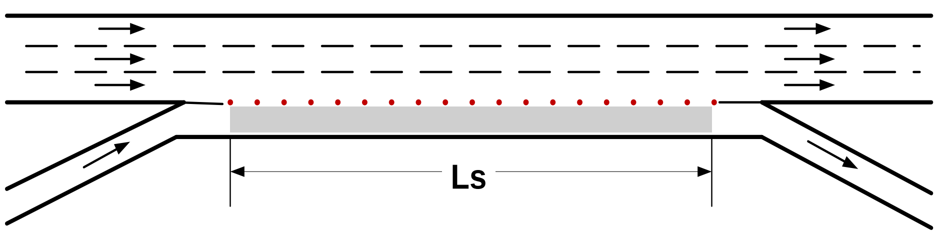


Figure 1.1. Freeway weaving segment.

Figure 1.2 shows a typical isolated freeway on-ramp with three main lanes and an auxiliary lane. The auxiliary lane immediately downstream of the on-ramp allows a merging vehicle to have additional roadway to adjust its speed and seek a desired gap before merging into the freeway. This could reduce the interference of the merging traffic on the main lane traffic, increase traffic volume and speed on freeway main lanes, and also help to reduce the conflicts between the merging vehicle and the vehicles on the freeway lanes.

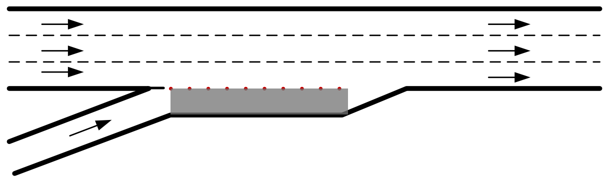


Figure 1.2. Freeway on-ramp junction.

Figure 1.3 shows a typical isolated freeway off-ramp with three main lanes and an auxiliary lane. The auxiliary lane immediately upstream of the off-ramp allows drivers to pull off the freeway main lane and decelerate safely in order to exit. This could reduce the interference of diverging traffic on the main lane traffic, increase traffic volume and speed on freeway main lanes, and also help to reduce the conflicts between the diverging vehicle and the vehicles on the freeway lanes.

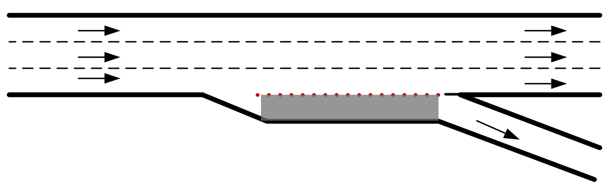


Figure 1.3. Freeway off-ramp junction.

In the past decades, more and more auxiliary lanes have been constructed to facilitate traffic operations at ramp areas on freeways. The AASHTO Green Book and several states' roadway design manuals have so far included little detail as to the auxiliary lane design, such as when to add an auxiliary lane and how long the auxiliary lane should be. A recent survey conducted as part of a Texas Department of Transportation (TxDOT) project on engineers in 26 state Departments of Transportation in the U.S. has found that there was little guidance in the

literature or manuals on when and how auxiliary lanes should be incorporated in freeway design (TxDOT, 2011). In addition, the existing method for assessing the operational impacts of auxiliary lanes, i.e. the method in HCM2010 Chapter 12 and Chapter 13, are too complicated, involving too many equations and inputs. The impacts are not clearly showed with simple charts or tables. Design engineers need to better understand the operational and safety impacts of auxiliary lanes, such as how adding an auxiliary lane affects the density, Level of Service (LOS), and traffic crashes/conflicts under different traffic demands and geometric conditions. In summary, there is little guidance on when and how auxiliary lanes should be implemented, and the impacts of auxiliary lanes under different geometric conditions and traffic demands.

1.2 Objective of Research

The objective of this research is to first analyze the operational and safety impacts of adding auxiliary lanes, and then to develop guidelines on when and how auxiliary lanes should be implemented as part of the freeway geometric design at ramp areas. In addition, look-up charts and tables will be developed to provide better quantitative understanding on how auxiliary lane improves operations and safety at freeway ramp areas.

1.3 Significance

These guidelines and look-up tables developed in this study will help design engineers to better understand the expected benefits of auxiliary-lane use, including how auxiliary lanes address both congestion concerns in the proximity of freeway ramps

Chapter 2

Literature Review and Survey of Current Practice

To have a better understanding of the current practice and research, literature review and engineer survey were conducted to collect information about existing guidelines used by engineers, existing studies on auxiliary lanes, methods and software used in assessing operational and safety performance at freeway ramp areas.

2.1 Current Guidelines in Use

2.1.1 General Implementation and Design Guidelines

AASHTO (2004) states that the traffic 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 road do not exit. 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 a two-lane exit, as illustrated in Figure 2.1.

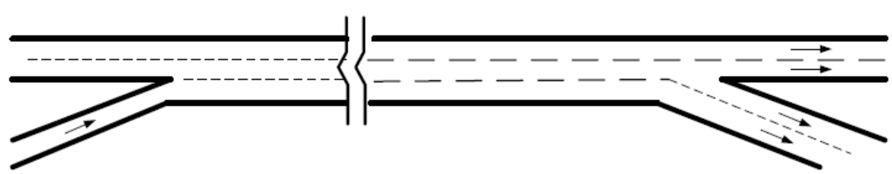


Figure 2.1. Two lane exit.

However, 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.

The Texas Department of Transportation (TxDOT) Roadway Design Manual (TxDOT, 2010) has some guidelines on ramp spacing; it states that for locations where an entrance ramp is followed by an exit ramp, the minimum acceptable distance between ramps depends on the presence of auxiliary lanes. The manual suggests that the minimum spacing shall be 2,000 ft (600 m) without an auxiliary lane, and 1,500 ft (450 m) with an auxiliary lane.

The Arizona Department of Transportation (ADOT) Roadway Design Guidelines (ADOT, 2007) states that 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.

The California Department of Transportation (CDOT) Highway Design Manual (CDOT, 2001) states that, auxiliary lanes should be provided in all cases when the weaving distance is less than 600 m (2000 ft).

The Illinois Department of Transportation (IDOT) Bureau of Design and Environment Manual (IDOT, 2010), Ohio Department of Transportation (ODOT) Location and Design Manual (ODOT, 2011), and Minnesota Department of Transportation (MNDOT) Roadway Design Manual (MNDOT, 2001) state that 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).

Montana Department of Transportation (MDOT) Road Design Manual (MDOT, 2007) states that 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).

To sum up, AASHTO and states guidebooks have only some qualitative guidelines and some spacing based quantitative guidelines on the implementation of auxiliary lanes. There is no detail geometric design and traffic condition related guidelines.

2.1.2 Guidelines for Operational Assessment

The most commonly used guidance for assessing the operational performance of auxiliary lanes at freeway ramp areas isHCM2010. Chapter 12 of HCM2010 (TRB, 2010) is devoted to the LOS analysis of FWSs. Chapter 13 is devoted to the LOS analysis of on-ramp and off-ramp junctions.

For FWSs, this LOS analysis procedure in Chapter 12 is the outcome of NCHRP Project 3-75 (Roess et al., 2008). The procedure consists of eight steps, which estimates the average space mean speed of all vehicles, converts it into density before determining the LOS.

A FWS has four traffic movements: freeway-to-freeway, freeway-to-ramp, ramp-to-freeway and ramp-to-ramp. The freeway-to-ramp and ramp-to-freeway movements are weaving movements while the freeway-to-freeway and ramp-to-ramp movements are non-weaving movements. Given a site's geometry and traffic volumes of the four movements, the analysis procedure starts with the examination of the minimum lane-changing rate for all vehicles (LC_{MIN} , in lane changes/hr), and checked L_S (in ft) against the maximum length of a FWS. It then calculates the capacity of the FWS. This is followed by the estimations of lane-changing rates of weaving and non-weaving vehicles.

The equivalent hourly lane-changing rate of weaving vehicles (in lane changes/hr) is determined from

$$LC_W = LC_{MIN} + 0.39\left[(L_S - 300)^{0.5} N^2 (1 + ID)^{0.8}\right] \tag{2.1}$$

in which N is the total number of lanes in the FWS (the sum of main lanes and auxiliary lane); and ID is the interchange density (in interchanges/mi). The equivalent hourly lane-changing rate of non-weaving vehicles (LC_{NW} , in lane changes/hr), is calculated from a set of equations, depending on "a non-weaving vehicle index". The total lane-changing rate of all vehicles (LC_{ALL} , in lane changes/hr) is then

$$LC_{ALL} = LC_W + LC_{NW} \tag{2.2}$$

The analysis procedure next estimates the average speed of weaving vehicles (in mph) from

$$S_W = 15 + \left(\frac{FFS - 15}{1 + 0.226\left(\frac{LC_{ALL}}{L_S}\right)} \right) \tag{2.3}$$

where FFS is the free-flow speed of the freeway main lanes (in mph).

The average speed of non-weaving vehicles (in mph) is

$$S_{NW} = FFS - (0.0072 LC_{MIN}) - \left(0.0048 \frac{v}{N}\right) \tag{2.4}$$

where v is the total volume (in pc/h) which is the sum of the weaving volume (v_W , in pc/h) and non-weaving volume (v_{NW} , pc/h).

The space mean speed of all vehicles in the weaving segment (in mph) is thus

$$S = \frac{v_W + v_{NW}}{\left(\frac{v_W}{S_W}\right) + \left(\frac{v_{NW}}{S_{NW}}\right)} \tag{2.5}$$

The space mean speed is converted into density (pc/mi/ln) by

$$D = \frac{1}{N}\left(\frac{v}{S}\right) \tag{2.6}$$

The LOS is then determined based on the value of *D*. Table 2.1 Lists HCM2010 LOS criteria for weaving segments.

Table 2.1. Level of service criteria for weaving segments (adopted from HCM2010).

LOS	Density (pc/mi/ln)	Comments
A	≤ 10	Unrestricted operations
B	>10-20	Merging and diverging maneuvers noticeable to drivers
C	>20-28	Weaving segment speeds begin to decline
D	>28-35	Weaving segment turbulence becomes intrusive
E	>35	Turbulence felt by virtually all drivers
F	Demand>Capacity	Ramp and freeway queues form

For on-ramp and off-ramp, the procedures in HCM2010 Chapter 13 allow for the identification of likely congestion at on-ramp junctions, LOS F, and for the analysis of operations at on-ramp junctions at LOS A through E. The model applies to single-lane, right-hand entrance/exit ramp areas. The analyzed influence area covers a length of 1500 ft downstream of the merge point or 1500 ft upstream of the diverge point in the two rightmost lanes on the freeway plus the auxiliary lane, as indicated in Figure 2.2. According to HCM2010, this is the area where most of the lane-changing events occur.

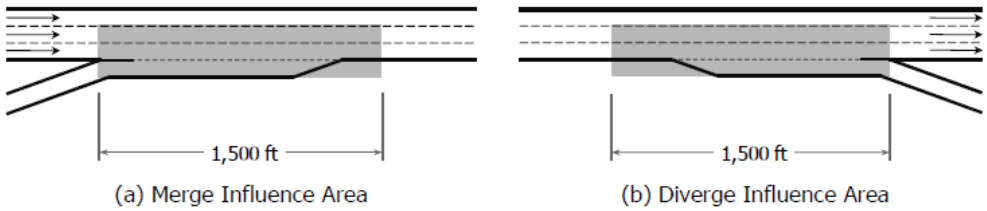


Figure 2.2. Merge and diverge influencing area.

The HCM2010 analysis procedure for on-ramp junctions and off-ramp junctions essentially consists of the following steps:

(1) Estimate the demand flow rate immediately upstream of the merge or diverge influence area in the two rightmost lanes on the freeway;

(2) Estimate the capacity of the merge or diverge area and compare the capacity with the demand flow rates (including the demand flow rate from the on-ramp);

(3) If the total demand flow rate is greater than capacity, LOS F is assigned; otherwise, estimate the density within the merge influence area and converting it into LOS. Table 2.2 Lists HCM2010 LOS criteria for on-ramp junctions and off-ramp junctions.

Table 2.2. level of service criteria for on-ramp and off-ramp junctions.

LOS	Density (pc/mi/ln)	Comments
A	≤ 10	Unrestricted operations
B	>10-20	Merging and diverging maneuvers noticeable to drivers
C	>20-28	Influence area speeds begin to decline
D	>28-35	Influence area turbulence becomes intrusive
E	>35	Turbulence felt by virtually all drivers
F	Demand>Capacity	Ramp and freeway queues form

2.2 Current Status of Study on Auxiliary Lanes

2.2.1 Operational Studies

In light to the Bottleneck Removal Projects in Texas, Walters et al. (2002; 2005) summarized and evaluated the effects of relatively small geometric and operational improvements at freeway bottleneck 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 2.3.

Table 2.3. Crash summaries, benefits, costs, and impacts of auxiliary lane implementation in Texas.

TxDOT district	Freeways	Description of bottleneck improvement	Crash Rate Change (per 100 MVMT)	Safety Benefit (% change)	Annual Benefit (in Millions)	Cost	Benefit /Cost	Impacts
Fort Worth	NB SH360 @ Division (SH180)	Converted outside shoulder to auxiliary lane between two closely spaced exit ramps	SH360 (NB) - 72.8 to 17.7	NB (+76%)	$0.2	$150K	10:1	Increased volumes and speeds, improve safety
Dallas	NB IH35E, IH30 to Dallas North Tollway	Addition of two auxiliary lanes by inside shoulder conversion	IH35E (NB) - 112.1 to 72.2	NB (+36%)	$0.6	$130K	37:1	Increased volumes, improved safety
El Paso	EB IH10 @ US54	Re-striped one lane ramp to two lanes, dropped main lane at exit, added lane back at entrance, added auxiliary lane	US54 (SB) - 61.9 to 28.4 IH10 (EB) - 51.7 to 48.7	SB (+54%) EB(+6%)	$1.3	$530K	20:1	Increased volumes and speeds, improve safety
Fort Worth	SB SH360 to WB IH20	Auxiliary lanes on SH360, dropped main lane on IH20 at SH360 exit, added lane back at SH360 entrance	SH360 (SB) - 65.9 to 30.3 IH20 (WB) - 35.9 to 34.1	SB (+54%) WB (+5%)	$0.03	$8K	32:1	Improved speeds, volumes, and safety
Fort Worth	SB SH360 @ Division (SH180)	Closed entrance ramp, forcing traffic through signal, added auxiliary lane to next entrance	SH360 (SB) - 48.6 to 16.2	SB (+67%)	$1.0	$440K	18:1	Reduced congestion, improved speeds,

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

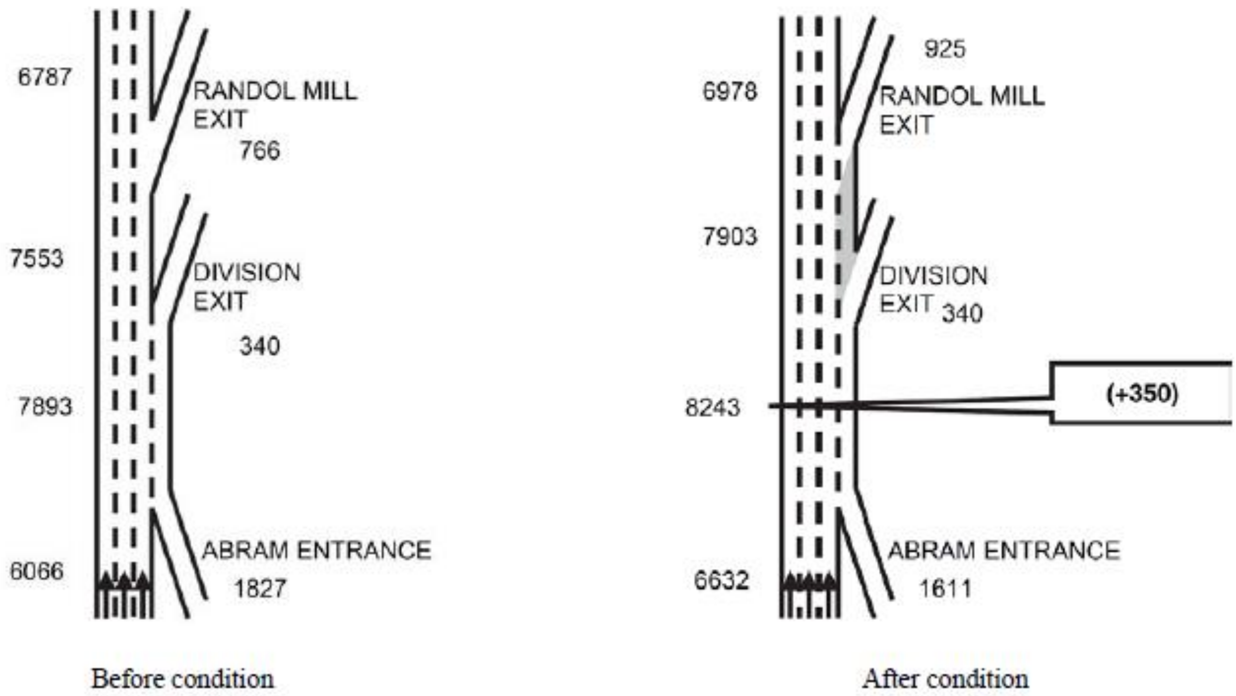


Figure 2.3. Northbound SH 360 at Division (SH 180): (a) before and (b) after study lane layout and volumes. (Source: Walters et al., 2005)

As one of the representative case studies that are associated with the use of auxiliary lanes, Figure 2.3 shows the layout in the before and after case, along with morning peak-hour volumes for Northbound SH 360 at Division (SH 180). TxDOT elected to extend the auxiliary lane to the Randol Mill exit (700 ft).

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 benefits of $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, it was found that an injury crash reduction of 76% 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.

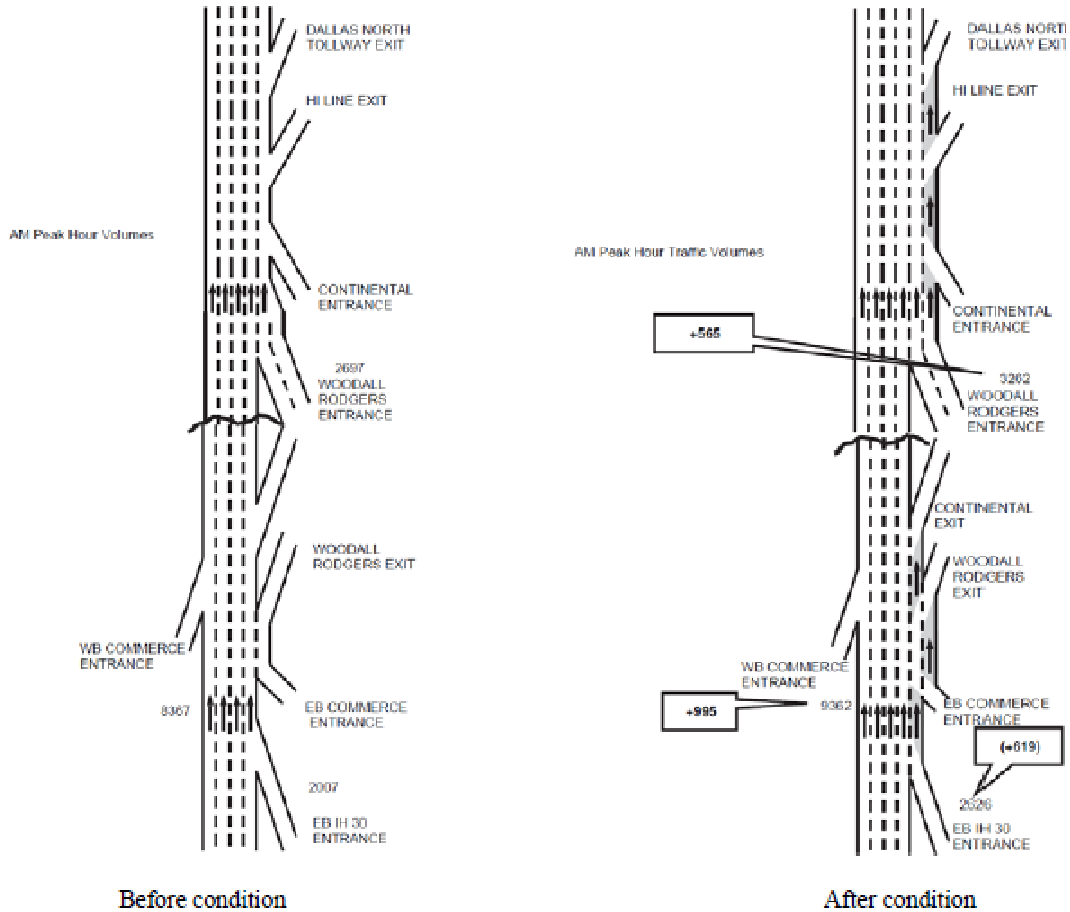


Figure 2.4. Northbound Interstate 35E, Interstate 30 to Dallas North tollway exit: (a) before and (b) after study lane layout and volumes. (Source: Walters et al., 2005)

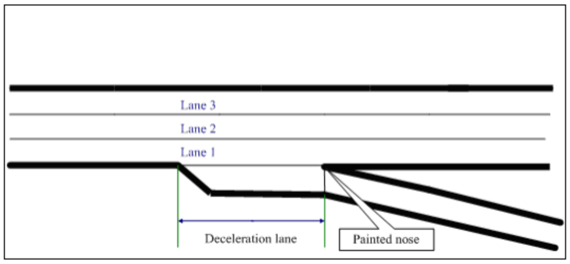
As another of the representative case studies regarding this project, Figure 2.4 shows the layout in the before and after case, along with morning peak-hour volumes for northbound Interstate 35E, Interstate 30 to Dallas North toll way exit. The calculated total annual benefits in delay reduction of $600,000, 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 two years before and two years after the improvement and found a reduction of 36% in the injury crash rate.

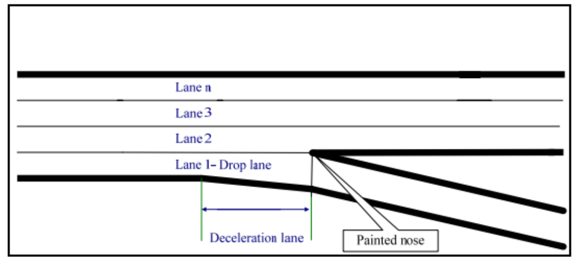
The findings underlined that, in addition to the auxiliary lanes designed specifically between an entrance and an exit ramp, providing extended auxiliary lanes between successive exit ramps or between successive entrance ramps can bring very positive operational and safety impacts.

Based on field data collected from Higashi-Meihan Expressway, Japan, Sate et al. (2011) found that, in presence of continuous auxiliary lanes at weaving segments, the average breakdown flow at the inbound bottleneck increased by 6% (190 vph) and at the outbound bottleneck increased by 3% (100 vph). The total delay was reduced by 24% in the inbound direction, 62% in the outbound direction, and on average 33% in both directions, reducing the total delay caused by traffic congestion at the weaving segments.

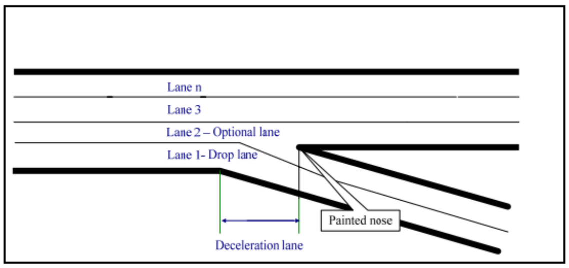
Neudirff et al. (2003) stated that there are a number of parameters of particular importance to the operation of ramp-freeway junctions. The length of the acceleration or deceleration lane has a significant effect on merging and diverging operations. The free-flow speed of the mainline freeway is also an influential factor.

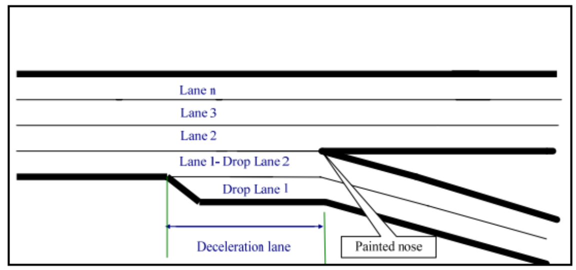
Lu et al. (2009) presented simulation results and mathematical models to evaluate operational performance of various types of exit ramps, see Figure 2.5. The four types of exit ramps were compared in terms of various measures of effectiveness (MOEs) in Table 2.4. The results showed that, in terms of number of lane change, Type I has the best performance; in terms of standard deviation of speed, Type IV has the best performance, while in terms of control delay per vehicle, Type II has the best performance.





(a) Type I Parallel and single-lane exit (b) Type II Single-lane exit without a taper





(c)Type III Two-lane exit and optional lane (d) Type IV Two-lane exit without optional lane

Figure 2.5. Four types of exit ramp.

Table 2.4. Comparison of exit ramp types in terms of various MOEs.

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

Based on loop-detector data for a segment on southbound Interstate 5 in Orange County, California, Cassidy et al (2002) 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 is 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 queues were confined to the right-

most exit lane, non-exiting drivers reduced their speeds upon seeing these queues and this diminished flows in all lanes. It is 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 over-saturated 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), 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.

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 one-lane exit ramp provides the best traffic operations, regardless of the weaving length, as opposed to 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 is reduced significantly whenever queues occupied or spilled over from the parallel exit ramp.

2.2.2 Safety Studies

Three types of freeway and ramp arrangement with closely spaced entrance and exit ramps were compared by Liu et al. (2010). As shown in the Figure 2.6, they are Type A – freeway segment without auxiliary lane between paired entrance and exit ramps, Type B – freeway segment with a continuous auxiliary lane which connects entrance and exit ramps and is dropped in a two-lane exit, and Type C – freeway segment with a continuous auxiliary lane which connects entrance and exit ramps and is dropped in a one-lane exit.

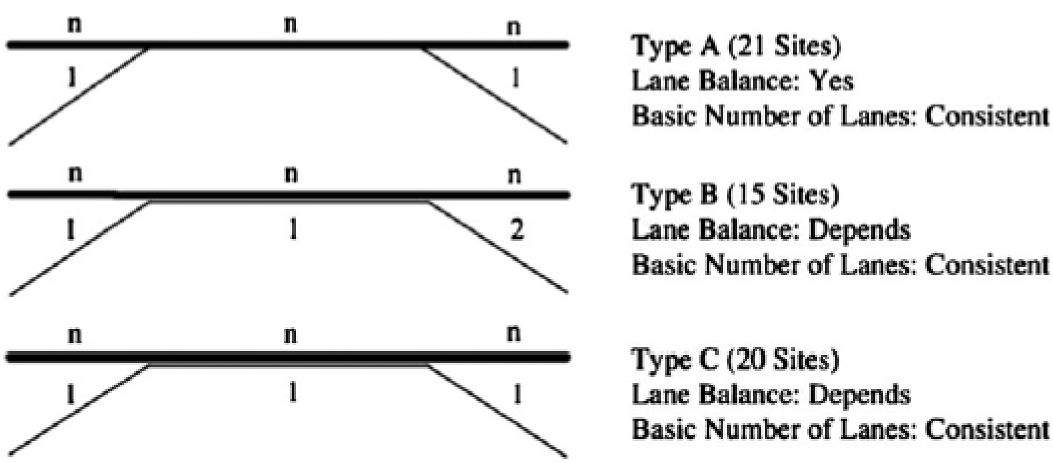


Figure 2.6. Types of freeway and ramp arrangement evaluated in Liu et al. (2010).

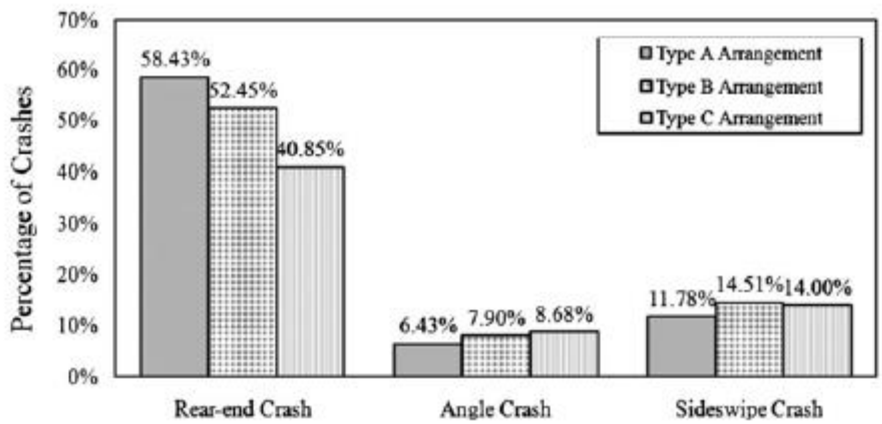


Figure 2.7. Comparison of crash type evaluated in Liu et al. (2010).

Historical crash data showed that among the three arrangements, Type C arrangement had the lowest average crash frequency and crash rate. 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. According to Kuhn et al. (2007), 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.

Mergia (2010) identified factors that affect crash injury severity and to understand how these factors affect injury severity. Candidate factors were categorized into e.g. 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 arrangement) and diverge influence areas (six types of lane arrangement) were used for developing the model. A generalized ordinal logit model and partial

proportional odds model was 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 study included:

- The use of continuous auxiliary lane 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.

In Florida, a total of 424 sample sites were collected for freeway diverge influence areas, including 220 sites for Type I exit ramps, 96 sites for Type II exit ramps, 77 sites for Type III exit ramps, 31 sites for Type IV exit ramps as shown in Figure 2.5 (Lu et al., 2009).The results showed that Type I exit ramp has the best safety performance in term of the lowest crash frequency and crash rate on freeway diverge influence areas. However, statistical tests show that crash severity and crash types did not have significant differences among the four types at 90% confidence level.

A predictive model was built. The coefficients of the model show that the crash counts at freeway diverge influence areas increase with the number of mainline lanes, the deceleration lane length, mainline ADT, ramp ADT and posted speed limit difference between mainline sections and ramp sections, however, decrease with the entire ramp length, and posted speed limit on mainline sections.

The model also quantifies the impacts of the different exit ramp types on crash counts. For one-lane freeway exit ramp, replacing a Type I exit ramp with a Type II exit ramp will increase crash counts at freeway diverge influence area by 15.57%. For two-lane exit ramp, replacing a Type III ramp with a Type IV ramp will increase crash counts at freeway areas by 10.80%.

The safety performances of freeway at merge and diverge influence areas is generally affected by a large number of factors that influence driver behavior in such areas. Sarhan et al. (2008) 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.

Some important findings 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.
- The number of collisions will decrease with increasing length of speed-change lane.

The datasets analyzed by Glad et al. (2001) 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.

Le (2009) studied a typical lane arrangement in the presence of continuous auxiliary lanes between an entrance ramp and a one-lane exit ramp. Two surrogate safety measures, including deceleration rate and crash potential index, were formulated and used as safety indicators.

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 author stated that even with its current limitation, this technique can be used to evaluate safety performances of different designs of weaving sections.

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

Continuous auxiliary lane connecting an entrance ramp and a one-lane exit ramp

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.

Continuous auxiliary lane connecting an entrance ramp and a two-lane exit ramp

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.

Parallel exit ramp at an isolated diverge influence area

One-lane parallel exit ramp are associated with the lower average crash frequency and crash rate compared to one-lane taper exit ramp. On the other hand, for two-lane exit ramp, taper exit ramps are safer than parallel exit ramp (Lu et al., 2009).

Contributing factors

The factors that have been identified by previous studies as significant influencing factors to the safety included: number of mainline lanes, deceleration lane length, mainline Average Daily Traffic (ADT), ramp ADT, posted speed limit differential between the mainline and ramp, and the entire ramp length.

2.3 Engineer Survey

A recent survey was conducted as part of a Texas Department of Transportation (TxDOT) project on engineers in the U.S. to identify current guidelines, performance measures, tools/software, design conditions, and impacts of auxiliary lanes. The survey was developed through a website, Surveymonkey, from November 9, 2011 to December 15, 2011. It is distributed to engineers nationwide.

A total of 59 unique responses were received. Of those, 26 were from 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. If the number of respondent is more than one, the number is included in a bracket:

- 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)

2.3.1 Design Manuals in Use

Question 1: Do you use any manual when designing auxiliary lanes? (you may select more than one answer from the list, and specify any other manuals not listed)

In this question, respondents were asked to select any manual they were using in the design of auxiliary lanes. The respondent can select from 6 listed national manuals, which are American Association of State Highway and Transportation Officials (AASHTO) 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 (MUTCD) 2006 and 2009 editions (FHWA 2004, 2009), Highway Capacity Manual (HCM) 2000 and 2010 editions (TRB 2000, 2010), and specify all others manuals they are using. The number of respondents for this question was 50.

Listed National Manuals

As shown in Figure 2.8, the majority of respondents in both Texas and other states selected AASHTO A Policy for Geometric Design of Highways and Streets 2004 edition (AASHTO2004), followed by HCM2010, MUTCD 2009 edition (MUTCD2009) and HCM 2000 edition (HCM2000). The AASHTO A Policy for Geometric Design of Highways and Streets 2011 edition (AASHTO2011), as a newly available manual, has not been widely used. The MUTCD 2006 edition (MUCTD2006) appeared to have been superseded by MUTCD2009.

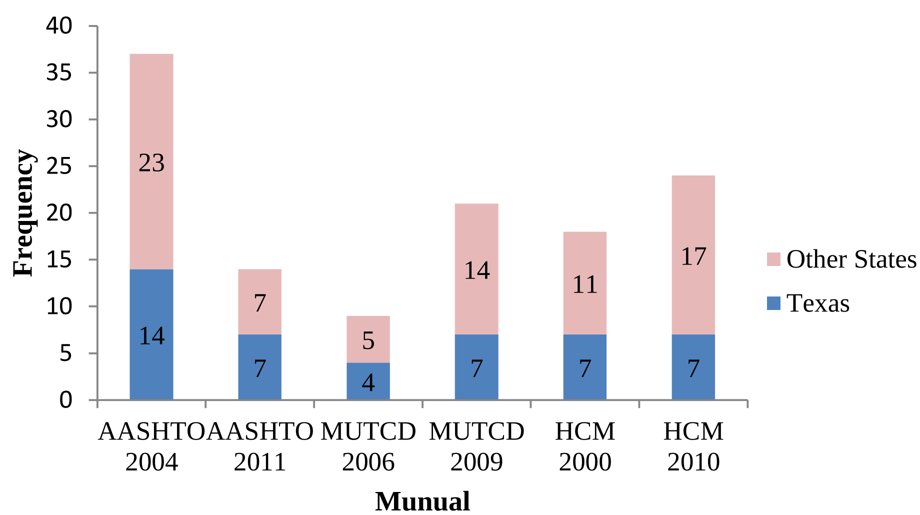


Figure 2.8. Current manuals.

Other Manuals

For Texas respondents, the only manual they specified is the TxDOT Roadway Design Manual. For other states respondents, several manuals were specified, as listed in Table 2.5. These states appear to have their own manuals that are modified from or to supplement the national manuals.

Table 2.5. Manuals used in other states

States	Other design manuals
Arizona	MUTCD 2003 Edition and Arizona Supplement to the 2003 MUTCD; Expect to adopt MUTCD 2009 in January 2012.
Arkansas	AASHTO 2011 Green Book as soon as it is received.
Illinois	IDOT's Bureau of Design & Environment's Design Manual (for policy issues) and AASHTO 2004 Green Book.
Kentucky	KYTC Design Guidance Manual and Design Memo
Maine	MaineDOT Highway Design Guide
Michigan	Michigan DOT Geometric Design
Ohio	ODOT Location and Design Manual, Vol. 1.
Oregon	Oregon Highway Design Manual
Washington	WSDOT Design Manual

2.3.2 Performance Measures

Question 2: What are the performance measures you are using to measure the quality of service at weaving segments and on-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 on-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 2.9, 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 measures.

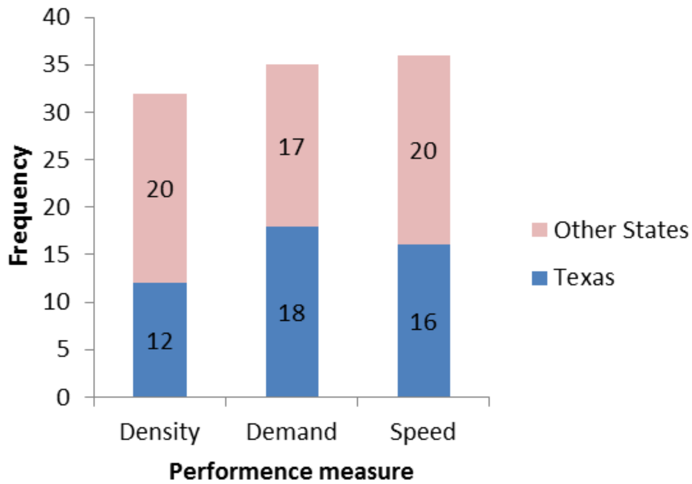


Figure 2.9. Performance measures.

Table 2.6 lists the other performance measures used in Texas and other states.

Table 2.6. Other performance measures.

State	**Other performance measures**
Texas	LOS
Nebraska	LOS (as in HCM2010)
Pennsylvania	Volume/capacity ratio, LOS, Delay
Washington	Travel time, throughput of downstream lanes

2.3.3 Tools and Software

Question 3: What tools and/or software are you using to determine the level of service at weaving segments and on-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 on-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.

For modeling operational impacts, several tools have been frequently listed. They are: HCS, VISSIM, CORSIM, Microstation, GeoPak, Synchro, VISSUM, Paramitics, TransModeller, and FREEVAL. Figure 2.10 shows the frequency count of these tools. As shown in Figure 2.10, the most commonly used software/tools for modeling operational impacts are HCS, VISSIM and CORSIM.

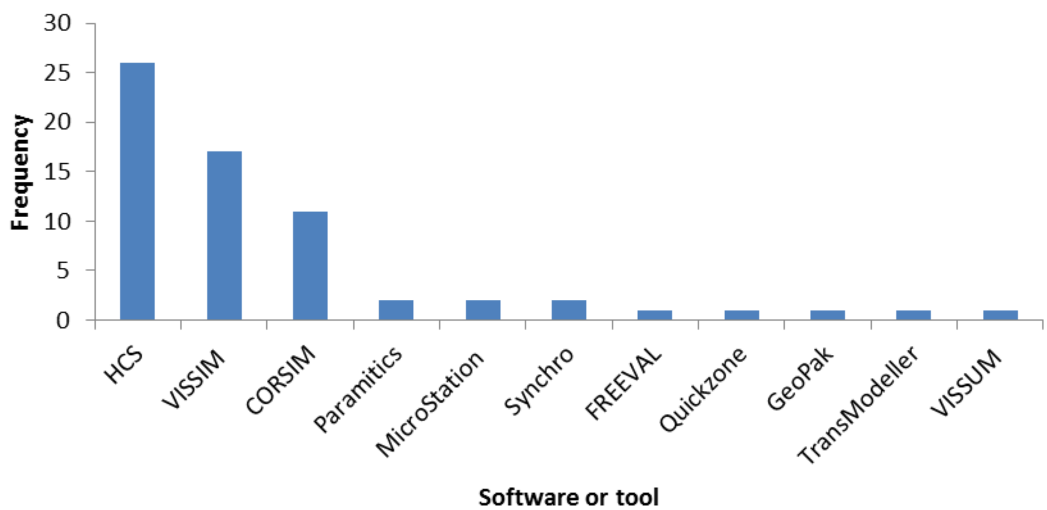


Figure 2.10. Software and tools.

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 author'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 SSAM, and Safety Analyst.

2.3.4 Design Conditions

Question 4: 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 to 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.

Based on the responses, it can be concluded that auxiliary lanes are considered under following conditions:

- When the entrance or exit ramp has high percentage of trucks; or
- When the entrance or exit ramp has high volumes; or
- When the traffic density is high; or
- When the on and off ramps are very close (e.g., less than 1000 ft); or
- If there is safety or operational issues; or
- 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 design and should be considered on all divided highway design. Another respondent (from Kansas) stated that they 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 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; and
- Availability of gaps for merging.

2.3.5 Impacts of Auxiliary Lanes

Question 5: What do you think auxiliary lanes can positively or negatively impact the operations, safety, or other aspects at weaving segments, on-ramp and/or off ramp junctions?

This is 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.

Of the 33 respondents, 23 respondents indicated that auxiliary lanes can positively impact the operations, and/or safety at weaving segments, on-ramp and/or off ramp junctions. The remaining 10 respondents thought that the impacts are depending on the length of the auxiliary lanes.

Of the 23 respondents indicating positive impacts, seven respondents said that auxiliary lane has operational benefit; three respondents think it has safety benefits, while 7 respondents cited that it has both operational and safety benefits. There were six respondents who mentioned positive impacts, but did not specify whether they were operational or safety benefits.

According to the respondents, the positive operational impacts are because auxiliary lanes provide more space for vehicles to maneuver resulting in easier merging and land changing. This contributes to gradual speed change which leads to a reduction of traffic conflicts.

Of the 10 respondents with controversial opinions about auxiliary lanes, they think that the impacts of auxiliary lanes are depending on the length. If the auxiliary lane is too short, it can become an issue especially for older drivers, and it might also create weaving conflicts. However, if the auxiliary lane is too long, drivers may think it is a new freeway lane or they cannot see where the lane begins and ends, it can have negative impacts on their vehicle maneuvers.

2.4 Chapter Summary

Based on literature review and engineer survey, it can be concluded that: for existing guidelines, AASHTO is the most popular guidelines in use, and only a few states have their own guideline manuals. AASHTO and states guidebooks have only some qualitative guidelines and some spacing based quantitative guidelines on the implementation of auxiliary lanes at freeway weaving segments. There are no guidelines on implementation of auxiliary lane at on-ramp and off-ramp junctions. In addition, detailed geometric conditions and traffic volumes needed to be incorporated in the guidelines.

For traffic operation, previous studies focused on 1) conducting case studies to quantify the operational benefits of adding auxiliary lanes at corridor level and at isolated weaving segments; 2) identifying influencing factors for merge and diverge area, such as acceleration/deceleration lane length, freeway speed, and exit type. The results showed that auxiliary lanes mostly have positive impacts on traffic operation. In the engineer survey, most

respondents agreed on those positive impacts. However, a few respondents stated that, if weaving length is too short or too long, there might be negative impacts.

The limitations in the previous studies include:

- There are no studies to quantify the operational benefits of adding auxiliary lanes at freeway on-ramps and off-ramps, and for weaving segments, the operational benefits are only quantified at some case studies.
- More influencing factors need to be identified, and their effects quantified for weaving segments, on-ramp and off-ramp junctions.
- The influence of auxiliary lane in the upstream and downstream of a weaving segment has not been studied yet.

For safety impact, previous studies focused on 1) before and after crash rate and crash severity comparison at freeway weaving segments, 2) identification of factors that affect crash rate and severity. The results showed that after adding auxiliary lanes at freeway weaving segments, there is no significant improvement in crash rate. In addition, the crash severity became worse. The engineer survey also show when weaving length is too short or too long, may have safety concerns. There is no study that compares the crash rate and severity before and after adding auxiliary lanes at freeway on-ramp and off-ramp junctions.

To sum up, previous studies are not extensive enough to contribute to a better understanding of the operational and safety impacts of auxiliary lanes. Therefore, the objective of this research is to

- Assess the operational and safety impacts of auxiliary lanes at freeway weaving segments, on-ramp and off-ramp junctions.
- Identify the design factors and quantify their operational and safety impacts.

Develop detailed implementation, design, and assessment guidelines for auxiliary lanes based on the study results.

Chapter 3

Research Methodology

3.1 Types of Analyses Conducted in this Study

To achieve the research objective, five analyses were conducted:

- *Analysis (1): Operational analysis of weaving segment*

This analysis will be conducted to evaluate the operational impacts of auxiliary lanes at weaving segment. At first, this analysis will quantify the operational benefits of adding auxiliary lanes at FWSs under different combinations of traffic volume and geometric configurations, and then develop design recommendations on when to add auxiliary lanes at FWSs.

- *Analysis (2): Operational analysis of on-ramp junction*

This analysis will be conducted to evaluate the operational impacts of auxliary lanes at isolated on-ramp junctions. At first, this analysis will compare the operational performance of isolated freeway on-ramp junctions with and without an auxiliary lane. From this comparison, the operational benefits of installing auxiliary lanes at isolated freeway on-ramp junctions can be quantified; and then this analysis will evaluate the operational performance of on-ramp junctions with different geometry (e.g., number of lanes, length of auxiliary lane) and traffic volumes (e.g., freeway and ramp volumes). Based on the operational performance in the design scenarios, recommendations on the conditions under which auxiliary lane should be included in the on-ramp junction design, and the length of auxiliary lane will be developed, with anticipated improvement in traffic operations.

- *Analysis (3): Operational analysis of off-ramp junction*

This analysis will be conducted to evaluate the operational impacts of auxiliary lanes at isolated off-ramp junctions. This analysis will evaluate the operational performance of isolated

freeway off-ramp junctions with different design scenarios which consider different length of auxiliary lane and traffic demand (e.g., freeway and ramp volumes). Based on the operational performance in the design scenarios, recommendations on the conditions under which auxiliary lane should be included in the off-ramp junction design, together with the length of auxiliary lane will be developed, with anticipated before-and-after improvement in traffic operations.

- *Analysis (4): Safety analysis of on-ramp junction*

This analysis will be conducted to evaluate the safety impacts of auxiliary lanes at isolated freeway on-ramp junctions. At first, the safety performance of freeway on-ramp junctions with auxliary lanes are compared with freeway on-ramp junctions without an auxiliary lane using three safety indicators: crash rate, crash severity and major crash types. Secondly, regression models are developed to relate crash frequency with geometric and traffic factors, using data from sites with auxiliary lanes.

- *Analysis (5): Analysis on upstream/downstream influencing areas of weaving segment*

This analysis will be conducted to evaluate the operational impacts of auxiliary lanes at upstream and downstream of a FWS. At first, the influencing area upstream and downstream of FWSs under different combination of traffic volume and geometric configurations with and without auxiliary lanes will be identified and compared, and then equations will be developed to predict the length of influencing area with and without auxiliary lanes.

Note that, safety analysis at weaving segments has already been conducted in previous studies, and for off-ramp junctions, there are few isolated off-ramp locations with auxiliary lanes found in Texas. Therefore, only safety analysis at on-ramp junctions is conducted in this study.

3.2 Methodologies for Each Analysis

For each analysis, the methodology are introduced as follow,

3.2.1 Methodology for Operational Analysis of Weaving Segments

A recent survey (TxDOT, 2011) has found that the tools commonly used by state transportation engineers for analyzing traffic operations at FWSs are Highway Capacity Software (HCS), VISSIM, and CORSIM. Of which, HCS is the most popular tool. Therefore, this study used the 2010 version of HCS (HCS2010) (McTrans, 2010) to assess the operational impacts of auxiliary lanes at FWSs with and without auxiliary lane.

For FWSs with auxiliary lane, the LOS analysis procedure in the Chapter 12 of HCM2010 were used, which has been developed based on data collected at 14 sites across the U.S. (Roess and Ulerio, 2005a, Roess and Ulerios, 2005b, and Roess et al., 2008). Prior to the application of HCS2010 in this research, field data were collected at three independent FWSs in El Paso, Texas, to validate the HCS2010 calculations.

Table 3.1 lists the three sites, dates and hours selected for data collection. Only these three sites in El Paso met the criteria of having (i) an auxiliary lane; (ii) an L_A not exceeding the maximum length as specified in HCM2010; (iii) lane markings that conform to the latest edition of MUTCD (FHWA, 2009); (iv) at least a traffic surveillance camera with the necessary view for recording the video; and (iv) no proximity any work zone or unusual traffic pattern. All the three sites have one auxiliary lane, a one-lane on-ramp and a one-lane off-ramp. Video recordings of traffic operations at the hours (usually the morning and afternoon peak hours) as listed in Table 3.1 were obtained from TxDOT El Paso District's Transvista Traffic Management Center. The video recordings were replayed in the laboratory for data extraction. For each hour, traffic volumes of the four movements were counted. For each movement, the travel times of approximately 30 vehicles between fixed markers were captured. The movement's space mean speed was then estimated from the sample.

Table 3.1. Data collection for validation.

Freeway	Upstream on-ramp	Downstream off-ramp	L_S (ft)	N	Date	Time
U.S. 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.
U.S. 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.

For each hour of observation, the site geometry, traffic volumes and *FFS* were entered into HCS2010 to predict S. At the same time, the observed S_W and S_{NW} were aggregated to form S, using Equation (2.5). Figure 3.1 plots the S values estimated by HCS2010 against the S values 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 video recordings. The plotted data points in Figure 3.1 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 0.01 level of significance. Therefore, it was concluded that the HCM2010 analysis procedure and the HCS2010 software produced satisfactory estimates of S. The detail of the HCS2010 weaving module input and output interfaces are shown in Appendix A.

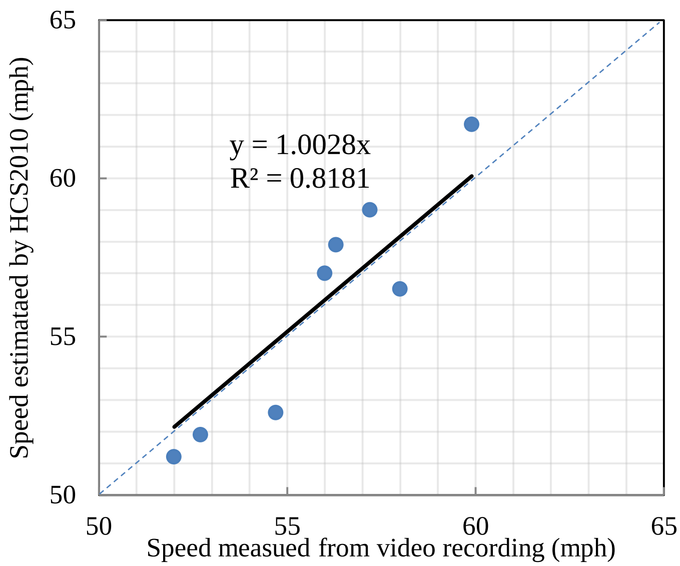


Figure 3.1. Comparison of space mean speeds.

HCM2010 defines a FWS in which vehicles in the freeway-to-ramp movement and ramp-to-freeway movement "cross path" with each other. Therefore, the procedure described in Chapter 12 of HCM2010 cannot be used to analyze a freeway segment between an on-ramp and an off-ramp without an auxiliary lane. For the scenarios without auxliary lanes, the freeway segment was treated as (i) an on-ramp with an adjacent downstream off-ramp and (ii) an off-ramp with an adjacent upstream on-ramp respectively (see Figure 3.2). The densities are computed separately at the on-ramp junction and the off-ramp junction by the ramp module in HCS2010. The detail of the HCS2010 ramp module input and output interfaces are shown in Appendix A. According to HCM2010 (TRB, 2010), whenever a series of ramps on a freeway is analyzed, if the ramp influence areas overlap with each other, the operation in the overlapping region is determined by the ramp having the highest density. Therefore, the higher value among the on-ramp density and off-ramp density was selected to be the density without an auxiliary lane.

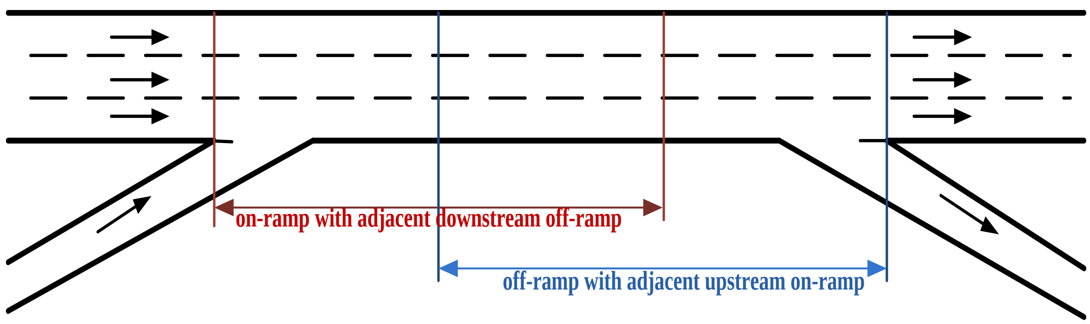


Figure 3.2. Weaving segment without auxiliary lanes.

3.2.2 Methodology for Operational Analysis of On-Ramp Junctions

A recent survey (TxDOT, 2011) among the design engineers in Texas as well as in other state departments of transportation has found that the software tools commonly used by state transportation engineers for analyzing operational impacts of auxiliary lanes are Highway Capacity Software (HCS), VISSIM, and CORSIM. Of which, HCS is the most popular tool. Therefore, this study used the 2010 version of HCS (HCS2010)[7] to assess the operational performance of on-ramp junctions with and without auxiliary lanes.

3.2.3 Methodology for Operational Analysis of Off-Ramp Junctions

A recent survey (TxDOT, 2011) among the design engineers in Texas as well as in other state departments of transportation has found that the software tools commonly used by state transportation engineers for analyzing operational impacts of auxiliary lanes are Highway Capacity Software (HCS), VISSIM, and CORSIM. Of which, HCS is the most popular tool. Therefore, this study used the 2010 version of HCS (HCS2010) to assess the operational performance of off-ramp junctions with and without auxiliary lanes.

3.2.4 Methodology for Safety Analysis of On-Ramp Junctions

This analysis tested the hypothesis that adding an auxiliary lane at on-ramp junctions would improve safety in the merge influencing area. To analyze the safety performance of

freeway on-ramp junctions, the historical crash records from year 2003 through year 2008 (six years) were extracted from Crash Record Information System (CRIS), the official state database for traffic crashes that occurred in Texas, maintained by the Texas Department of Transportation (TxDOT, 2012). ArcGIS 9.2 (ERSI, 2007) was then used to filter the historical crash records at the study sites. The Highway Capacity Manual 2010 (TRB, 2010) specifies an on-ramp junction's operational influence area as the acceleration (auxiliary) lane, lanes 1 and 2 of the freeway (the two right-most lanes) for a distance of 1500 ft downstream from the merge point. At each selected study site, the crash records within the influence area (as marked in Figure 3.4) were selected from the CRIS database. In this dissertation, crashes in all the freeway lanes were included in this analysis because the CRIS database did not provide information on the lane number in which a crash occurred. Therefore, it was impossible to filter out the crashes that occurred in the two rightmost lanes of the freeway and in the auxiliary lane, if any.

To select appropriate crash records from the database, a buffer covering the 1500 ft freeway segment at each site was created in a ArcGIS layer. Crash records with the name of the highway, latitude, longitude, and travel direction that met the selection criteria were extracted. In the CRIS database, the crash related information (including latitude and longitude, crash type, crash severity) is recorded in a file named *crash.cris* while the vehicle related information (including the vehicle's travel direction) is archived in a file named *vehicle.cris*. Information related to the same crash is identified by a common attribute in these two files named *Crash_Number*. Microsoft Access was used to combine information from these two files into a single record. Crashes that were attributed to Driving Under Influence (DUI) were excluded next.

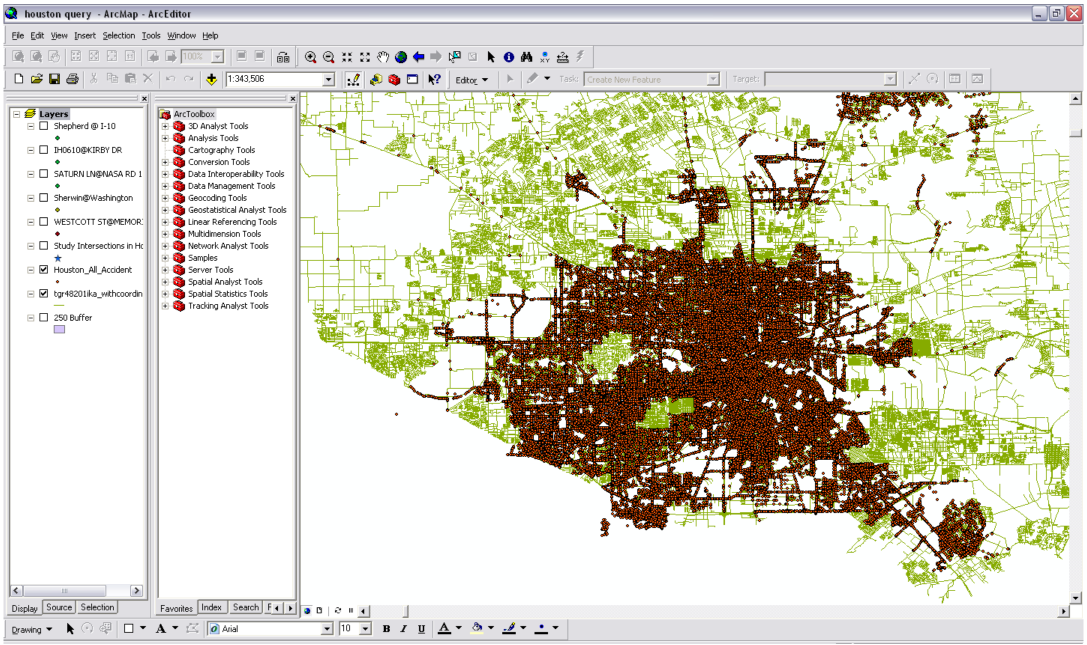


Figure 3.3. Identify crashes with ArcGIS.

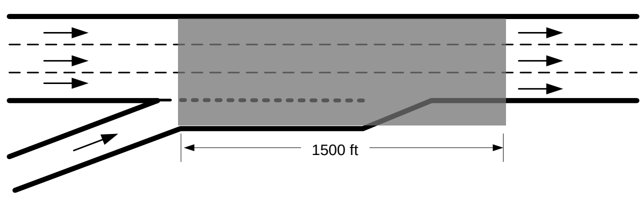


Figure 3.4. Influence area at freeway on-ramp junction.

3.2.5 Methodology for Analysis of Upstream/Downstream Influencing Areas of Weaving Segment

- *Definition of influencing area*

To define the influencing area upstream and downstream of a weaving segment, a survey was conducted among 104 drivers with the following question:

You are driving on a freeway, e.g., I-10, in your normal speed, e.g., 65 mph. You are following the traffic (that is, going with the flow). Then, without paying attention to the speedometer, you "feel" that the traffic has slowed down. You check the speedometer and realize that the speed has decreased by ΔS *mph. How much the speed must slows down in order for you to "feel" it?*

Select only 1 answer:

A: $\Delta S=5$ *mph* *B:* $\Delta S=10$ *mph* *C:* $\Delta S=15$ *mph*

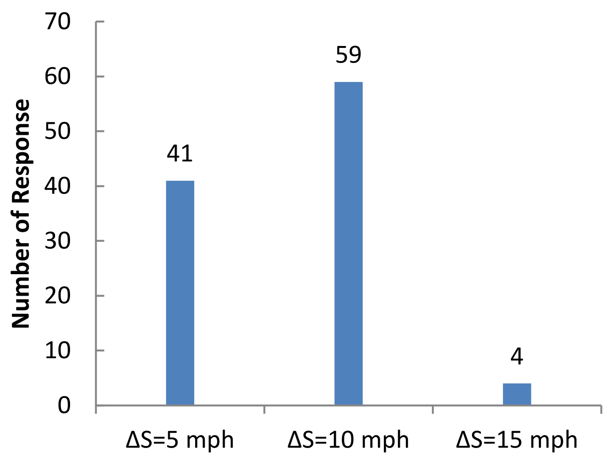


Figure 3.5. Survey response.

As shown in Figure 3.5, almost half of respondents think they could feel the slowdown in traffic when the speed decreases by 5 mph. To give consideration to the most sensitive drivers, influencing area in this study was defined as the area where the speed is decreased by 5 mph or more from the normal operating speed. For the design scenarios in this study, the speed limit at freeway mainline is 65 mph, according to the survey results, the influencing area are defined as the area when the average speed is below 60 mph. In addition, the maximum influence area length is set to be 3000 ft.

- *VISSIM model development and validation*

As HCM2010 does not have an analysis procedure to estimate the upstream or downstream influence area of a FWS, the VISSIM simulation model is used in this analysis. According to (Gomes et al., 2004) and (Hughes et al., 2011), following parameters need to be adjusted before using VISSIM:

1) Waiting time before diffusion, which defines the maximum amount of time a vehicle can wait at the emergence stop position waiting for a gap to change lanes in order to stay on its route.
2) Lane change distance, which defines the distance at which vehicles will begin to attempt to change lanes (e.g. distance of signpost prior to a junction)
3) Following behaviors (CC) Parameter, including CC0, which defines the desired distance between stopped cars, and CC1, headway time, which is the time that a driver wants to keep
4) Temporary Lack of attention, which results to vehicles not react to a preceding vehicle for a certain amount of time
5) Safety distance reduction factor. During lane changes the reduction factor is regarded, which takes effect for the safety distance of the trailing vehicle in the new lane for the decision whether to change lanes or not; the own safety distance during a lane change; and the distance to the leading (slower) lane changing vehicle.

To adjust above parameters, a study site at US54 at Hondo Pass in the City of El Paso, Texas, was selected. Figure 3.6 shows geometric configuration of the study site, and Table 3.2 shows traffic volume collected on Feb 23, 2012.

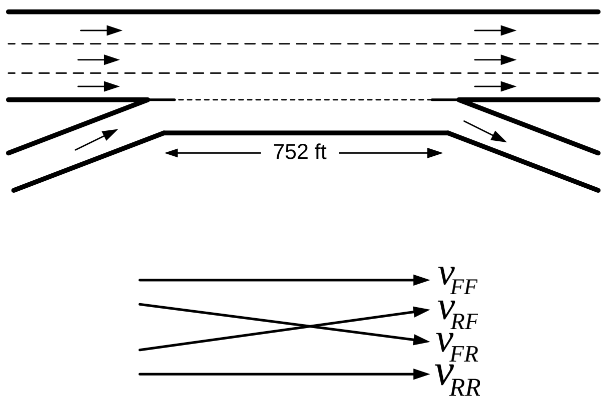


Figure 3.6. U.S. 54 southbound at Hondo Pass.

Table 3.2. Study site traffic volume.

Data Collection Period	v_{FF} (vph)	v_{RF} (vph)	v_{FR} (vph)	v_{RR} (vph)
7 a.m. - 8 a.m. On 02/23/2012	4092	571	259	15

Following observed travel times was selected as the Measures of Effectiveness (MOEs) to adjust the parameters. TT_{FF}: Travel time from freeway upstream to freeway downstream (distance=1050 ft),

- TT_{RF}: Travel time from freeway upstream to off-ramp (distance=1050 ft)
- TT_{FR}: Travel time from on-ramp to freeway downstream (distance=1050 ft)

Table 3.3 shows the average observed values for these MOEs.

Table 3.3. Observed travel times.

Data Collection Period	TT_{FF} (s)	TT_{RF} (s)	TT_{FR} (s)
7am-8am	13.04	13.53	13.23
Sample size	10	10	10

VISSIM model was then developed to simulate the traffic conditions at study site. The site's Google Map image and scale were used as a background to draw the study site geometric configurations in VISSIM (see Figure 3.7). After that, the Google Map image will be deleted, and the travel time collection points will be set up at upstream and downstream of the weaving segment (see Figure 3.8).

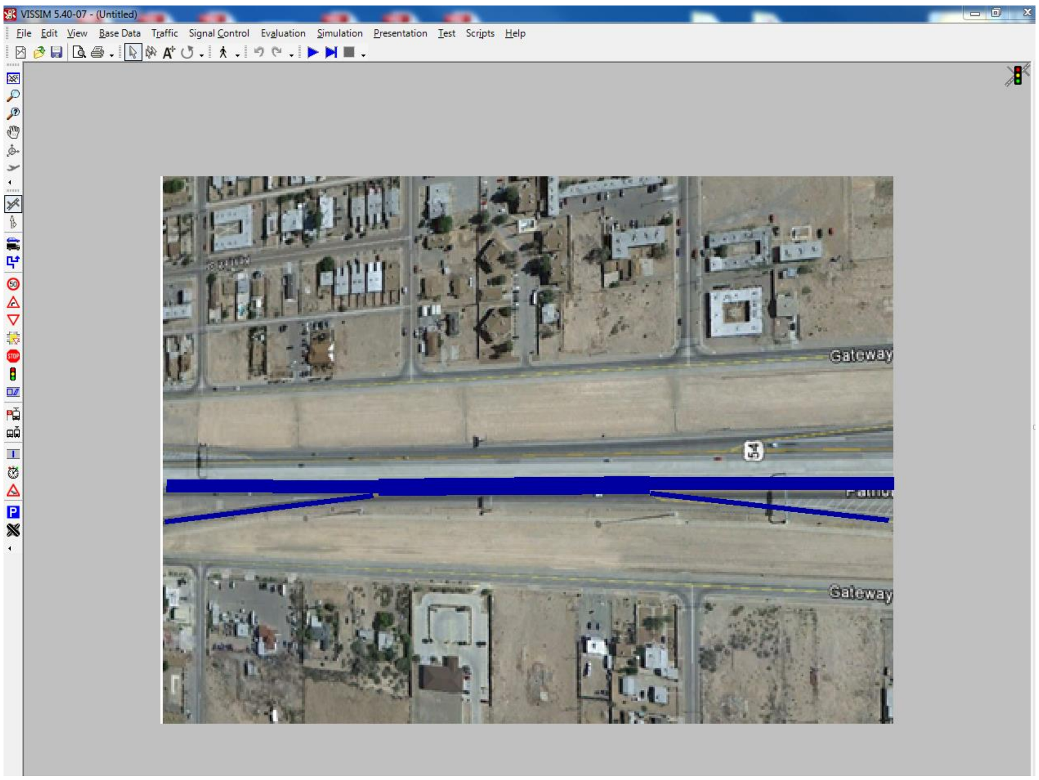


Figure 3.7. Develop study site in VISSIM with Google Map image.

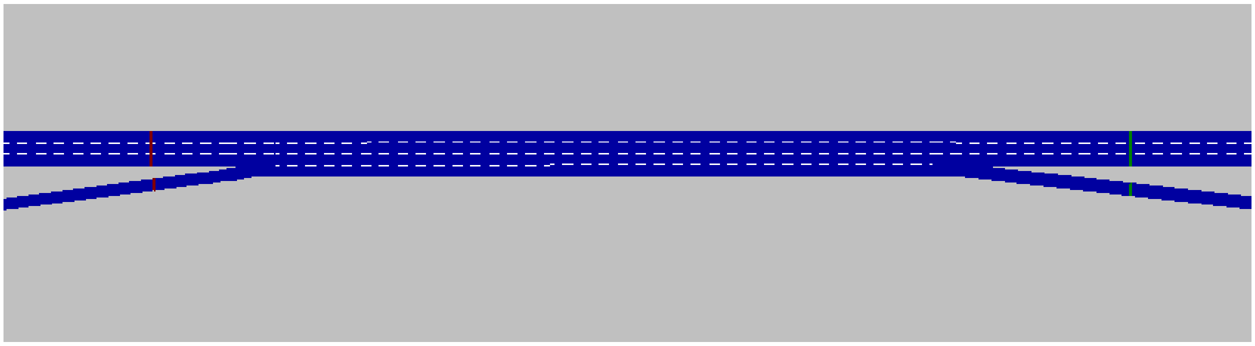


Figure 3.8. Study site configuration in VISSIM.

Following section show the parameter adjusting process, which is a sequential process. The value of one parameter was modified while kept others' constant.

In VISSIM the default parameter setting is:

- Waiting time before diffusion: 60 s
- Lane change distance: 1000ft
- Following behavior (CC) parameters: CC0, 5.0. CC1 0.9
- Temporary lack of attention, 0 second and 0 %
- Safety distance reduction factor: 0.8

1) Adjusted parameter: waiting time before diffusion

Possible values of waiting time before diffusion (*T*): {60s, 1s}

Table 3.4. Waiting time before diffusion.

T (s)	TT_{FF} (s)	TT_{RF} (s)	TT_{FR} (s)
60	26.3	24.7	33.9
1	12.4	14.1	14.4
Observed	13.04	13.53	13.23

Therefore, the waiting time before diffusion is set to be 1 s.

2) Adjusted parameter: lane change distance

- LLD_{FFUP}: lane change distance for the connector connecting freeway to freeway at upstream of the weaving segment,

  Possible values are {500ft, 1000ft, 1500ft, 2000ft, 1/2mile, 1 mile};

- LLD_{FFDOWN}: lane change distance for the connector connecting freeway to freeway at upstream of the weaving segment,

  Possible values are {500ft, 1000ft, 1500ft, 2000ft, 1/2mile, 1 mile};

- LLD_{RF}: lane change distance for the connector connecting on-ramp and freeway,

  Possible values are {500ft, 1000ft, 1500ft, 2000ft, 1/2mile, 1 mile};

- LLD_{FR}: lane change distance for the connector connecting freeway and off-ramp,

  Possible values are {500ft, 1000ft, 1500ft, 2000ft, 1/2mile, 1 mile};

Note that, waiting time before diffusion is 1s, while all other parameters remain at the default values.

LLD_{FFUP}, LLD_{FFDOWN}, *and* LLD_{RF} has no impacts on travel time. Only LLD_{FR} has impacts.

Table 3.5. Lane change distance.

LLD_{FR}	TT_{FF} (s)	TT_{RF} (s)	TT_{FR} (s)
500 ft	12.4	14.1	14.4
1000 ft	11.9	13.8	13.4
1500 ft	11.7	13.6	13.2
2000 ft	11.7	13.6	13.2
2500ft	11.5	13.6	13.1
½ mile	11.5	13.6	13.1
1 mile	11.5	13.6	13.1
Observed	13.04	13.53	13.23

Therefore, LLD_{FFUP}, LLD_{FFDOWN}, *and* LLD_{RF} were set to be 1000ft, and LLD_{FR} was set to be 1 mile, see Table 3.6.

Table 3.6. Lane change distance parameter.

Parameters	Values
LLD_{FFUP}	1000ft
LLD_{FFDOWN}	1000ft
LLD_{RF}	1000ft
LLD_{FR}	1 mile

3) Adjusted parameter: following behaviors (CC) parameter

Possible values for CC0 are: {4.5, 5.0, 5.5}

Possible values for CC1 are: {0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0}. Note that, waiting time before diffusion is 1s, LLD_{FR} is set to be ½ mile, and all other parameters remain at the default values.

It was found that CC0 has no impacts on travel time; however, CC1 has impacts and its effects are shown in Table 3.7.

Table 3.7. Following behaviors parameter.

CC1	TT_{FF} (s)	TT_{RF} (s)	TT_{FR} (s)
0.9	11.5	13.6	13.1
1.0	11.6	13.7	13.1
1.1	11.8	13.8	13.1
1.2	11.9	13.9	13.3
1.3	12.1	13.9	13.4
1.4	12.2	14.1	13.4
1.5	12.6	14.4	13.6
1.6	13.5	15.0	14.2
Observed	13.04	13.53	13.23

Therefore, CC1 is set to be 1.5.

4) Adjusted parameter: temporary lack of attention

Possible values for Duration are: {0, 0.1, 0.2, 0.3, 0.4, 0.5} seconds

Percentage: 10%

Note that, at this stage, the waiting time before diffusion is 1s, LLD_{FR} is set to be ½ mile, CC1 is set to be 1.5, and all other parameters remain at the default values.

Table 3.8. Temporary lack of attention.

Duration	Percentage	TT_{FF} (s)	TT_{RF} (s)	TT_{FR} (s)
0	10%	12.6	14.4	13.6
0.1	10%	12.6	14.4	13.6
0.2	10%	12.7	14.4	13.6
0.3	10%	12.8	14.5	13.6
0.4	10%	12.8	14.5	13.8
0.5	10%	12.7	14.4	13.7
Observed		13.04	13.53	13.23

From Table 3.8, it can be seen that, duration and percentage of the temporary lack of attention have no significant impacts, Therefore, default setting, 0s, 0 percent will be used.

5) Adjusted parameter: safety distance reduction factor

Possible values of safety distance reduction factor: {0.4, 0.5, 0.6, 0.7, 0.8, 0.9}

Note that, waiting time before diffusion is 1s, LLD_{FR} is set to be ½ mile, CC1 is set to be 1.5, and all other parameters remain default.

Table 3.9. Safety distance reduction factor.

Safety distance reduction factor	TT_{FF} (s)	TT_{RF} (s)	TT_{FR} (s)
0.4	12.2	14.1	13.4
0.5	12.5	14.3	13.4
0.6	12.5	14.2	13.4
0.7	12.6	14.3	13.5
0.8	12.6	14.4	13.6
0.9	12.8	14.6	13.9
Observed	13.04	13.53	13.23

Therefore, the safety distance reduction factor was set to 0.6.

The following are the finalized/adjusted parameters:

- Waiting time before diffusion:1 s
- Lane change distance: LLD_{FR} =1 mile
- Following behavior (CC) parameters: CC1=1.5
- Safety distance reduction factor: 0.6

An important aspect in developing the VISSIM model is to measure the lane specific speed at regular longitudinal intervals so as to capture the influence areas. At VISSIM, the upstream and downstream freeway segments were divided as several 100ft sub-segments. The speeds at each sub segments are recorded.

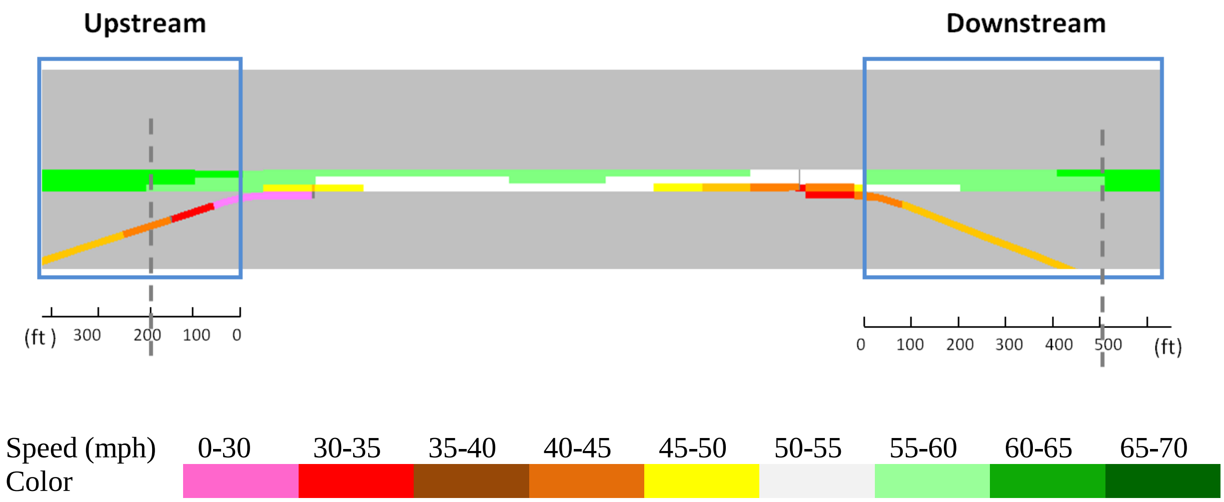


Figure 3.9. Identification of influencing area.

Figure 3.9 shows the speeds for each 100 ft sub-segment at the upstream and downstream of a FWS. The influencing areas can be visually identified in the figure by adding the sub-segments (longitudinally) that has a speed lower than 60 mph. However, since it takes time to visualize the influencing areas in the figure, the influencing areas in this study are actually identified by means of Microsoft Excel. The speeds at all the sub-segment are outputted into an Excel file, then the length of an influencing area are calculated in Excel by adding the sub-segments that has a speed lower than 60 mph. The calculation steps were recorded in an Excel Macro, and then applied to all the simulated scenarios.

Chapter 4

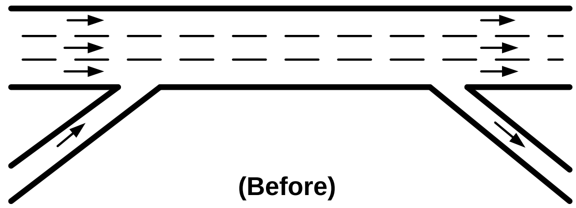
Study Scenarios Designs and Data Collection

In this chapter, the study scenarios and data collection for each analysis mentioned in Chapter 3 are introduced.

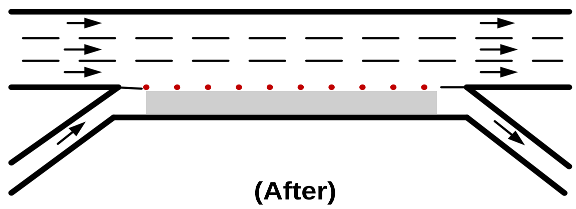
4.1 Study Scenarios for Operational Analysis of Weaving Segment

In this section, the study scenarios under different traffic and geometric conditions at FWSs are described.

Figure 4.1 shows a FWS with three main lanes before and after the addition of an auxiliary lane. A set of 147 scenarios have been designed for the geometric configurations as shown in Figure 4.1(a). Another set of 147 scenarios have also been designed for the geometric configurations as shown in Figure 4.1(b). The comparisons of the HCS2010 outputs between the two sets of design (each with 147 scenarios) permitted the author to determine the operational effects of adding an auxiliary lane at the FWSs.



(a) N_A=0, N_{OFF} =1



(b) N_A=1, N_{OFF} =1

Figure 4.1. Freeway weaving segment before and after the addition of an auxiliary lane.

According to the HCM2010 LOS analysis procedure, and based on site observations (from driving on Texas freeways and observing the designed geometry in Google Earth elsewhere), the following important factors were initially identified in the design of FWSs:

- Number of lanes (main lanes plus auxiliary lane) in the weaving segment, *N*;
- Number of auxiliary lane, N_A;
- 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 ;
- Freeway-to-freeway volume, v_{FF} ;
- Weaving volume (sum of freeway-to-ramp and ramp-to-freeway volumes): v_W ; and
- Ramp-to-ramp volume, v_{RR} .

The above factors were then assigned numerical values based on the following considerations:

- Most of the freeways in urban areas have at least three main lanes. According to a preliminary sensitivity test with HCS2010, when there were three or more main lanes, the number of main lanes has no significant effect on S in the FWSs. Therefore, N was set to 3 without an auxiliary lane and 4 with an auxiliary lane (as depicted in Figure 4.1).
- Almost all the FWSs in Texas have at most one auxiliary lane. Weaving segments with two auxiliary lanes are almost non-existent. Therefore, N_A={0, 1}
- Most of the on-ramps have only one lane that feeds traffic into the freeways. Therefore, N_{ON}=1.
- Most of the off-ramps have one lane. Therefore, N_{Off}=1.
- For L_S, although the minimum distance of 1500 ft is specified in the TxDOT Roadway Design Manual (TxDOT, 2010), sites with shorter L_S have been found. Other states have used up to L_S=2500 ft (TxDOT, 2011). Depending on the traffic volume, the HCM2010 LOS analysis procedure may consider an on-ramp and an off-ramp with L_s>3,000 ft as isolated ramp junctions and so they should be analyzed with another procedure. Therefore, three L_S values have been assigned: L_S={750, 1500, 2250} ft.
- Based on the range of traffic count data collected in the previous section, v_{FF}={500, 750, 1000, 1250, 1500, 1750, 2000} pc/h/ln and v_W={200, 400, 600, 800, 1000, 1200,

1400} pc/h/ln. These values are the design volumes, which can be the projected value for future traffic demand.

- Since very few vehicles entered the on-ramp and exited immediately at the off-ramp (as observed in the data collected in the previous section), v_{RR} was set to 0 pc/h/ln in all the scenarios, i.e, v_{RR} =0 pc/h/ln.

Note that, other factors, such as *FFS* and *ID*, were found to have insignificant impact on the estimated *S*, *D* and LOS. Therefore *FFS* was set to 70 mph and *ID* set to 1 interchange/mi.

4.2 Study Scenarios for Operational Analysis of On-Ramp Junction

In this section, study scenarios under different traffic and geometric conditions at on-ramp junctions are described.

Based on the HCM2010 analysis procedure, the important design factors for isolated freeway on-ramp junctions may be grouped as freeway factors and on-ramp factors. The notations of the factors, if provided, are adopted from HCM2010. Otherwise, they are defined in this section.

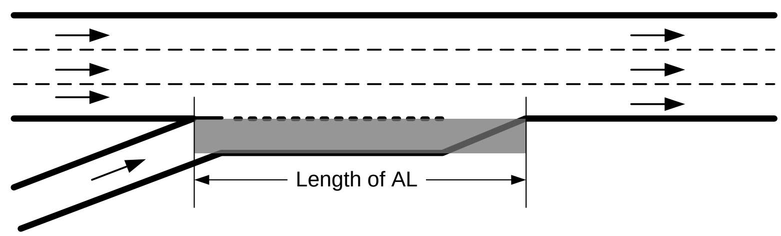
The freeway factors are:

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

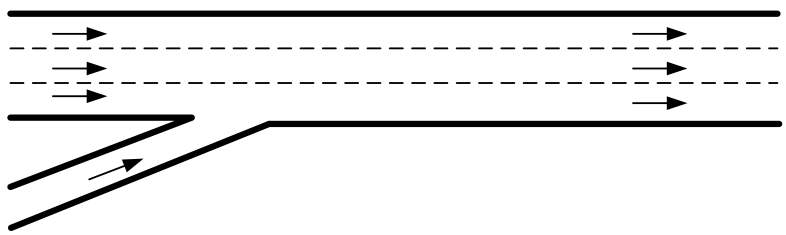
The on-ramp factors are:

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

In the HCM2010 analysis procedure, L_A is measured from the merge point to the downstream end of tapered portion of the ramp (as shown in Figure 4.2(a)).



(a) with auxiliary lane



(b) without auxiliary lane

Figure 4.2. Freeway on-ramp junctions with and without auxiliary lane.

The numerical values assigned to each factor are:

- N_F={2, 3, 4} lanes;
- v_F={500, 750, 1000, 1250, 1500, 1750, 2000} pc/h/ln;
- FFS_F=70 mph;
- N_R=1 lane;
- v_R={100, 200, 300, 400, 500, 600, 700, 800, 900, 1000} pc/h/ln;
- FFS_R=50 mph;
- L_A ={0, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, 1500} ft.

Based on a sensitivity test conducted using HCS2010, FFS_F of 65, 70 and 75 mph did not result in any change in density in the merge influence area. This could be because vehicles are no longer travelling 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 decided that the FFS_F has no significant effect on the traffic operations in the merge influence area at the volumes of interest, and FFS_F of 70 mph (the mid-value) was used for all the design scenarios. Another sensitivity test conducted using HCS2010 on the effect of FFS_R on traffic density in the merge influence area showed that, changing FFS_R did not result in any change in the LOS and density. FFS_F of 50 mph was therefore assumed for all the design scenarios. It is also important to note that L_A =0 ft represents an on-ramp junction without an auxiliary lane. There are 15 values of L_A >0 ft. Although it is highly likely that L_A<500 ft is not practical, these lengths were included in the HCS2010 analysis for completeness. The v_F and v_R values, in pc/h/ln, reflect the peak 15-minute volumes within the peak hour. They are assumed to have been adjusted to account for heavy vehicles and driver population. v_F is the demand volume measured at upstream end of an on-ramp junction. In total, 210 scenarios for on-ramp junctions without an auxiliary lane, and 210*15=3150 scenarios for on-ramp junctions with auxiliary lanes of different lengths have been designed.

4.3 Study Scenario for Operational Analysis of Off-Ramp Junctions

In this section, study scenarios under different traffic and geometric conditions at isolated freeway off-ramp junctions are described.

Based on the HCM2010 analysis procedure, the important design factors for isolated freeway off-ramp junctions may be grouped as freeway factors and off-ramp factors. The

notations of the factors, if provided in HCM2010, are adopted. Otherwise, they are defined in this section.

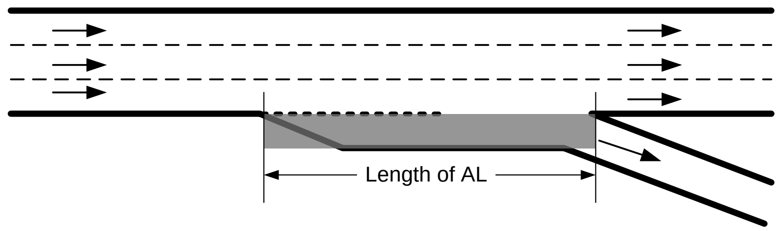
The freeway factors are:

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

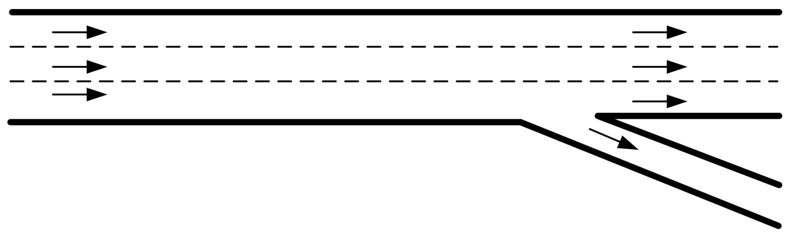
The off-ramp factors are:

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

In the HCM2010 analysis procedure, L_D is measured from the beginning of the taper to the the point where the alignment of ramp roadway begins (as shown in Figure 4.3(a)).



(a) with auxiliary lane



(b) without auxiliary lane

Figure 4.3. Freeway off-ramp junctions with and without auxiliary lane.

The numerical values assigned to each factor are:

- N_F=3 lanes;
- v_F={500, 750, 1000, 1250, 1500, 1750, 2000} pc/h/ln;
- FFS_F=70 mph;
- N_R=1 lane;
- v_R={100, 200, 300, 400, 500, 600, 700, 800, 900, 1000} pc/h/ln;
- FFS_R=50 mph;
- L_D ={0, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, 1500} ft.

N_R was set to 1 lane because the HCM2010 analysis procedure applies to only 1-lane off-ramps. N_F was fixed at 3 lanes. Based on a sensitivity test conducted using HCS2010, FFS_F of 65, 70 and 75 mph did not result in any change in density in the diverge influence area. This could be because vehicles are no longer travelling at the free-flow speed in the diverge influence

area. That is, the average operating speed of the vehicles in the diverge influence area is lower than the free-flow speed. It was therefore decided that the FFS_F has no significant effect on the traffic operations in the diverge influence area at the volumes of interest, and FFS_F of 70 mph (the mid-value) was used for all the design scenarios. Another sensitivity test conducted using HCS2010 on the effect of FFS_R on traffic density in the diverge influence area showed that, changing FFS_R did not result in any change in the LOS and density. Again, this could be because vehicles at the off-ramp are traveling at speeds lower than the free-flow speed, at the volumes of interest. FFS_F of 50 mph was therefore assumed for all the design scenarios. It is also important to note that L_D =0 ft represents an off-ramp without an auxiliary lane. There are 15 values of L_D >0 ft. Although it is highly likely that L_D<500 ft is not practical, these lengths were included in the HCS2010 analysis for completeness. The v_F and v_R values, in pc/h/ln, reflect the peak 15-minute volumes within the peak hour. They are assumed to have been adjusted to account for heavy vehicles and driver population. v_F is the demand volume measured at upstream of an off-ramp junction. In total, 70 scenarios for off-ramps without an auxiliary lane, and 70*15=1050 scenarios for off-ramps with auxiliary lanes of different lengths have been designed.

4.4 Data Collection for Safety Analysis of On-Ramp Junctions

Sixteen on-ramp junctions with auxiliary lanes and 19 on-ramp junctions without auxiliary lane were selected in the City of Fort Worth, Texas, and the City of Houston, Texas, for analysis. The decision of selecting only the sites within Texas was because of the availability of the CRIS database. The locations of these sites are shown in Figures 4.4 and 4.5 respectively. Table 4.1 lists the names and locations of the sites, their geometric characteristics and freeway Average Daily Traffic (ADT). These on-ramp junctions are at least 2500 ft from the nearest on-

ramps and off-ramps. This distance to the nearest ramp junction exceeds the 1500 ft operational influence area as defined by the HCM2010 (TRB, 2010). Sites that met the minimum ramp spacing criterion but at horizontal curves were excluded from the analysis. Note that most of the sites in Houston are without auxiliary lane, while all the sites in Fort Worth are with auxiliary lanes. Furthermore, most of the sites are along the same highways. This could be due to the design practices of the different Texas Department of Transportation districts, and the year in which the freeways were designed.

Figure 4.4. Study sites in City of Fort Worth, TX, for safety analysis of on-ramp junctions (source: Google Earth).

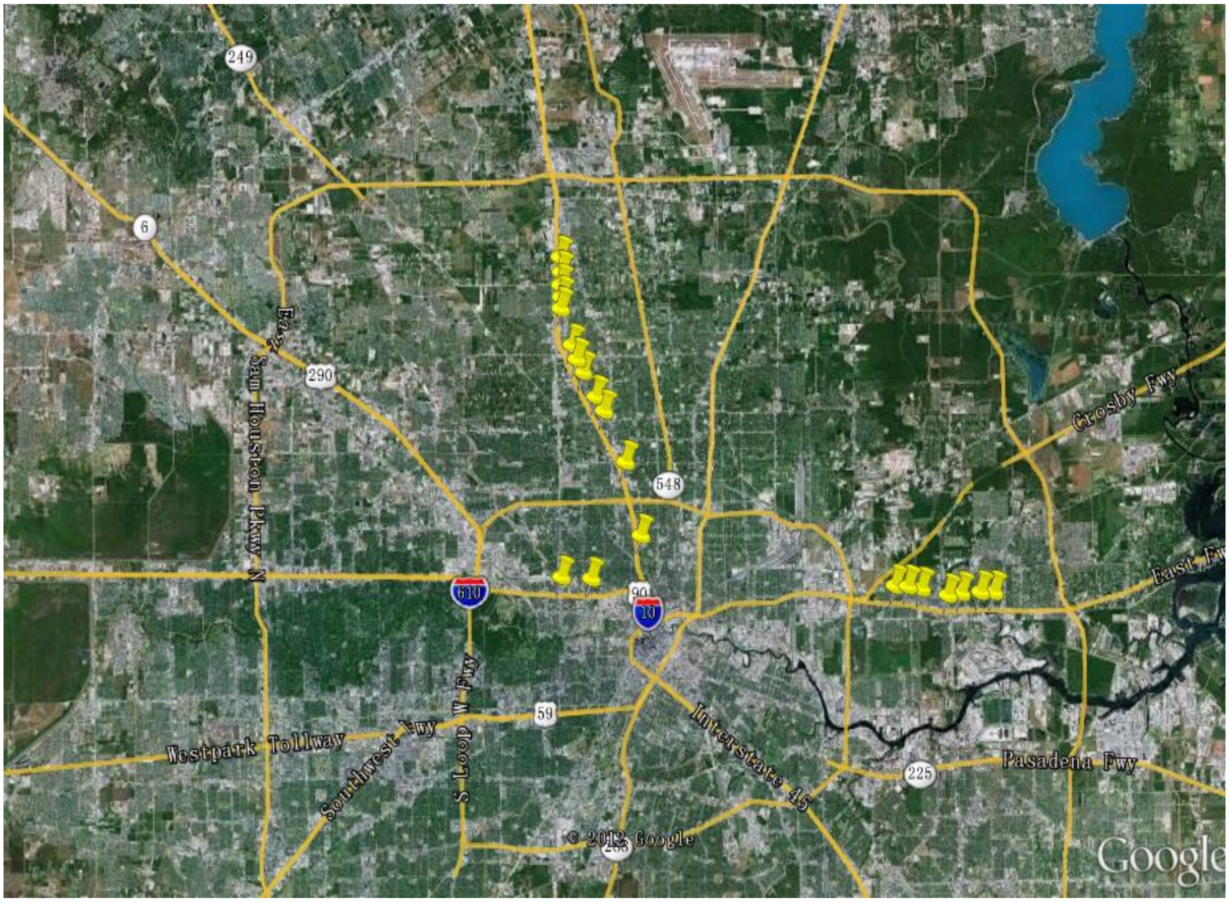


Figure 4.5. Study sites in City of Houston, TX, for safety analysis of on-ramp junctions (source: Google Earth).

Table 4.1. Selected sites for safety analysis of on-ramp junctions.

Site no.	City	Freeway and direction	Off-ramp cross street	No. of auxiliary lane	Length of auxiliary lane, if any (ft)	No. of crashes (2003-2008)	Freeway ADT (veh/day)
1	Houston	I-10 EB	TC Jester Blvd	0	-	36	210120
2	Houston	I-10 WB	Studewood St	0	-	20	210120
3	Houston	I-10 WB	Westshire Dr.	0	-	128	207870
4	Houston	I-10 EB	Akron St	0	-	40	161390
5	Houston	I-10 WB	Centerwood Dr	0	-	63	161390
6	Houston	I-10 EB	Mae Dr	0	-	148	173030
7	Houston	I-10 WB	Normandy St	0	-	90	173030
8	Houston	I-10 EB	Normandy St	0	-	39	173030
9	Houston	I-10 WB	Uvalde Rd	0	-	21	173030
10	Houston	I-45 SB	Blue Bell Rd	0	-	104	263920
11	Houston	I-45 SB	Hidden Valley Dr	0	-	175	268310
12	Houston	I-45 SB	De Walt St	0	-	40	268310
13	Houston	I-45 NB	W Rittenhouse St	0	-	110	268310
14	Houston	I-45 SB	W Rittenhouse St	0	-	115	271470
15	Houston	I-45 NB	Obion Rd	0	-	109	271470
16	Houston	I-45 SB	E Witcher Ln	0	-	97	263410
17	Houston	I-45 NB	E Crosstimbers St	0	-	25	263410
18	Houston	I-45 SB	Riggs Rd	0	-	160	287780
19	Houston	I-45 NB	Monroe Pr 1 Dr	0	-	96	149960
20	Fort Worth	I-35 NB	Timberland Blvd	1	150	5	44870
21	Fort Worth	I-35 NB	Western Center Blvd	1	600	25	111290
22	Fort Worth	I-35 SB	Alliance Gateway Fwy	1	100	7	44870
23	Fort Worth	I-35 NB	Heritage Trace Pkwy	1	330	13	59970
24	Fort Worth	I-35 SB	E Rosedale St	1	400	34	138540
25	Fort Worth	I-35 WB	E Berry St	1	580	16	138540
26	Fort Worth	I-30 EB	Las Vegas Trail	1	280	9	84940
27	Fort Worth	I-30 WB	S Cherry Ln	1	260	15	84940
28	Fort Worth	I-30 EB	Beach St	1	510	6	114000
29	Fort Worth	I-30 WB	Oakland Blvd	1	490	12	114000
30	Fort Worth	I-30 EB	Holt St	1	430	7	100180
31	Fort Worth	I-30 WB	E Loop 820	1	770	2	100180
32	Fort Worth	I-30 WB	Cooks Ln	1	600	6	109250
33	Fort Worth	I-30 EB	Eastchase Pkwy	1	450	18	109250
34	Houston	I-45 NB	W Gulf Bank Rd	1	290	98	263920
35	Houston	I-45 NB	W Mitchell Rd	1	260	137	268310

4.5 Study Scenarios for Analysis on Upstream/Downstream Influencing Areas of Weaving Segments

Similar to Section 4.1, the scenarios for the analysis of upstream and downstream influencing area of weaving segments were designed as follow,

- The Number of lanes at freeway mainline is set to be 3.
- N_A ={0, 1}
- N_{ON} =1.
- Most of the off-ramps in Texas have one lane. Therefore, N_{Off} =1.
- L_S = {500, 1000, 1500, 2000} ft.
- v_{FF} ={500, 750, 1000, 1250, 1500, 1750, 2000} pc/h/ln and v_W ={200, 400, 600, 800, 1000, 1200, 1400} pc/h/ln.
- v_{RR} =0 pc/h/ln.

Note that, other factors, such as *FFS*, were found to have insignificant impact on the estimated *S* and LOS. Therefore *FFS* was set to 65 mph.

Chapter 5

Operational Impacts of Auxiliary Lanes

This chapter assessed the impacts of auxiliary lanes at freeway weaving segment, on-ramp junctions, and off-ramp junctions. The results for weaving segments, on-ramp junctions, and off-ramp junctions are represented separately in section 5.1, 5.2, and 5.3.

5.1 Operational Impact of Auxiliary Lanes at Weaving Segments

There are a total of 147 scenarios for FWSs without auxiliary lanes, and 147 with an auxiliary lane.

5.1.1 Effects of Adding an Auxiliary Lane

This part of the study compared the operational performance of the FWSs before and after the addition of an auxiliary lane under different design scenarios. The performance measure selected was density, since in HCM2010, the LOS of FWSs is directly determined by density.

Table 5.1 visualized the density and LOS with and without auxiliary lanes under different scenarios. Table 5.2 lists the reduction in density and percentage reduction in density.

It can be seen from Table 5.1 that after the addition of an auxiliary lane, there is a reduction in density in every scenario. In addition, the changes in LOS are also compared by using colors codes in Table 5.1. With an auxiliary lane, the LOS all became better or stayed the same. Table 5.2 shows that adding an auxiliary lane can decrease the density in the range of 1.6 to 16.5 pc/mi/ln, or 4% to 50%. The density reduction is greater at shorter weaving segment length, i.e., at L_S=750 ft.

Table 5.1. Comparison of density and LOS with and without auxiliary lanes at weaving segments.

Density in the weaving segment (pc/mi/ln)

Without auxiliary lane

Weaving segment Length	v_{FF} (pc/h/ln)	v_W (pc/h/ln) 200	400	600	800	1000	1200	1400
L_S =750 ft	500	14.0	15.1	16.1	17.0	17.6	18.8	19.9
	750	18.2	19.9	21.4	22.8	23.6	23.6	24.5
	1000	22.1	24.3	26.4	28.3	30.1	30.1	30.1
	1250	25.9	28.3	30.9	33.4	35.8	36.5	36.5
	1500	29.4	32.0	35.1	38.1	41.0	43.0	43.0
	1750	32.8	35.2	38.9	42.5	45.9	49.2	49.4
	2000	35.8	38.1	42.4	46.5	50.4	54.3	55.9
L_S =1500 ft	500	13.8	14.2	14.9	15.7	16.6	17.5	18.5
	750	18.0	18.5	19.4	20.3	21.1	21.8	22.4
	1000	22.1	22.4	23.6	24.7	25.8	26.8	27.7
	1250	25.9	26.0	27.4	28.8	30.1	31.4	32.6
	1500	29.4	29.6	30.8	32.5	34.1	35.7	37.2
	1750	32.8	32.9	33.8	35.8	37.7	39.6	41.3
	2000	35.8	35.9	36.4	38.7	40.9	43.1	45.1
L_S =2250 ft	500	13.8	13.9	14.5	15.4	16.2	17.1	18.0
	750	18.0	18.2	18.7	19.4	20.0	20.7	21.7
	1000	22.1	22.2	22.6	23.5	24.3	25.1	25.9
	1250	25.9	26.0	26.2	27.2	28.3	29.2	30.2
	1500	29.4	29.6	29.7	30.6	31.8	33.0	34.1
	1750	32.8	32.9	33.0	33.5	35.0	36.3	37.7
	2000	35.8	35.9	36.1	36.3	37.7	39.3	40.9

With auxiliary lane

Weaving segment Length	v_{FF} (pc/h/ln)	v_W (pc/h/ln) 200	400	600	800	1000	1200	1400
L_S =750 ft	500	6.9	8.0	9.1	10.3	11.6	12.9	14.2
	750	10.1	11.3	12.6	13.9	15.2	16.7	18.1
	1000	13.4	14.7	16.1	17.5	19.0	20.6	22.2
	1250	16.8	18.3	19.8	21.3	23.0	24.7	26.5
	1500	20.3	21.9	23.5	25.2	27.0	28.9	30.8
	1750	24.0	25.6	27.4	29.3	31.2	33.2	35.4
	2000	27.7	29.5	31.4	33.4	35.6	37.8	40.1
L_S =1500 ft	500	7.0	8.0	9.1	10.2	11.4	12.6	13.8
	750	10.1	11.3	12.5	13.7	15.0	16.4	17.7
	1000	13.4	14.7	16.0	17.4	18.8	20.2	21.8
	1250	16.8	18.2	19.6	21.1	22.7	24.3	25.9
	1500	20.3	21.8	23.4	25.0	26.7	28.5	30.3
	1750	23.9	25.6	27.3	29.0	30.9	32.8	34.8
	2000	27.6	29.4	31.2	33.2	35.2	37.3	39.5
L_S =2250 ft	500	7.0	8.0	9.1	10.2	11.3	12.5	13.7
	750	10.1	11.3	12.5	13.7	14.9	16.2	17.5
	1000	13.4	14.7	16.0	17.3	18.7	20.1	21.6
	1250	16.8	18.2	19.6	21.1	22.6	24.1	25.7
	1500	20.3	21.8	23.3	24.9	26.6	28.3	30.1
	1750	23.9	25.5	27.2	28.9	30.7	32.6	34.5
	2000	27.6	29.4	31.2	33.1	35.0	37.1	39.2

LOS	A	B	C	D	E	F
Density (pc/mi/ln)	<=10	10-20	20-28	28-35	>35	Demand Exceed Capacity

Table 5.2. Reduction in density after adding auxiliary lanes at weaving segments.

Weaving segment length, L_S (ft)	Reduction in density after adding auxiliary lane	
	Reduction in density (pc/mi/ln)	Percent reduction (%)
750	5.7-16.5	23-50
1500	4.7-9.1	13-49
2250	1.6-9.1	4-49

5.1.2 Recommendations on when to Add Auxiliary Lane

The engineer survey (TxDOT, 2011) has found that state transportation engineers considered the use of auxiliary lanes under the following conditions:

- When the ramp has high percentage of trucks; or
- When the ramp has high volumes; or
- When the traffic density is high; or
- If there is safety or operational issues; or
- If the predicted LOS is D or worse for the design year peak hour traffic.

The first four conditions are qualitative in nature. However, the condition based on LOS provides a clearer threshold. Therefore, the following criterions were set up to develop the quantitative recommendations for including auxiliary lanes at FWSs:

(a) If there is no auxiliary lane, the LOS in the FWSs is D or worse; and

(b) With the inclusion of an auxiliary lane, the LOS in the FWSs becomes C or better.

The identification of scenarios that meet the LOS improvement criteria is illustrated in Figure 5.1 with the use of Table 5.1. The scenarios that meet criterion (a) are determined from the nested tables in the left column of Table 5.1 (without auxiliary lane). For each nested table that represents a fixed L_S value, the combinations of v_W and v_{FF} values that result in LOS D or worse are outlined in red and shown in Figure 5.1. In Figure 5.1, the regions below the red lines

represent LOS D or worst when no auxiliary lane is included at the FWSs. The scenarios that meet criterion (b) are determined in the same fashion from the nested tables in the right column of Table 5.1 (with auxiliary lane). In Figure 5.1, the regions above the blue lines represent LOS C or better after an auxiliary lane has been included. Each shaded region between the red and blue line in Figure 5.1 encloses the v_W and v_{FF} values that satisfy both criteria (a) and (b). It represents the combinations of L_S, v_W and v_{FF} values which auxiliary lane should be designed to improve the LOS from D or worst to C or better. Auxiliary lane is not recommended for the regions above the red lines in Figure 5.1 because even without an auxiliary lane, the LOS is always C or better. Likewise, auxiliary lane is not recommended for the regions below the blue lines in Figure 5.1 because even with an auxiliary lane the LOS will not become C or better. This implies that other geometric improvement options, e.g., increasing the number of freeway lanes, should be considered.

The application of Figure 5.1 in combination with Table 5.1 may be illustrated through the following example. If a FWS has Ls=750 ft, design volumes of v_{FF}=1250 pc/h/ln and v_W=600 pc/h/ln, according to the first chart in Figure 5.1, an auxiliary lane should be added. By doing so, the LOS is expected to be B (from the first nested table in the right column of Table 5.1). However, if the site geometry permits, L_S may be extended to 1500 ft without having to add an auxiliary lane, as recommended by the second chart in Figure 5.1. Under this option, the LOS will, however, be C (from the second nested table in the left column of Table 5.1).

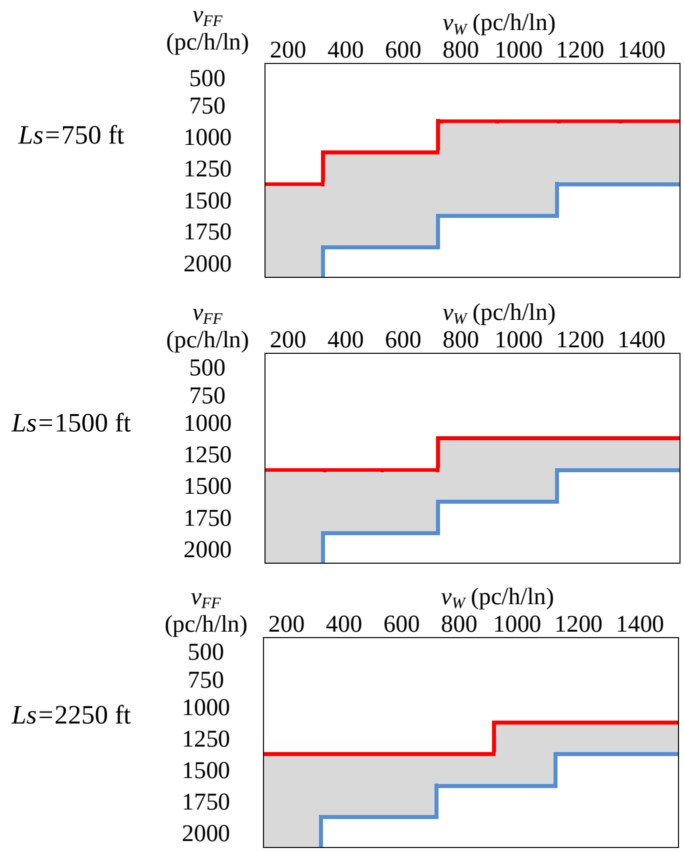


Figure 5.1. Design scenarios in which auxiliary lanes should be added at weaving segments.

5.2 Operational Impacts of Auxiliary Lanes at On-Ramp Junctions

The 210 scenarios for on-ramp junctions without an auxiliary lane, and 210*15=3150 scenarios for on-ramp junctions with auxiliary lanes are run in the HCS2010 ramp module.

The outputs are analyzed in terms of density and LOS in the merge influence area. The following sub-sections present the results in three parts:

(1) Comparison of density and LOS with and without an auxiliary lane, from which the operational benefits of adding auxiliary lanes at on-ramp junctions are quantified;

(2) Development of recommendations on when to add auxiliary lanes at on-ramp junctions, based on the findings in (1); and

(3) Development of recommendations for minimum L_A under different design factors.

5.2.1 Comparison of Density and LOS with and without Auxiliary Lane

The 210 scenarios of on-ramp junctions without an auxiliary lane (i.e., L_A=0 ft) are compared with the 3150 scenarios with different L_A>0 values. There are 15 L_A values used with the presence of auxiliary lanes. As a typical example, the results with L_A=1500 ft are presented in Table 5.3. The results for the total 15 L_A values are presented in Tables A1, A2, and A3 in Appendix B. The results listed in Table 5.3 represent the operational benefits achievable under different v_F and v_R if an auxiliary lane of 1500 ft is added to an on-ramp junction. In Table 5.3, there are six nested tables; each of them shows, for a specific N_F and L_A values, the density and LOS under different combinations of v_F and v_R. The improvement in density and LOS at a given N_F, before and after the addition of an auxiliary lane of L_A=1500 ft, may be identified by comparing the two nested table in the same row. It can be seen from Table 5.3 that, the density with the auxiliary lane is less than the density without an auxiliary lane. Similarly, the LOS in the merge influence area is better with the auxiliary lane. The drops in density and improvements in LOS with the presence of auxiliary lanes are expected. However, in this research, the HCS calculations have quantified that, if an auxiliary lane of L_A=1500 ft is added to an on-ramp junction, the density decreases by 8.9 to 9.4 veh/mi/ln, or by 19% to 76%. Table 5.4 lists the ranges in the reduction in density when auxiliary lane of different lengths is added to an on-ramp junction, according to the HCS2010 calculations for all the design scenarios. This table provides design engineers better and qualitative justifications for adding auxiliary lanes at on-ramp junctions.

Table 5.3. Comparison of density and LOS with and without auxiliary lanes of 1500 ft at on-ramp junctions.

Density in the merge influence area (pc/mi/ln)

Without auxiliary lane, L_A=0 ft

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	14.0	14.7	15.5	16.2	16.9	17.7	18.4	19.1	19.9	20.6
750	17.9	18.6	19.4	20.1	20.8	21.6	22.3	23.0	23.8	24.5
1000	21.8	22.5	23.3	24.0	24.7	25.5	26.2	26.9	27.7	28.4
1250	25.7	26.4	27.2	27.9	28.6	29.4	30.1	30.8	31.6	32.3
1500	29.6	30.3	31.1	31.8	32.5	33.3	34.0	34.7	35.5	36.2
1750	33.5	34.2	35.0	35.7	36.4	37.2	37.9	38.6	39.4	40.1
2000	37.4	38.1	38.9	39.6	40.3	41.1	41.8	42.5	43.3	44.0

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	13.0	13.7	14.4	15.2	15.9	16.6	17.4	18.1	18.8	19.6
750	16.3	17.1	17.8	18.5	19.3	20.0	20.7	21.5	22.2	23.0
1000	19.7	20.5	21.2	21.9	22.7	23.4	24.1	24.9	25.6	26.3
1250	23.1	23.8	24.6	25.3	26.0	26.8	27.5	28.2	29.0	29.7
1500	26.5	27.2	27.9	28.7	29.4	30.1	30.9	31.6	32.4	33.1
1750	29.9	30.6	31.3	32.1	32.8	33.5	34.3	35.0	35.7	36.5
2000	33.2	34.0	34.7	35.4	36.2	36.9	37.6	38.4	39.1	39.8

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	12.4	13.2	13.9	14.7	15.4	16.1	16.9	17.6	18.3	19.1
750	15.6	16.3	17.0	17.8	18.5	19.2	20.0	20.7	21.4	22.2
1000	18.7	19.4	20.2	20.9	21.6	22.4	23.1	23.8	24.6	25.3
1250	21.8	22.5	23.3	24.0	24.7	25.5	26.2	26.9	27.7	28.4
1500	24.9	25.7	26.4	27.1	27.9	28.6	29.3	30.1	30.8	31.5
1750	28.0	28.8	29.5	30.3	31.0	31.7	32.5	33.2	33.9	34.7
2000	31.2	31.9	32.6	33.4	34.1	34.8	35.6	36.3	37.0	37.8

With auxiliary lane, L_A=1500 ft

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	4.6	5.3	6.1	6.8	7.5	8.3	9.0	9.7	10.5	11.2
750	8.5	9.2	10.0	10.7	11.4	12.2	12.9	13.6	14.4	15.1
1000	12.4	13.1	13.9	14.6	15.3	16.1	16.8	17.5	18.3	19.0
1250	16.3	17.0	17.8	18.5	19.2	20.0	20.7	21.4	22.2	22.9
1500	20.2	20.9	21.7	22.4	23.1	23.9	24.6	25.3	26.1	26.8
1750	24.1	24.8	25.6	26.3	27.0	27.8	28.5	29.2	30.0	30.7
2000	28.0	28.7	29.5	30.2	30.9	31.7	32.4	33.1	33.9	34.6

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	4.1	4.8	5.5	6.3	7.0	7.7	8.5	9.2	9.9	10.7
750	7.7	8.4	9.1	9.9	10.6	11.3	12.1	12.8	13.5	14.3
1000	11.3	12.0	12.8	13.5	14.2	15.0	15.7	16.4	17.2	17.9
1250	14.9	15.7	16.4	17.1	17.9	18.6	19.3	20.1	20.8	21.5
1500	18.5	19.3	20.0	20.8	21.5	22.2	23.0	23.7	24.4	25.2
1750	22.2	22.9	23.6	24.4	25.1	25.8	26.6	27.3	28.0	28.8
2000	25.8	26.5	27.3	28.0	28.7	29.5	30.2	30.9	31.7	32.4

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	3.0	3.8	4.5	5.2	6.0	6.7	7.4	8.2	8.9	9.7
750	6.2	6.9	7.6	8.4	9.1	9.8	10.6	11.3	12.0	12.8
1000	9.3	10.0	10.8	11.5	12.2	13.0	13.7	14.4	15.2	15.9
1250	12.4	13.1	13.9	14.6	15.3	16.1	16.8	17.5	18.3	19.0
1500	15.5	16.3	17.0	17.7	18.5	19.2	19.9	20.7	21.4	22.1
1750	18.6	19.4	20.1	20.8	21.6	22.3	23.0	23.8	24.5	25.3
2000	21.8	22.5	23.2	24.0	24.7	25.4	26.2	26.9	27.6	28.4

LOS	A	B	C	D	E	F
Density (pc/mi/ln)	<=10	10-20	20-28	28-35	>35	Demand Exceed Capacity

Table 5.4. Reduction in density after adding auxiliary lanes at on-ramp junctions.

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

5.2.2 Recommendation on when to Add Auxiliary Lane

Based on the results of the engineer survey (TxDOT, 2011), the following criterions were set up to develop the quantitative recommendations for including auxiliary lane in on-ramp junction design:

(a) If there is no auxiliary lane at the on-ramp junction the LOS in the merge influence area is D or worse; and

(b) With the inclusion of an auxiliary lane, the LOS in the merge influence area becomes C or better.

The identification of scenarios (i.e., combinations of N_F, v_R and v_F) that meet the LOS improvement criteria is best illustrated with the use of Table 5.3 and Figure 5.2. Table 5.3 and Figure 5.2 are for L_A=1500 ft. The scenarios that meet criterion (a) are determined from the nested tables (for L_A=0 ft) in the left column of Table 5.3. For each nested table that represents a fixed N_F value, the combinations of v_R and v_F values that result in LOS D or worse are outlined in red and shown in Figure 5.2. In Figure 5.2, the regions below the red lines represent LOS D or worst when no auxiliary lane is included at the on-ramp junction. The scenarios that meet criterion (b) are determined in the same fashion. In Figure 5.2, the regions above the blue lines represent LOS C or better after an auxiliary lane of L_A=1500 ft has been included. Each shaded region between the red and blue line in Figure 5.2 encloses the v_R and v_F values that satisfy both criteria (a) and (b). It represents the combinations of N_F, v_R and v_F values which auxiliary lane of L_A=1500 ft should be designed to improve the LOS from D or worst to C or better. Figure 5.2 also reveals that, as N_F increases, auxiliary lane of L_A=1500 ft should be provided when both v_R and v_F are both relatively high. Auxiliary lane is not recommended for the regions above the red lines in Figure 5.2 because even without an auxiliary lane, the LOS is always C or better. Likewise, auxiliary lane is not recommended for the regions below the blue lines in Figure 5.2 because even with L_A=1500 ft the LOS will not become C or better. This implies that other geometric improvement options, e.g., increasing N_F, should be considered.

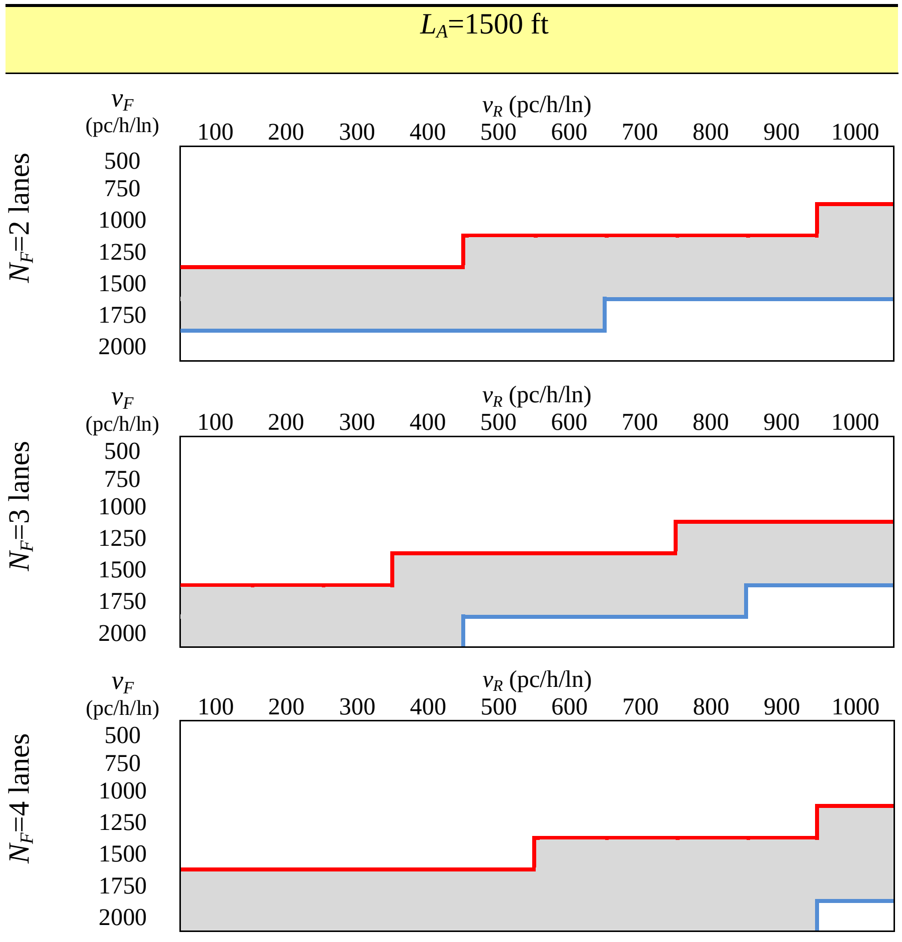


Figure 5.2. Design scenarios in which auxiliary lanes of 1500 ft should be added at on-ramp junctions.

Figure 5.3 shows the scenarios in which auxiliary lane of L_A=500 and 1000 ft should be included as part of the on-ramp junctions. The regions of N_F, v_R and v_F values are developed, and can be interpreted in the similar way as in Figure 5.3. From both Figures 5.2 and 5.3, one can notice that, with a fixed N_F, the shaded regions become larger as L_A increases from 500 to 1000 ft and then to 1500 ft. The increase is mainly due to the lowering of the blue lines. This reflects that fact that, at higher v_R or v_F value, or both, only longer L_A is recommended.

5.2.3 Minimum Length of Auxiliary Lane

Figures 5.2 and 5.3 only illustrate the design scenarios in which auxiliary lane of L_A=500, 1000 or 1500 ft should be considered as part of an on-ramp junction. Consider the design scenario of N_F=3 lanes, v_R=800 pc/h/ln and v_F =1500 pc/h/ln. From Figure 5.3, it is clear that L_A=500 ft will not meet the LOS improvement criteria but L_A=1000 ft will. The minimum L_A that will meet the LOS improvement criteria is somewhere between 500 and 1000 ft. In this research, the design scenarios actually covered L_A from 100 to 1500 ft at increments of 100 ft. It is possible to construct figures similar to Figures 5.2 and 5.3 for all the L_A values experimented, and deduce the minimum L_A values for any given combination of N_F, v_R and v_F.

Table 5.5 summarizes that minimum L_A values at the resolution of 100 ft. As mentioned before, L_A<500 ft may not be practical. Therefore, if an auxiliary lane has been determined to be necessary, the design engineer may want to set the minimum L_A to at least 500 ft. In Table 5.5, the cells without value near the left top corner indicate the design scenarios in which no auxiliary lane is necessary (from operational point of view), while the cells without value near the bottom right corner indicate the design scenarios in which other geometric improvements should be considered.

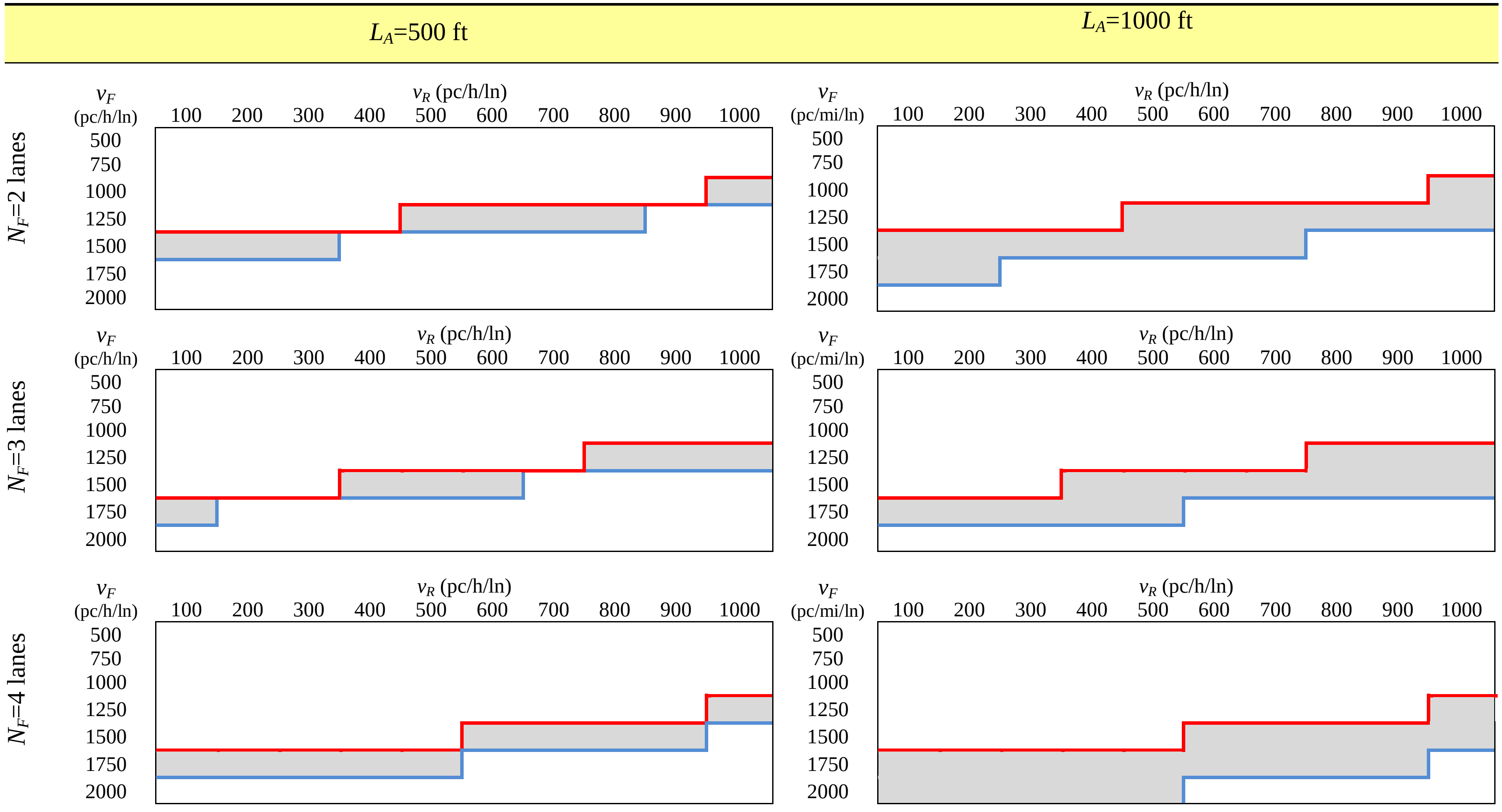


Figure 5.3. Design scenarios in which auxiliary lanes of 500 ft and 1000 ft should be added at on-ramp junctions.

Table 5.5. Minimum length of auxiliary lane at on-ramp junctions.

(a) N_F=2 lanes

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	-	-	-	-	-	-	-	-	-	-

(b) N_F=3 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	-	-	-	-	-	-

(c) N_F=4 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	-

5.3 Operational Impacts of Auxiliary Lanes at Off Ramp Junctions

The 70 scenarios of isolated off-ramp junctions without an auxiliary lane (i.e., L_D=0 ft) are compared with the 1050 scenarios with different L_D>0 ft values. There are 15 L_D values used with the presence of auxiliary lanes. The results with L_D=500, 1000 and 1500 ft are presented in Table 5.6. The results for the total 15 L_D values are presented in Table B1 in Appendix C. The results listed in Table 5.6 represent the operational performance (density and LOS) achievable under different v_F and v_R if an auxiliary lane of 500, 1000, 1500 ft, respectively, is added to an isolated off-ramp junction. In Table 5.6, there are four nested tables. The first nested table shows the density and LOS under different combinations of v_F and v_R, when no auxiliary lane is incorporated (i.e., L_D=0 ft). The last three nested tables shows the density and LOS under different combinations of v_F and v_R, when an auxiliary lanes of 500, 1000, 1500 ft are added. It can be seen from Table 5.6 that, with the presence of an auxiliary lane, the density and LOS at the diverge influence area have improved; the longer the auxiliary lane, the better the improvement.

Table 5.6. Comparison of Density and LOS with and without auxiliary lanes.

	Density in the diverge influence area (pc/mi/ln)										
	v_F	v_R (pc/h/ln)									
Without auxiliary lane L_D=0 ft	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	13.8	13.9	14.1	14.4	14.6	14.8	15.0	15.3	15.5	15.8
	750	18.0	18.2	18.4	18.6	18.8	19.0	19.2	19.4	19.7	19.9
	1000	22.1	22.2	22.4	22.6	22.8	23.0	23.2	23.4	23.6	23.8
	1250	25.9	26.0	26.2	26.4	26.5	26.7	26.9	27.1	27.3	27.5
	1500	29.4	29.6	29.7	29.9	30.0	30.2	30.4	30.6	30.8	31.0
	1750	32.8	32.9	33.0	33.1	33.3	33.5	33.6	33.8	34.0	34.2
	2000	35.8	35.9	36.1	36.2	36.3	36.5	36.6	36.8	36.9	37.1
	v_F	v_R (pc/h/ln)									
With one auxiliary lane L_D=500 ft	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	9.3	9.4	9.6	9.9	10.1	10.3	10.5	10.8	11.0	11.3
	750	13.5	13.7	13.9	14.1	14.3	14.5	14.7	14.9	15.2	15.4
	1000	17.6	17.7	17.9	18.1	18.3	18.5	18.7	18.9	19.1	19.3
	1250	21.4	21.5	21.7	21.9	22.0	22.2	22.4	22.6	22.8	23.0
	1500	24.9	25.1	25.2	25.4	25.5	25.7	25.9	26.1	26.3	26.5
	1750	28.3	28.4	28.5	28.6	28.8	29.0	29.1	29.3	29.5	29.7
	2000	31.3	31.4	31.6	31.7	31.8	32.0	32.1	32.3	32.4	32.6
	v_F	v_R (pc/h/ln)									
With one auxiliary lane L_D=1000 ft	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	4.8	4.9	5.1	5.4	5.6	5.8	6.0	6.3	6.5	6.8
	750	9.0	9.2	9.4	9.6	9.8	10.0	10.2	10.4	10.7	10.9
	1000	13.1	13.2	13.4	13.6	13.8	14.0	14.2	14.4	14.6	14.8
	1250	16.9	17.0	17.2	17.4	17.5	17.7	17.9	18.1	18.3	18.5
	1500	20.4	20.6	20.7	20.9	21.0	21.2	21.4	21.6	21.8	22.0
	1750	23.8	23.9	24.0	24.1	24.3	24.5	24.6	24.8	25.0	25.2
	2000	26.8	26.9	27.1	27.2	27.3	27.5	27.6	27.8	27.9	28.1
	v_F	v_R (pc/h/ln)									
With one auxiliary lane L_D=1500 ft	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	0.3	0.4	0.6	0.9	1.1	1.3	1.5	1.8	2.0	2.3
	750	4.5	4.7	4.9	5.1	5.3	5.5	5.7	5.9	6.2	6.4
	1000	8.6	8.7	8.9	9.1	9.3	9.5	9.7	9.9	10.1	10.3
	1250	12.4	12.5	12.7	12.9	13.0	13.2	13.4	13.6	13.8	14.0
	1500	15.9	16.1	16.2	16.4	16.5	16.7	16.9	17.1	17.3	17.5
	1750	19.3	19.4	19.5	19.6	19.8	20.0	20.1	20.3	20.5	20.7
	2000	22.3	22.4	22.6	22.7	22.8	23.0	23.1	23.3	23.4	23.6

LOS	A	B	C	D	E	F
Density (pc/mi/ln)	<=10	10-20	20-28	28-35	>35	Demand Exceeds Capacity

By comparing the nested tables in Table 5.6, at each combination of v_F and v_R values, the improvements in density and LOS when an auxiliary lane at different lengths (L_D) can be observed. Table 5.7 summarized the absolute and percent reductions in density in the off-ramp junction when an auxiliary lane with different L_D has been added, compared to the density without an auxiliary lane. It should be noted that, according to the HCM2010 analysis procedure, even with different v_F and v_R values, the absolute reduction in density is the same as long as L_D is constant (see the second column in Table 5.7). Only the percent reduction is different. As expected, the absolute reduction in density increases with L_D.

Table 5.7. Reduction in density after adding auxiliary lanes.

L_D (ft)	Reduction in density after adding auxiliary lane of length L_D	
	Reduction in density (pc/mi/ln)	Percent reduction (%)
100	0.9	2-7
200	1.8	5-13
300	2.7	7-20
400	3.6	10-26
500	4.5	12-33
600	5.4	15-39
700	6.3	17-46
800	7.2	19-52
900	8.1	22-59
1000	9.0	24-65
1100	9.9	27-72
1200	10.8	29-79
1300	11.7	32-85
1400	12.6	34-92
1500	13.5	36-98

In Table 5.6, it can be observed that, without an auxiliary lane, when $v_F \geq 1500$ pc/h/ln, the LOS is D or E. After adding an auxiliary lane of 500, 1000 or 1500 ft, even with $v_F \geq 1500$ pc/h/ln the LOS becomes C or better. Therefore, it may be concluded that the addition of an auxiliary lane at isolated freeway off-ramp junctions can potentially improve the LOS in the diverge influence area from D or worse to C or better, at heavy freeway demand flow rate. It appears that the minimum length of an auxiliary lane should be design for $v_F \geq 1500$ pc/h/ln.

Table 5.8 lists the minimum length of auxiliary lane at different combinations of design v_F and v_R, values and is developed as follows. First, v_F of 1500, 1750 and 2000 pc/h/ln were selected. Next, v_R was given 100, 200, 300, 400, 500, 600, 700, 800, 900 or 1000 pc/h/ln. For each combination of v_F and v_R values, L_D was increased from 0 to 1500 ft at 100 ft increments. At each L_D value the LOS was estimated according to the HCM2010 analysis procedure. As L_D increased, the LOS was expected to improve. The shortest L_D that produced LOS C (at a given combination of of v_F and v_R values) is recorded in Table 5.8.

In Table 5.8, it can be seen that, when v_F =1500 pc/h/ln, the minimum L_D is 200 to 400 ft. In practice, the minimum length of L_D=500 ft may be used. When v_F =1750 pc/h/ln, the minimum L_D is 600 to 700 ft; and when v_F =2000 pc/h/ln, the minimum L_D is 900 to 1100 ft.

Table 5.8. Minimum length of auxiliary lane that gives LOS C

Minimum L_D (ft)										
v_F (pc/h/ln)	v_R (pc/h/ln)									
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
1500	200	200	200	300	300	300	300	300	400	400
1750	600	600	600	600	600	700	700	700	700	700
2000	900	900	900	1000	1000	1000	1000	1000	1000	1100

5.4 Chapter Summary

This chapter assessed the operational impacts of auxiliary lane at freeway weaving segments, on-ramp junctions, and off-ramp junctions.

For FWSs, based on the analysis of traffic density and LOS in the FWSs with and without auxiliary lane, the operational benefits of adding auxiliary lanes at FWSs are visualized and quantified (see Tables 5.1 and 5.2). The results of this study show that adding an auxiliary lane reduces density by 1.6 to 19.5 pc/mi/ln or 4% to 50%. A higher percentage reduction in density can be achieved when L_S is shorter and v_W is higher. This research has also developed charts (Figure 5.1) which contain recommendations on when to add auxiliary lanes at FWSs under different combinations of freeway volume, weaving volume and weaving segment length.

For on-ramp junctions, based on the analysis of traffic density and LOS in the merge influence area before and after the inclusion of an auxiliary lane, the operational benefits of adding auxiliary lanes are visualized and quantified (see Tables 5.3 and 5.4). The results showed that, after the addition of an auxiliary lane, the density in the merge influence area reduces by 3.0 pc/mi/ln for L_A=500 ft, and up to 9.4 pc/mi/ln for L_A=1500 ft. This research has also developed recommendations for the minimum L_A under different combinations of N_F, v_F and V_R design scenarios. The minimum L_A are the length that, after the provision of the auxiliary lane, the LOS in the merge influence area will improve from D or worst to C or better. Look-up tables (Table 5.5) for the minimum L_A are developed for design engineers to use as a quick reference.

For off-ramp junctions, based on the analysis of traffic density and LOS in the diverge influence area before and after the inclusion of an auxiliary lane, the operational benefits of adding auxiliary lanes are visualized and quantified (see Table 5.6 and 5.7). The results showed that, after the addition of an auxiliary lane, the density has reduced and LOS improved. In

addition, longer auxiliary lane leads to higher reduction in density and better LOS. This research has also developed recommendations for the minimum auxiliary lane length under different combinations of v_F and v_R design scenarios. The minimum L_D are the length that, after the provision of the auxiliary lane, the LOS in the diverge influence area will improve from D or worst to C or better. The results showed that, if v_F is 1500 pc/h/ln, the minimum L_D is 200 to 400 ft (this is subjected to the practical minimum length of 500 ft); if v_F is 1750 pcphpl, the minimum L_D is 600 to 700 ft; and if v_F is 2000 pc/h/ln, the minimum L_D is 900 to 1100 ft. A look-up table (Table 5.8) for minimum L_D has been developed for design engineers to use as a quick reference.

Chapter 6

Safety Impacts of Auxiliary Lane at On-Ramp Junctions

This chapter presents a two-part study to quantify the safety impacts of auxiliary lanes at isolated on-ramp junctions on freeways. In the first part of this study, the safety performance of on-ramp junctions with auxiliary lanes was compared with isolated on-ramp junctions without an auxiliary lane. In the second part of this study, regression models have been developed to relate crash rate with influencing factors for on-ramp junctions with auxiliary lanes.

6.1 Comparison of Crash Rates with and without Auxiliary Lane

From Table 4.1, the average ADT for sites with auxiliary lanes is 117,941 veh/day while that for sites without an auxiliary lane is 222,072 veh/day. Therefore, it is necessary to nomalize the crash occurrences with traffic volume. The crash rate at each study site was calculated as crashes per Million Entering Vehicles (crashes/MEV), adopted from Green and Agent (2003):

$$R = \frac{C * 1{,}000{,}000}{ADT * 365 * Y} \tag{6.1}$$

where R is the crash rate, C is the number of crashes during the period of data collection, ADT is the average daily traffic (veh/day), and Y is the number of years analyzed. In our computation, the ADT was taken as the freeway ADT in all the main lanes in 2003. Each crash record in the CRIS database has the ADT of the crash location. However, the database only contains the 2003 ADT value, although the crashes occurred between 2003 and 2008. The ramp ADT was not available in CRIS and in any other database in Texas.

Table 6.1 shows the crash rates computed at all the selected sites. The average crash rate from all the sites with auxiliary lanes is 0.0771 crashes/MEV. This is less than half the average crash rate of sites without auxiliary lane (0.1762 crashes/MEV). The reduction in average crash rate is approximately 56%. A one-tailed t-test was conducted to see if the reduction in the

average crash rate is statistically significant. The *p*-value of the *t*-test is 0.0006, which means that the reduction in the average crash rate at sites with auxiliary lanes is statistically significant at 0.001 level. Therefore, it can be concluded that on-ramp junctions with auxiliary lanes have a significantly lower average crash rate compared to on-ramp junctions without an auxiliary lane.

Table 6.1. Comparison of crash rates at on-ramp junctions.

Without auxiliary lane		With auxiliary lane	
Site no.	Crash rate (crashes/MEV)	Site no.	Crash rate (crashes/MEV)
1	0.0782	20	0.0509
2	0.0435	21	0.1026
3	0.2812	22	0.0712
4	0.1132	23	0.0990
5	0.1782	24	0.1121
6	0.3906	25	0.0527
7	0.2375	26	0.0484
8	0.1029	27	0.0806
9	0.0554	28	0.0240
10	0.1799	29	0.0481
11	0.2978	30	0.0319
12	0.0681	31	0.0091
13	0.1872	32	0.0251
14	0.1934	33	0.0752
15	0.1833	34	0.1696
16	0.1681	35	0.2332
17	0.0433		
18	0.2539		
19	0.2923		
Average	0.1762	Average	0.0771
Standard deviation	0.0989	Standard deviation	0.0580

6.2 Comparison of Crash Severities with and without Auxiliary Lanes

In the CRIS database, the severity of a crash may be classified into Property Damage Only (PDO), injury, or fatal. Similar to Li and Bai (2008), in this study, severe crashes are

defined as accidents that are fatal or result in injuries. PDO crash rate is defined as the number of PDO crashes per MEV at a site. Severe crash rate is defined as the number of crashes per million MEV at a site that are fatal or result in injuries. Crash severity is defined as the percentage of severe crashes out of all crashes at a site. Table 6.2 lists the site specific PDO crash rates, severe crash rates as well as crash severities. The average rates computed across the sites are listed at the bottom of the table. The average PDO crash rate and the average severe crash rate are lower for sites with auxiliary lanes. For on-ramp junctions with auxiliary lanes, the average crash severity is also lower. *t-tests* were conducted to test the hypotheses that (i) there was no difference between the average PDO crash rates; (ii) there was no difference between the average severe crash rates; and (iii) there was no difference between the crash severities, for sites without and with auxiliary lanes. The outcomes of the *t*-tests are summarized in Table 6.3. The reductions in average PDO crash rate and average severe crash rate are both statistically significant at 0.01 level (*p*-value of at most 0.002). Although the average crash severity is lower at on-ramp junctions with auxiliary lanes, the reduction is found to be not significant even at 0.10 level (*p*-value at 0.7509). Therefore, it can be concluded that (i) compared to on-ramp junctions without an auxiliary lane, on-ramp junctions with auxiliary lanes have lower average crash rates at all severities. Although there is a significant reduction in overall crash rates (see Table 6.1) and PDO crash rate (see Table 6.3), there is no significant change in the average crash severity or the proportion of PDO crashes among all crashes. The statistically significant reduction in overall crash rate is mostly contributed by the reduction in PDO crash rate.

Table 6.2. Comparison of crash severities at on-ramp junctions.

Without auxiliary lane			
Site no.	PDO crash rate (crashes/ MEV)	Severe crash rate (crashes/ MEV)	Crash severity (%)
1	0.0500	0.0283	63.89
2	0.0152	0.0283	35.00
3	0.1889	0.0923	67.19
4	0.0707	0.0424	62.50
5	0.1245	0.0538	69.84
6	0.2586	0.1319	66.22
7	0.1214	0.1161	51.11
8	0.0475	0.0554	46.15
9	0.0396	0.0158	71.43
10	0.1021	0.0779	56.73
11	0.1838	0.1140	61.71
12	0.0408	0.0272	60.00
13	0.1123	0.0749	60.00
14	0.1127	0.0807	58.26
15	0.1093	0.0740	59.63
16	0.1075	0.0607	63.92
17	0.0312	0.0121	72.00
18	0.1571	0.0968	61.88
19	0.1492	0.1431	51.04
Average	0.1064	0.0698	59.92
Std dev.	0.0631	0.0392	9.11

With auxiliary lane			
Site no.	PDO crash rate (crashes/ MEV)	Severe crash rate (crashes/ MEV)	Crash Severity (%)
20	0.0305	0.0204	40.00
21	0.0780	0.0246	24.00
22	0.0102	0.0611	85.71
23	0.0685	0.0305	30.77
24	0.0692	0.0428	38.24
25	0.0297	0.0231	43.75
26	0.0269	0.0215	44.44
27	0.0484	0.0323	40.00
28	0.0080	0.0160	66.67
29	0.0360	0.0120	25.00
30	0.0182	0.0137	42.86
31	0.0091	0.0000	0.00
32	0.0125	0.0125	50.00
33	0.0334	0.0418	55.56
34	0.1021	0.0675	39.80
35	0.1413	0.0919	39.42
Average	0.0451	0.0320	41.64
Std dev.	0.0378	0.0241	18.82

Table 6.3. Crash severity: results of t-tests.

Comparison	*p*-value	Results
Average PDO crash rate	0.0018	Significant at 0.01 level
Average severe crash rate	0.0020	Significant at 0.01 level
Average crash severity	0.7509	Not significant at 0.10 level

6.3 Comparison of Major Crash Types with And without Auxiliary Lanes

There are more than 40 crash types in the CRIS database, of which only nine crash types are possible to occur at on-ramp junctions. The nine possible crash types were grouped into four categories in this study:

- Read-end crashes between two or more vehicles;
- Sideswipe crashes between two or more vehicles;
- Object related (i.e., crashes between a vehicle and an object);
- All other crashes.

Table 6.4 lists the crash rates (number of crashes per MEV) by the four identified crash types. Table 6.5 further presents the percentages of the four crash types at each site. From Table 6.5, it is obvious that the major crashes types at the on-ramp junctions are rear-end crashes, sideswipe crashes, and object related crashes. These three types of crashes account for 96% of all the crashes at sites without an auxiliary lane, and 94% of the crashes at the sites with auxiliary lanes.

From Table 6.4, it appears that, for the same crash type, the average crash rate for sites with auxiliary lanes is lower than the average crash rate for sites without auxiliary lane. This is consistent with the statistics of overall crash rates presented in Table 6.1. A one-tail *t*-test was subsequently conducted to test the hypothesis that the average crash rates for sites with and without an auxiliary lane were the same, against the alternate hypothesis that the average crash rate at sites with auxiliary lanes was significantly lower. The hypothesis test was performed for rear-end, sideswipe and object related crashes, respectively. The outcomes of the tests are reported in the first half of Table 6.6. Based on the *p*-values obtained, we can conclude that the average crash rates for rear-end, sideswipe and objected related crashes at sites with auxiliary lanes are each lower than that for sites without an auxiliary lane, at <0.05 level of significance.

Table 6.4. Comparison of crash rates by crash type at on-ramp junctions.

Without auxiliary lane					With auxiliary lane				
Site no.	Crash rate (crashes/MEV)				Site no.	Crash rate (crashes/MEV)			
	Rear-end	Sideswipe	Object related	Others		Rear-end	Sideswipe	Object related	Others
1	0.0261	0.0152	0.0348	0.0022	20	0.0102	0.0204	0.0102	0.0102
2	0.0196	0.0152	0.0065	0.0022	21	0.0451	0.0369	0.0205	0.0000
3	0.1538	0.0813	0.0417	0.0044	22	0.0204	0.0204	0.0305	0.0000
4	0.0340	0.0396	0.0255	0.0141	23	0.0152	0.0381	0.0381	0.0076
5	0.0820	0.0283	0.0622	0.0057	24	0.0593	0.0330	0.0198	0.0000
6	0.1557	0.1135	0.1108	0.0106	25	0.0165	0.0231	0.0132	0.0000
7	0.1082	0.0501	0.0686	0.0106	26	0.0269	0.0054	0.0161	0.0000
8	0.0554	0.0264	0.0211	0.0000	27	0.0591	0.0108	0.0108	0.0000
9	0.0264	0.0053	0.0238	0.0000	28	0.0120	0.0040	0.0040	0.0040
10	0.1280	0.0242	0.0225	0.0052	29	0.0040	0.0080	0.0360	0.0000
11	0.1957	0.0579	0.0357	0.0085	30	0.0091	0.0000	0.0228	0.0000
12	0.0425	0.0170	0.0085	0.0000	31	0.0046	0.0000	0.0046	0.0000
13	0.1038	0.0528	0.0306	0.0000	32	0.0167	0.0042	0.0042	0.0000
14	0.1060	0.0488	0.0353	0.0034	33	0.0418	0.0125	0.0167	0.0042
15	0.1194	0.0421	0.0219	0.0000	34	0.0917	0.0346	0.0433	0.0000
16	0.0936	0.0381	0.0191	0.0173	35	0.1208	0.0698	0.0374	0.0051
17	0.0191	0.0121	0.0104	0.0017					
18	0.1142	0.0746	0.0603	0.0048					
19	0.1522	0.0426	0.0853	0.0122					
Ave.	0.0914	0.0413	0.0381	0.0054	Ave.	0.0346	0.0201	0.0205	0.0019
Std dev.	0.0537	0.0271	0.0277	0.0053	Std dev.	0.0336	0.0188	0.0130	0.0033

Another set of three one-tail *t*-tests were performed for the average percentages of crash types, for read-end, sideswipe and object related crashes respectively, based on the statistics as reported in Table 6.5. The first test was based on the null hypothesis that the average percentages of rear-end crashes at sites with and without an auxiliary lane were the same, against the alternate hypothesis that the average percentage of rear-end crashes at sites with auxiliary lanes was significantly lower. The second test was based on the null hypothesis that the average percentages of sideswipe crashes at sites with and without an auxiliary lane were the same, against the alternate hypothesis that the average percentage of sideswipe crashes at sites with

auxiliary lanes was significantly lower. The third test used the null hypothesis that the average percentages of object related crashes at sites with and without auxiliary lane were the same, against the alternate hypothesis that the average percentage of objected related crashes at sites with auxiliary lanes was significantly higher. The outcomes of the tests are reported in the lower half of Table 6.6. Based on the *p*-values obtained, we can conclude that the average percentage of rear-end crashes at on-ramp junctions with auxiliary lanes is lower than that for sites without auxiliary lane, at 0.10 level of significance. On the other hand, the average percentage of object related crashes at on-ramp junctions with auxiliary lanes are higher than that for sites without an auxiliary lane, at 0.10 level of significance. However, there is no significant difference in the average percentages of sideswipe crashes. It appears that adding an auxiliary lane at an on-ramp junction will significantly reduce the proportion of rear-end crashes but significantly increase the proportion of object related crashes. With the presence of auxiliary lanes, the reduction of rear-end crash rate and proportion of rear-end crashes are within expectation because drivers of the merging vehicles and freeway main lane vehicles have more space to negotiate with each other, thereby reducing the probability of having to make an emergency brake. However, the statistics of objected related crashes are harder to explain. The data and *t*-tests have shown that, although there is a reduction in the average rate of objected related crashes with the presence of auxiliary lanes, the average percentage of this type of crash among all the crashes has increased. It appears that, instead of rear-end crashes caused by “forced merges”, drivers are able to merge at higher speeds and this combines with certain evasive actions may have caused them to crash with roadside objects.

Table 6.5. Percent crashes by crash type at on-ramp junctions.

Without auxiliary lane					With auxiliary lane				
Site no.	Percent of all crashes (%)				Site no	Percent of all crashes (%)			
	Rear-end	Sideswipe	Object related	All others		Rear-end	Sideswipe	Object related	All others
1	33.33	19.44	44.44	2.79	20	20.00	40.00	20.00	20.00
2	45.00	35.00	15.00	5.00	21	44.00	36.00	20.00	0.00
3	54.69	28.91	14.84	1.56	22	28.57	28.57	42.86	0.00
4	30.00	35.00	22.50	12.50	23	15.38	38.46	38.46	7.70
5	46.03	15.87	34.92	3.18	24	52.94	29.41	17.65	0.00
6	39.86	29.05	28.38	2.71	25	31.25	43.75	25.00	0.00
7	45.56	21.11	28.89	4.44	26	55.56	11.11	33.33	0.00
8	53.85	25.64	20.51	0.00	27	73.33	13.33	13.33	0.01
9	47.62	9.52	42.86	0.00	28	50.00	16.67	16.67	16.66
10	71.15	13.46	12.50	2.89	29	8.33	16.67	75.00	0.00
11	65.71	19.43	12.00	2.86	30	28.57	0.00	71.43	0.00
12	62.50	25.00	12.50	0.00	31	50.00	0.00	50.00	0.00
13	55.45	28.18	16.36	0.01	32	66.67	16.67	16.68	0.00
14	54.78	25.22	18.26	1.74	33	55.56	16.67	22.22	5.55
15	65.14	22.94	11.93	0.00	34	54.08	20.41	25.51	0.00
16	55.67	22.68	11.34	10.31	35	51.82	29.93	16.06	2.19
17	44.00	28.00	24.00	4.00					
18	45.00	29.38	23.75	1.87					
19	52.08	14.58	29.17	4.17					
Ave.	50.92	23.60	22.32	3.15	Ave.	42.88	22.35	31.51	3.25
Std dev.	10.75	7.01	10.26	3.35	Std dev.	18.69	13.41	19.39	6.34

Table 6.6. Crash type: results of t-test.

Comparison	*p*-value	Results
Average rear-end crash rate	0.0004	Significant at 0.01 level
Average sideswipe crash rate	0.0063	Significant at 0.01 level
Average object related crash rate	0.0128	Significant at 0.05 level
Average rear-end crash %	0.0711	Significant at 0.10 level
Average sideswipe crash %	0.3702	Not significant at 0.10 level
Average object related crash %	0.0511	Significant at 0.10 level

6.4 Identification of Influencing Factors for Crashes at On-Ramp Junctions with Auxiliary Lane

The second part of this study performed regression analysis to relate crash frequency with influencing factors at freeway on-ramp junctions with auxiliary lanes. The data collected at the 16 on-ramp junctions with auxiliary lanes (sites 20 to 35 in Table 4.1) was used to develop the regression models. In this part of the study, crash frequency at a site is defined as the number of crashes per year. The dependent variables experimented were crash frequency. Among the independent variables tested were:

- *L*, the length of auxiliary lanes measured from the end of continuous while marking until the beginning of the taper in ft;
- *N*, the number of main lanes on freeway;
- ADTPL, Average Daily Traffic Per Lane on the freeway, in veh/day/lane (computed from the available 2003 ADT); and
- P_{HV}, the percentage of heavy vehicles among the traffic on the freeway, in %.

The CRIS and other databases in Texas do not have information on the ramp volume and heavy vehicle percentage on the ramp. Traffic data from the ramp was not included among the independent variables. Table 6.7 shows the factors along with the crash frequency and crash severity for the 16 on-ramp junctions with auxiliary lanes.

Table 6.7. Lists of factors, crash frequency and crash severity for on-ramp junctions with auxiliary lanes.

Site no.	*L* (ft)	*N*	ADTPL (veh/day/lane)	Truck percentage (%)	Crash frequency (crashes/year)
20	150	2	22435	16.9	0.83
21	600	2	55645	12.7	4.17
22	100	2	22435	16.9	1.17
23	330	2	29985	15.1	2.17
24	400	4	34635	9.1	5.67
25	580	4	34635	9.1	2.67
26	280	3	28313	13.5	1.50
27	260	3	28313	13.5	2.50
28	510	4	28500	8.2	1.00
29	490	4	28500	8.2	2.00
30	430	3	33393	8.8	1.17
31	770	3	33393	8.8	0.33
32	600	3	36417	8.4	1.00
33	450	3	36417	8.4	3.00
34	290	4	65980	8.2	16.33
35	260	4	67078	8.2	22.83

Multiple linear regression and binomial regression were performed with the data as described above. The dependent variable (crash frequency) was regressed with many combinations of the independent variables. It was found that, with the same dependent variables, the multiple linear regression model provided a better fit than the binomial regression model. Table 6.8 shows the best model found. The models may be written as:

$$\text{Crash frequency} = -0.01748L + 0.0920N + 3.454\text{x}10^{-4}\text{ADTPL} - 0.4016P_{HV} \qquad (6.2)$$

Table 6.8. Results of the best multiple linear regression analysis

Independent variables	Crash frequency (crashes/year)	
	Estimated coefficient	*p*-value of coefficient
L	-0.01748	1.630×10^{-5}
N	0.9920	0.0784
ADTPL	3.454×10^{-4}	3.456×10^{-7}
P_{HV}	-0.4016	4.630×10^{-4}
R^2	0.9555	
p-value of the model	1.463×10^{-7}	

The results in Table 6.9 and equation (2) show that crash frequency at on-ramp junctions with auxiliary lanes is significantly affected by the length of the auxiliary lane (*L*), the number of lanes on the freeway (*N*), the ADTPL on the freeway and percentage of heavy vehicles on the freeway (P_{HV}). The R^2 value of the model is 0.9555. The *p*-value of the model is 1.463×10^{-7}, which means that the model explains the variation of crash frequency between on-ramp junction sites significantly at <0.001 level. The coefficient of *L* is -0.01748. In terms of geometry of the auxiliary lane, longer auxiliary lane will result in fewer crashes per year. The coefficient may be interpreted that every 100 ft increase in the length of auxiliary lane will reduce 1.748 crashes per year (when $100 \text{ ft} \leq L \leq 770 \text{ ft}$). *N* has a positive coefficient. That may be because a higher *N* will result in more lane changing activities. A positive coefficient is also found for ADTPL. This is expected as a higher traffic volume per lane means more exposure. However, increasing the percentage of heavy vehicles in the traffic composition will reduce the crash frequency. This may be because heavy vehicles tend to be driven with smaller fluctuation in speed on freeways, due to their inertia.

To demonstrate the accuracy of predictions of equation (2) compared to historical crash frequency, Figure 6.1 plots the predicted crash frequency versus the observed crash frequency at the 16 sites. Most of the data points fall closely to the 45% line, indicating that the fitted multiple linear regression model provides a reasonably good prediction. The only exception is the data point for site 31, which the model gives a negative crash frequency. According to the results of the multiple linear regression, the model has a root mean squared error of 1.975 crashes/year.

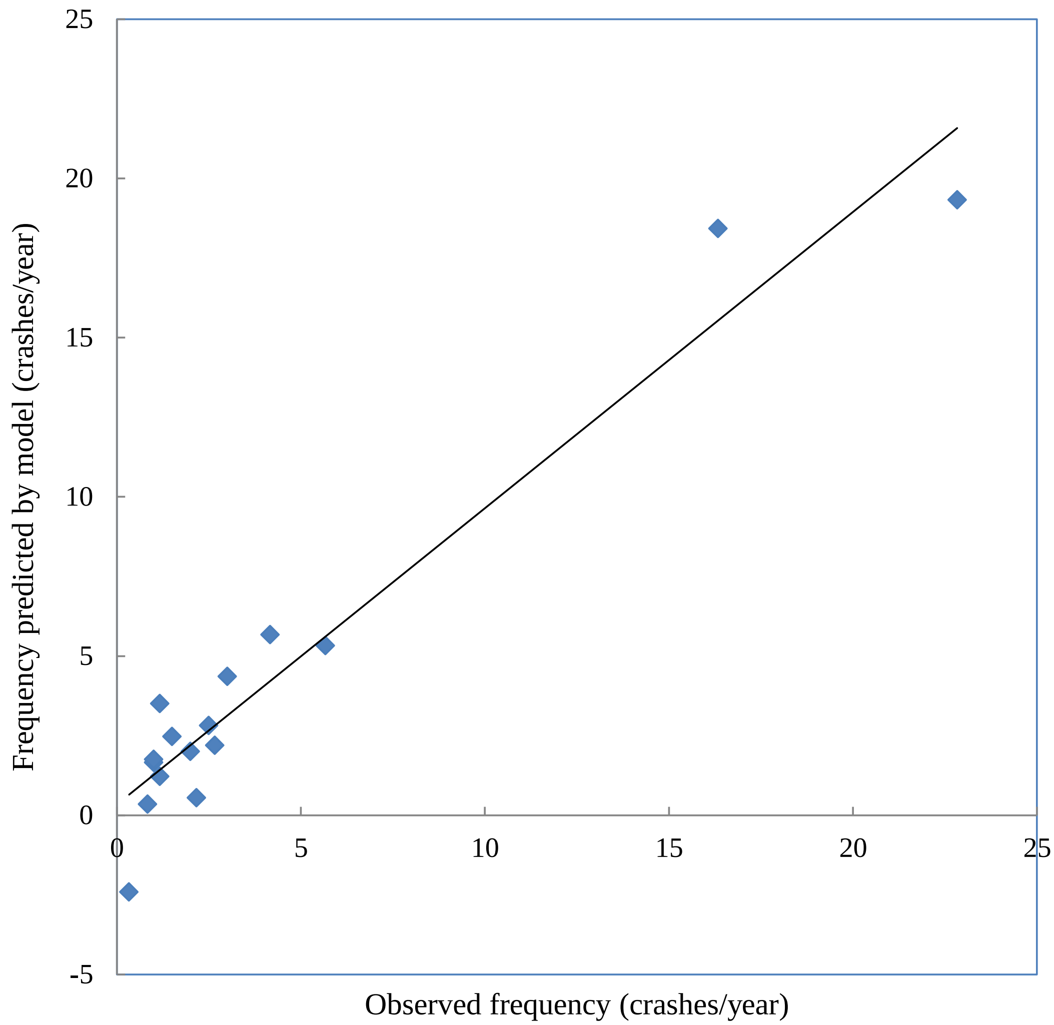


Figure 6.1. Predicted crash frequency versus observed crash frequency.

Other dependent variables, such as crash severity, were regressed with different combinations of independent variables. However, the resulting models were found to be not statistically significant in explaining the variation in the dependent variables.

6.5 Chapter Summary

To quantitatively assess the safety impacts of having auxiliary lanes at isolated freeway on-ramp junctions, a two-part study have been conducted: (1) comparisons of crash rate, crash severity, and major crash types at sites with and without an auxiliary lane, and (2) developing a linear regression model for on-ramp junctions with auxiliary lanes to relate crash frequency with influencing geometric and traffic factors.

The results of the first part of study show that on-ramp junctions with auxiliary lanes have a significantly lower average crash rate (in terms of number of crashes per MEV). Although the average crash rate is lower at the on-ramp junctions with auxiliary lanes, there is no significant change in the average crash severity (i.e., portion of crashes that are fatal or result in injuries). With regards to crash types, sites with auxiliary lanes are observed to have significantly lower proportion of rear-end crashes and higher proportion of objected related crashes.

The results of the second part of study show that crash frequency at on-ramp junctions with auxiliary lanes is negatively influenced by the length of the auxiliary lane, the percentage of heavy vehicles on the freeway. Nonetheless, it is positively influenced by the number of lanes on the freeway and the average daily traffic per lane on the freeway.

Chapter 7

Influencing Areas of Weaving Segments

This analysis was conducted to evaluate the operational impacts of auxiliary lanes at upstream and downstream of a FWS. First, the lengths of influencing areas upstream and downstream of FWSs under different combinations of traffic volume and geometric configurations with and without auxiliary lanes will be identified and compared. Then, equations will be developed to predict the length of influencing area with and without auxiliary lanes.

7.1 Comparison of Length of Influence Areas with and without Auxiliary Lane

There are a total of 196 scenarios with auxiliary lanes and 196 scenarios without auxiliary lanes. The lengths of the influence areas are estimated by VISSIM for both the upstream and downstream of the weaving segment for each scenario. Table 7.1 shows the lengths of influencing areas at upstream and downstream of a weaving segment with auxiliary lane. Table 7.2 shows the lengths of influencing areas at upstream and downstream, of a weaving segment without an auxiliary lane. From Table 7.1 and Table 7.2, it can be seen that, with the addition of an auxiliary lane, the upstream and downstream influencing areas become shorter; that is, adding an auxiliary lane can mitigate the influence of weaving movements on mainline traffic.

Table 7.1. Influencing area length at weaving segment with auxiliary lane.

Influencing Area Length at weaving segment with auxiliary lane (ft)															
	Upstream								Downstream						
	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	100	200	300	400	500	600	700
L_s=1000 ft	500	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	750	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1250	0	0	0	0	0	0	0	0	0	0	0	100	300	600
	1500	0	0	0	1100	2700	3000	2800	0	100	400	900	1300	1400	1800
	1750	3000	2900	3000	3000	3000	3000	3000	2600	2800	3000	3000	3000	3000	3000
	2000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
L_s=1500 ft	500	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	750	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1250	0	0	0	0	0	0	0	0	0	0	0	0	0	100
	1500	0	0	0	1200	2600	3000	3000	0	0	100	500	1000	1300	2000
	1750	2400	3000	3000	3000	3000	3000	3000	2800	3000	3000	3000	3000	3000	3000
	2000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
L_s=2000 ft	500	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	750	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1250	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1500	0	0	0	1000	2500	3000	3000	0	0	0	300	500	1200	1700
	1750	2800	3000	3000	3000	3000	3000	3000	2600	2900	3000	3000	3000	3000	3000
	2000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
L_s=2500 ft	500	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	750	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1250	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1500	0	0	0	0	2500	2700	2900	0	0	0	100	400	700	1800
	1750	2600	3000	3000	3000	3000	3000	3000	2300	3000	3000	3000	3000	3000	3000
	2000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000

Table 7.2. Influencing area length at weaving segment without auxiliary lane.

Influencing Area Length at weaving segment without auxiliary lane (ft)

L_s=1000 ft

	Upstream								Downstream						
v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700
500	0	0	0	0	200	200	300	500	0	0	0	0	0	0	100
750	0	0	0	100	200	300	300	750	0	0	0	0	100	200	200
1000	0	0	0	200	300	400	400	1000	0	0	100	200	300	400	400
1250	0	0	200	300	400	400	500	1250	0	200	400	400	500	500	600
1500	100	300	400	700	1200	2000	2900	1500	400	600	700	700	700	800	800
1750	2600	3000	3000	3000	3000	3000	3000	1750	1600	1400	1700	1200	1100	1000	1000
2000	3000	3000	3000	3000	3000	3000	3000	2000	2900	2800	1500	1200	1200	1200	1200

L_s=1500 ft

	Upstream								Downstream						
v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700
500	0	0	0	0	200	200	300	500	0	0	0	0	0	0	0
750	0	0	0	0	200	300	400	750	0	0	0	0	100	100	200
1000	0	0	0	200	300	300	400	1000	0	0	0	200	300	300	400
1250	0	0	200	300	400	400	500	1250	0	200	300	400	500	500	500
1500	0	300	500	700	700	2500	3000	1500	300	600	600	700	700	800	700
1750	2700	3000	3000	3000	3000	3000	3000	1750	1500	1700	1500	1100	1000	1000	1000
2000	3000	3000	3000	3000	3000	3000	3000	2000	2900	2800	1900	1900	1900	1900	1900

L_s=2000 ft

	Upstream								Downstream						
v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700
500	0	0	0	0	200	200	300	500	0	0	0	0	0	0	0
750	0	0	0	100	200	300	400	750	0	0	0	0	100	100	200
1000	0	0	0	200	300	300	500	1000	0	0	100	200	300	300	400
1250	0	0	200	300	400	400	600	1250	0	200	300	400	500	500	500
1500	0	300	500	700	1800	2700	3000	1500	300	600	700	700	700	700	700
1750	2500	3000	3000	3000	3000	3000	3000	1750	2000	1400	1100	1100	1100	1100	1100
2000	3000	3000	3000	3000	3000	3000	3000	2000	2800	2300	2300	2300	2300	2300	2300

L_s=2500 ft

	Upstream								Downstream						
v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700
500	0	0	0	0	200	200	300	500	0	0	0	0	0	0	0
750	0	0	0	100	200	300	400	750	0	0	0	0	0	100	100
1000	0	0	0	200	300	400	500	1000	0	0	100	200	300	300	300
1250	0	0	200	300	400	500	600	1250	0	200	300	400	500	500	500
1500	100	300	500	900	2100	2600	2800	1500	300	500	600	700	700	700	700
1750	2300	3000	3000	3000	3000	3000	3000	1750	1900	1300	1200	1100	1000	1000	1000
2000	3000	3000	3000	3000	3000	3000	3000	2000	2800	2800	1700	1700	1700	1700	1700

7.2 Models for Predicting the Lengths of Influencing Area

Based on the lengths of influencing areas under different combinations of weaving segment length (L_s), freeway volume (v_F) and ramp volume (v_R), equations are developed for predicting the lengths of the influencing areas. The results showed that, weaving segment length (L_s) has no significant impacts on the length of influencing area; while freeway volume (v_F) and ramp volume (v_R) have significant impacts on the length of influencing area. Therefore, in the equations developed as follow, the dependent variables are the lengths of influencing area upstream or downstream of a weaving segment with or without auxiliary lanes. The independent variables are freeway volume (v_F) and ramp volume (v_R). The following parts of this section show the equations for weaving segment with auxiliary lane and without auxiliary lane separately.

- *Weaving segment with an auxiliary lane*

Equation (7.1) was developed, by means of linear regression analysis, to predict the length of influencing area at the upstream of a weaving segment with auxiliary lane.

$$L_{1UPI} = \exp(0.0063v_F + 0.0024v_R - 5.9873) \quad R^2 = 0.70 \qquad (7.1)$$

where L_{1UPI} is the length of influencing area upstream of a weaving segment with an auxiliary lane. In L_{1UPI}, the subscript "1" denote the presence of an auxiliary, while the subscript "*UPI*" denotes upstream influence area. Table 7.3 shows the *p*-values for the model and coefficients for Equation (7.1).

The results in Equation (7.1) and Table 7.3 showed the length of influencing area upstream of a weaving segment with auxiliary lane is significantly affected by the freeway volume (v_F) and ramp volume (v_R). The R^2 value of the equation is 0.70. The *p*-value of the model is 7.41×10^{-51}, which means that the equation explains the variation of influencing area

length significantly at <0.001 level. The coefficients of v_F and v_R are both positive, which means higher freeway volume and ramp volume will result in a longer influencing area.

Table 7.3. *p*-value for Equation (7.1).

	p-value
Model	7.41E-51
Intercept coefficient	1.49E-24
v_F coefficient	2.54E-51
v_R coefficient	0.0014

Equation (7.2) was developed to predict the influencing area length at the downstream of a weaving segment with auxiliary lane.

$$L_{1DOWNI} = \exp(0.0063 v_F + 0.0026 v_R - 5.9431) \quad R^2 = 0.74 \tag{7.2}$$

where L_{1DOWNI} is the length of influencing area downstream of a weaving segment with an auxiliary lane. In L_{1DOWNI}, the subscript "1" denote the presence of an auxiliary, while the subscript "*DOWNI*" denotes upstream influence area. Table 7.4 shows the *p*-values for equation 7.2.

The results in Equation (7.2) and Table 7.4 show that the length of influencing area downstream of a weaving segment with an auxiliary lane is significantly affected by the freeway volume (v_F) and ramp volume (v_R). The R^2 value of the equation is 0.74. The *p*-value of the model is 1.06×10^{-57}, which means that the equation explains the variation of influencing area length significantly at <0.001 level. The coefficients of v_F and v_R are both positive, which means higher freeway volume and ramp volume will result in longer influencing area length.

Table 7.4. *p*-value for Equation (7.2).

	P value
Model	1.06E-57
Intercept coefficient	2.78E-28
v_F coefficient	4.72E-58
v_R coefficient	0.0002

- *Weaving segment without an auxiliary lane*

Equation (7.3) was developed to predict the length of the influencing area length at the upstream of a weaving segment without an auxiliary lane.

$$L_{0UPI} = \exp(0.0043v_F + 0.0040v_R - 3.6082) \quad R^2 = 0.74 \qquad (7.3)$$

where L_{0UPI} is the length of influencing area upstream of a weaving segment without an auxiliary lane. . In L_{0UPI} , the subscript "0" denote the absence of an auxiliary, while the subscript "*UPI*" denotes upstream influence area. Table 7.5 shows the *p*-values for Equation (7.3).

The results in Equation (7.3) and Table 7.5 show that the length of influencing area upstream of a weaving segment without an auxiliary lane is significantly affected by the freeway volume (v_F) and ramp volume (v_R). The R^2 value of the equation is 0.74. The *p*-value of the model is 7.37×10^{-57}, which means that the equation explains the variation of influencing area length significantly at <0.001 level. The coefficients of v_F and v_R are both positive, which means higher freeway volume and ramp volume will result in longer influencing area length.

Table 7.5. P-value for equation 7.3.

	p-value
Model	7.37E-57
Intercept coefficient	2.53E-17
v_F coefficient	3.88E-45
v_R coefficient	4.65E-31

Equation (7.3) was developed to predict the influencing area length at the upstream of a weaving segment without auxiliary lane.

$$L_{0DOWNI} = \exp(0.0051 v_F + 0.0042 v_R - 3.4256) \quad R^2 = 0.77 \tag{7.4}$$

where L_{0DOWNI} is the length of influencing area downstream of a weaving segment without auxiliary lane. Table 7.6 shows the P-values for equation 7.4.

The results in Equation (7.4) and Table 7.6 showed the length of influencing area upstream of a weaving segment with auxiliary lane is significantly affected by the freeway volume (v_F) and ramp volume (v_R). The R^2 value of the equation is 0.77. The *p*-value of the model is 9.01×10^{-63}, which means that the equation explains the variation of influencing area length significantly at <0.001 level. The coefficients of v_F and v_R are both positive, which means higher freeway volume and ramp volume will result in longer influencing area length.

Table 7.6. P-value for equation 7.4.

	p-value
Model	9.01E-63
Intercept coefficient	1.07E-18
v_F coefficient	1.38E-60
v_R coefficient	6.39E-14

7.3 Chapter Summary

This analysis identified and compared the lengths of influencing areas upstream and downstream of FWSs under different combinations of traffic volume and geometric configurations with and without auxiliary lanes. In addition, this analysis also developed equations to predict the length of influencing area with and without auxiliary lanes.

The results showed that, with the addition of an auxiliary lane, the upstream and downstream influencing areas become shorter; that is, adding an auxiliary lane can mitigate the influence of weaving movements on mainline traffic. In addition, the results also showed that the lengths of influencing area are significantly affected by the freeway volume and ramp volume, higher freeway volume and ramp volume will result in longer influencing area length.

Chapter 8

Conclusions and Recommendations for Future Research

8.1 Conclusions

In this dissertation, five analyses have been conducted to assess the operational and safety impacts of auxiliary lanes at freeway ramp locations, including (1) operational analysis of weaving segments; (2) operational analysis of on-ramp junctions; (3) operational analysis of off-ramp junctions; (4) safety analysis of on-ramp junctions; and (5) analysis on upstream and downstream influencing areas of weaving segments.

For analyses (1), (2) and (3), the operational performance of weaving segments, on-ramp junctions, and off-ramp junctions, with and without an auxiliary lane under different design scenarios have been evaluated by means of HCS2010. Based on the analysis of traffic density and LOS before and after the inclusion of an auxiliary lane, the operational benefits of adding auxiliary lanes are visualized and quantified (see Tables 5.1, 5.2, 5.3, 5.4, 5.6, and 5.7). The results show that, after adding an auxiliary lane, the density reduced and LOS improved. At weaving segments, adding an auxiliary lane reduces density by 1.6 to 19.5 pc/mi/ln or 4% to 50%. A higher percentage reduction in density can be achieved when the length of weaving segment is shorter and weaving volume is higher. At on-ramp junctions, after the addition of an auxiliary lane, the density in the merge influence area reduces by 3.0 pc/mi/ln when the length of acceleration lane is 500 ft, and up to 9.4 pc/mi/ln when the length of acceleration lane is 1500 ft. At off-ramp junctions, after the addition of an auxiliary lane, the density in the diverge influence area reduces by 4.5 pc/mi/h when the length of deceleration lane is 500 ft, and up to 13.5 pc/mi/ln when the length of deceleration lane is 1500 ft. In addition, based on the results of these three analyses, guidance charts (Figures 5.1 and 5.2) have been developed which contain

recommendations on when to add auxiliary lanes at FWSs and on-ramp junctions under different combinations of freeway volume and ramp volume. For off-ramps, auxiliary lanes should be added when freeway volume is greater than 1500 pc/h/ln. Finally, for on-ramp junctions and off-ramp junctions, recommendations for the minimum length of auxiliary lane under different combinations of number of freeway lanes, freeway volume and off-ramp speed have also been developed. Look-up tables (Tables 5.5 and 5.8) for the minimum length of auxiliary lane at isolated on- and off- ramps have been developed for design engineers to use as a quick reference.

For analysis (4), to quantitatively assess the safety impacts of having auxiliary lanes at isolated freeway on-ramp junctions, a two-part study have been conducted: (1) comparisons of crash rate, crash severity, and major crash types at sites with and without an auxiliary lane, and (2) developing a linear regression model for on-ramp junctions with auxiliary lanes to relate crash frequency with influencing geometric and traffic factors. The results of the first part of study show that on-ramp junctions with auxiliary lanes have a significantly lower average crash rate (in terms of number of crashes per MEV). Although the average crash rate is lower at the on-ramp junctions with auxiliary lanes, there is no significant change in the average proportions of crash severity (i.e., portion of crashes that are fatal or result in injuries). With regards to crash types, sites with auxiliary lanes are observed to have significantly lower proportion of rear-end crashes and higher proportion of objected related crashes. The results of the second part of study show that crash frequency at on-ramp junctions with auxiliary lanes is negatively influenced by the length of the auxiliary lane, the percentage of heavy vehicles on the freeway. Nonetheless, it is positively influenced by the number of lanes on the freeway and the average daily traffic per lane on the freeway.

For analysis (5), to identify the influence area of a weaving segment, VISSIM was used to simulate traffic operations in order to estimate the speeds at upstream and downstream of the weaving segments under different combinations of freeway volume and ramp volume. The influence areas were identified where the speeds were 5 mph lower than the free flow speed at freeways. Equations were developed for predicting the length of influence areas upstream and downstream of a weaving segment with or without an auxiliary lane. The results showed that the lengths of influencing area are exponentially affected by freeway volume and ramp volume; higher freeway volume and ramp volume will result in a longer influencing area.

8.2 Contributions

This research is believed to be one of the first to (i) quantify the operational improvements, in terms of density and LOS, before the after the implementation of auxiliary lanes at weaving segments, on-ramp junctions, and off-ramp junctions; (ii) develop recommendations on when to implement auxiliary lane at weaving segments, on-ramp junctions and off-ramp junctions; and how long auxiliary lane should be at on-ramp junctions and off-ramp junctions; (iii) investigated crash statistics at isolated freeway on-ramp junctions with and without an auxiliary lane; and (iv) investigate the extent of influence areas upstream and downstream of a weaving segment.

The developed guidelines can be used by engineers in the design of weaving segments, on-ramp junctions, and off-ramp junctions, without having to perform complex calculations according to HCM2010 analysis procedure.

8.3 Recommendations for Future Research

This dissertation investigated the operational and safety impacts of auxiliary lanes at freeway weaving segments, on-ramp junctions, and off-ramp junctions. The analyses of this

study are all based on isolated weaving segments, isolated on-ramps, and isolated off-ramps with one lane entrance or exit. That is, the weaving segments, on-ramp junctions and off-ramp junctions are at least 2500 ft from any on-ramp, off-ramp, work zone, geometric changes and etc that may cause disturbance in traffic flow. Future study can incorporate corridor level networks (i.e, weaving segments, on-ramp junctions and off-ramp junctions that are within 2500 ft from each other) to incorporate traffic interaction, if any. The weaving segments, on-ramp junctions and off-ramp junctions investigated in this study have only considered one-lane ramps. Future study should also include two-lane ramp in the designs.

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Appendix A

HCS2010 Input and Output Interfaces

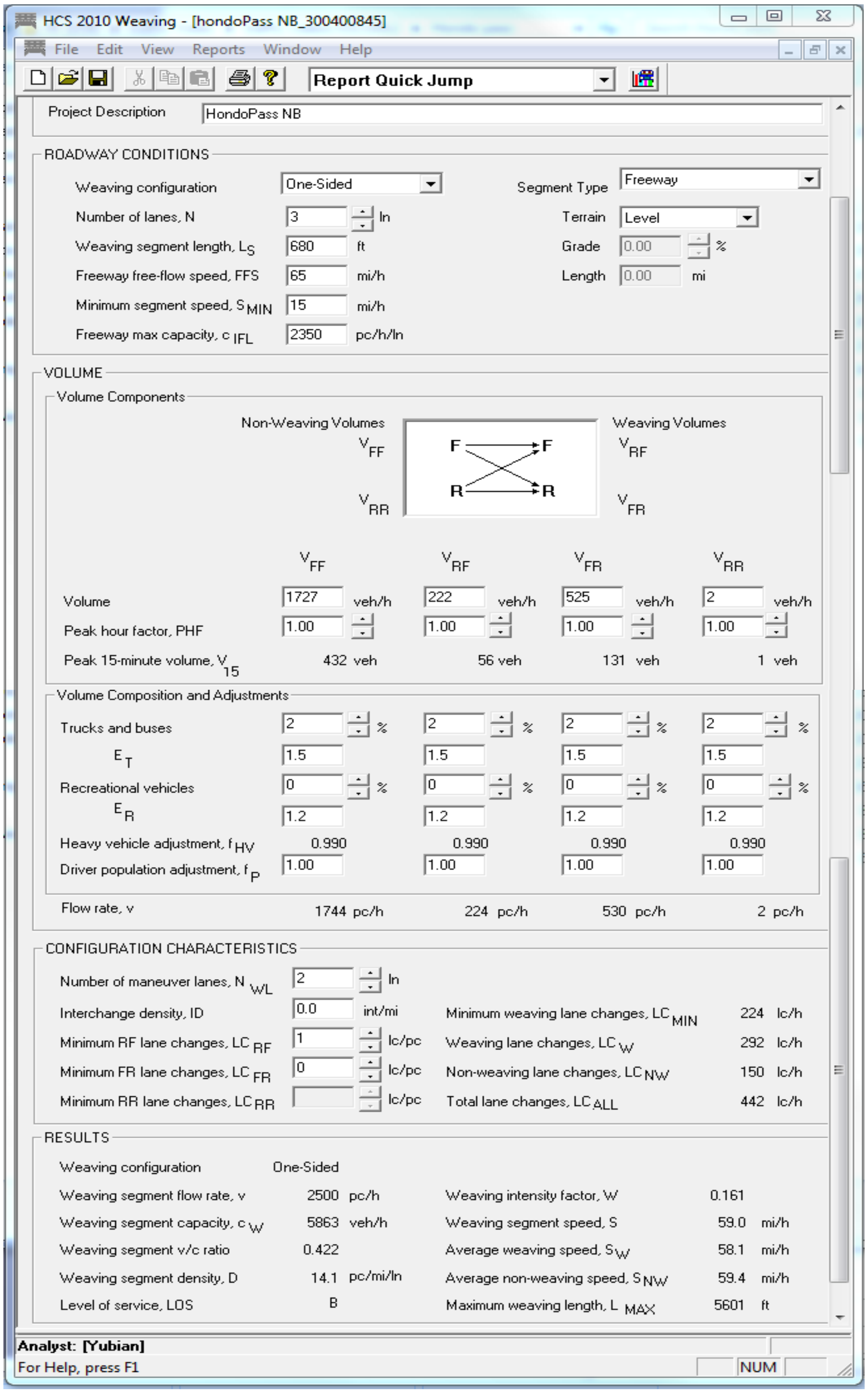

Figure A1. Screen shot of HCS2010 weaving module.

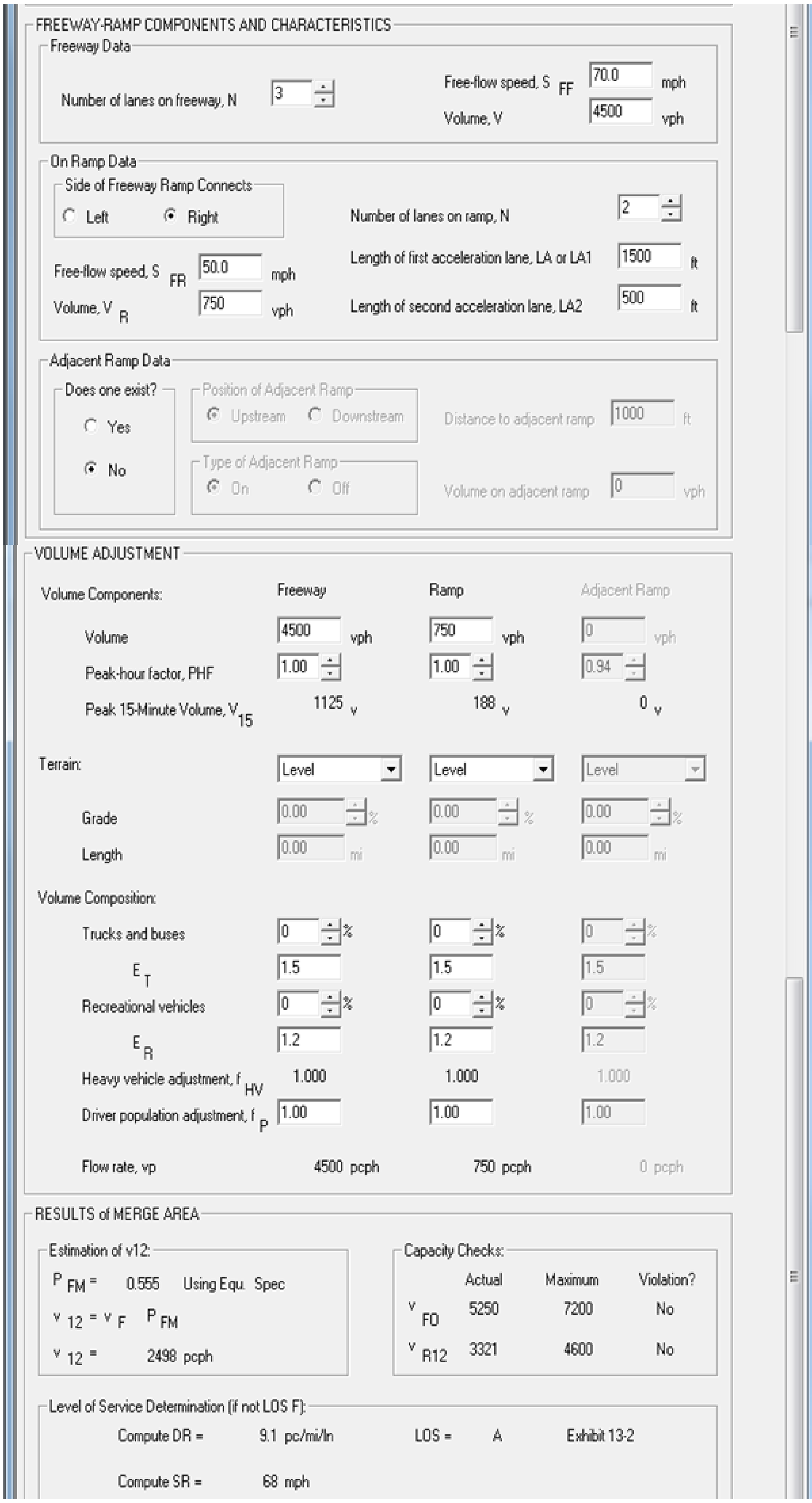

Figure A2. Screen shot of HCS2010 ramp module for on-ramp junctions.

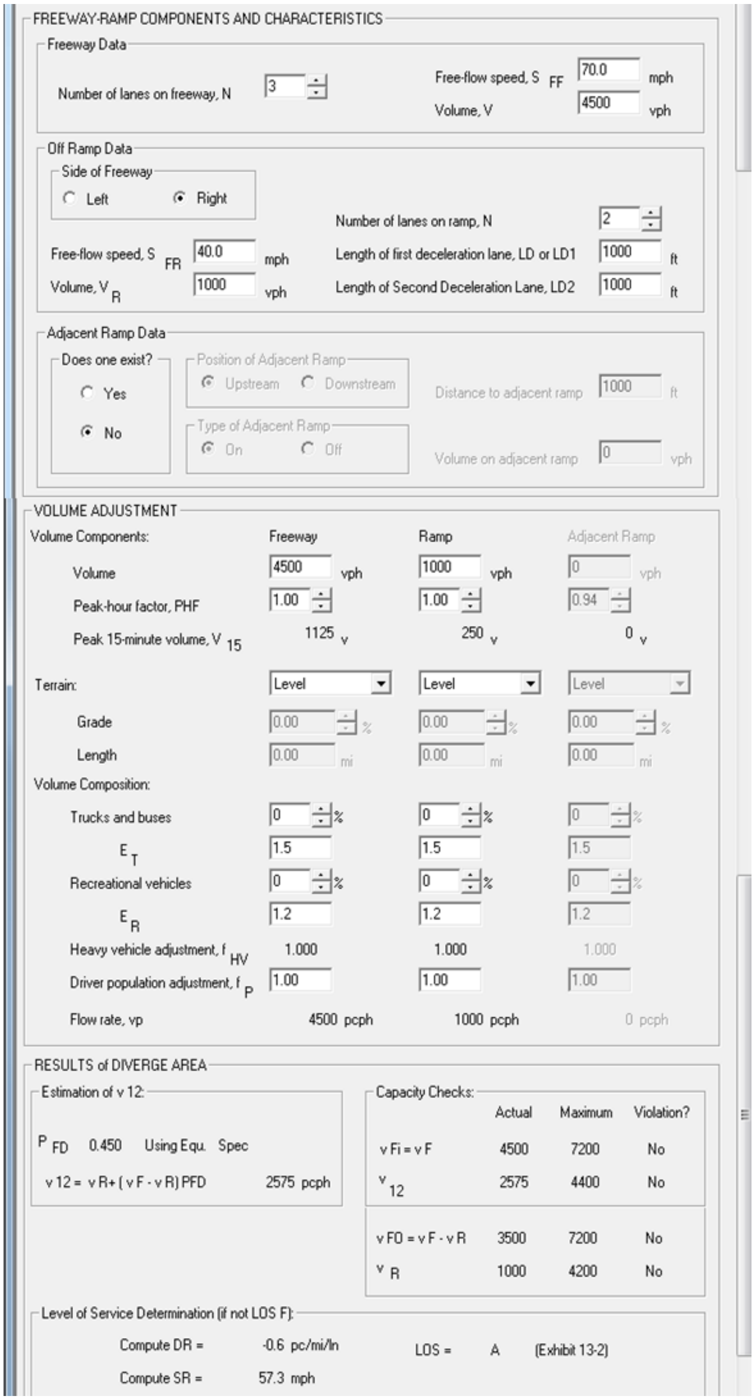

Figure A3. Screen shot of HCS2010 ramp module for off-ramp junctions.

Appendix B

Density in the Merge Influence Area under Different Length of Acceleration Lane Length

Table B1. Density in the merge influence area under different length of acceleration lane length for four lane two way freeway.

	Density in the merge influence area (pc/mi/ln)										
Without auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	14.0	14.7	15.5	16.2	16.9	17.7	18.4	19.1	19.9	20.6
	750	17.9	18.6	19.4	20.1	20.8	21.6	22.3	23.0	23.8	24.5
	1000	21.8	22.5	23.3	24.0	24.7	25.5	26.2	26.9	27.7	28.4
L_A=0 ft	1250	25.7	26.4	27.2	27.9	28.6	29.4	30.1	30.8	31.6	32.3
	1500	29.6	30.3	31.1	31.8	32.5	33.3	34.0	34.7	35.5	36.2
	1750	33.5	34.2	35.0	35.7	36.4	37.2	37.9	38.6	39.4	40.1
	2000	37.4	38.1	38.9	39.6	40.3	41.1	41.8	42.5	43.3	44.0
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	13.4	14.1	14.9	15.6	16.3	17.1	17.8	18.5	19.3	20.0
	750	17.3	18.0	18.8	19.5	20.2	21.0	21.7	22.4	23.2	23.9
	1000	21.2	21.9	22.7	23.4	24.1	24.9	25.6	26.3	27.1	27.8
L_A=100 ft	1250	25.1	25.8	26.6	27.3	28.0	28.8	29.5	30.2	31.0	31.7
	1500	29.0	29.7	30.5	31.2	31.9	32.7	33.4	34.1	34.9	35.6
	1750	32.9	33.6	34.4	35.1	35.8	36.6	37.3	38.0	38.8	39.5
	2000	36.8	37.5	38.3	39.0	39.7	40.5	41.2	41.9	42.7	43.4
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	12.8	13.5	14.2	15.0	15.7	16.4	17.2	17.9	18.6	19.4
	750	16.7	17.4	18.1	18.9	19.6	20.3	21.1	21.8	22.5	23.3
	1000	20.6	21.3	22.0	22.8	23.5	24.2	25.0	25.7	26.4	27.2
L_A=200 ft	1250	24.5	25.2	25.9	26.7	27.4	28.1	28.9	29.6	30.3	31.1
	1500	28.4	29.1	29.8	30.6	31.3	32.0	32.8	33.5	34.2	35.0
	1750	32.3	33.0	33.7	34.5	35.2	35.9	36.7	37.4	38.1	38.9
	2000	36.2	36.9	37.6	38.4	39.1	39.8	40.6	41.3	42.0	42.8
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	12.1	12.9	13.6	14.3	15.1	15.8	16.5	17.3	18.0	18.7
	750	16.0	16.8	17.5	18.2	19.0	19.7	20.4	21.2	21.9	22.6
	1000	19.9	20.7	21.4	22.1	22.9	23.6	24.3	25.1	25.8	26.5
L_A=300 ft	1250	23.8	24.6	25.3	26.0	26.8	27.5	28.2	29.0	29.7	30.4
	1500	27.7	28.5	29.2	29.9	30.7	31.4	32.1	32.9	33.6	34.3
	1750	31.6	32.4	33.1	33.8	34.6	35.3	36.0	36.8	37.5	38.2
	2000	35.5	36.3	37.0	37.7	38.5	39.2	39.9	40.7	41.4	42.1

Table B1. Density in the merge influence area under different length of acceleration lane length for four lane two way freeway. (Continued)

	Density in the merge influence area (pc/mi/ln)										
	v_F	v_R (pc/h/ln)									
With one auxiliary lane	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	11.5	12.2	13.0	13.7	14.4	15.2	15.9	16.6	17.4	18.1
	750	15.4	16.1	16.9	17.6	18.3	19.1	19.8	20.5	21.3	22.0
L_A=400 ft	1000	19.3	20.0	20.8	21.5	22.2	23.0	23.7	24.4	25.2	25.9
	1250	23.2	23.9	24.7	25.4	26.1	26.9	27.6	28.3	29.1	29.8
	1500	27.1	27.8	28.6	29.3	30.0	30.8	31.5	32.2	33.0	33.7
	1750	31.0	31.7	32.5	33.2	33.9	34.7	35.4	36.1	36.9	37.6
	2000	34.9	35.6	36.4	37.1	37.8	38.6	39.3	40.0	40.8	41.5
	v_F	v_R (pc/h/ln)									
With one auxiliary lane	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	10.9	11.6	12.3	13.1	13.8	14.5	15.3	16.0	16.7	17.5
	750	14.8	15.5	16.2	17.0	17.7	18.4	19.2	19.9	20.6	21.4
	1000	18.7	19.4	20.1	20.9	21.6	22.3	23.1	23.8	24.5	25.3
L_A=500 ft	1250	22.6	23.3	24.0	24.8	25.5	26.2	27.0	27.7	28.4	29.2
	1500	26.5	27.2	27.9	28.7	29.4	30.1	30.9	31.6	32.3	33.1
	1750	30.4	31.1	31.8	32.6	33.3	34.0	34.8	35.5	36.2	37.0
	2000	34.3	35.0	35.7	36.5	37.2	37.9	38.7	39.4	40.1	40.9
	v_F	v_R (pc/h/ln)									
With one auxiliary lane	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	10.2	11.0	11.7	12.4	13.2	13.9	14.7	15.4	16.1	16.9
	750	14.1	14.9	15.6	16.3	17.1	17.8	18.6	19.3	20.0	20.8
	1000	18.0	18.8	19.5	20.2	21.0	21.7	22.5	23.2	23.9	24.7
L_A=600 ft	1250	21.9	22.7	23.4	24.1	24.9	25.6	26.4	27.1	27.8	28.6
	1500	25.8	26.6	27.3	28.0	28.8	29.5	30.3	31.0	31.7	32.5
	1750	29.7	30.5	31.2	31.9	32.7	33.4	34.2	34.9	35.6	36.4
	2000	33.6	34.4	35.1	35.8	36.6	37.3	38.1	38.8	39.5	40.3
	v_F	v_R (pc/h/ln)									
With one auxiliary lane	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	9.6	10.4	11.1	11.8	12.6	13.3	14.0	14.8	15.5	16.2
	750	13.5	14.3	15.0	15.7	16.5	17.2	17.9	18.7	19.4	20.1
	1000	17.4	18.2	18.9	19.6	20.4	21.1	21.8	22.6	23.3	24.0
L_A=700 ft	1250	21.3	22.1	22.8	23.5	24.3	25.0	25.7	26.5	27.2	27.9
	1500	25.2	26.0	26.7	27.4	28.2	28.9	29.6	30.4	31.1	31.8
	1750	29.1	29.9	30.6	31.3	32.1	32.8	33.5	34.3	35.0	35.7
	2000	33.0	33.8	34.5	35.2	36.0	36.7	37.4	38.2	38.9	39.6

Table B1. Density in the merge influence area under different length of acceleration lane length for four lane two way freeway. (Continued)

	Density in the merge influence area (pc/mi/ln)										
With an auxiliary lane	v_F	v_R (pc/h/ln)									
	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	9.0	9.7	10.5	11.2	11.9	12.7	13.4	14.1	14.9	15.6
	750	12.9	13.6	14.4	15.1	15.8	16.6	17.3	18.0	18.8	19.5
	1000	16.8	17.5	18.3	19.0	19.7	20.5	21.2	21.9	22.7	23.4
L_A=800 ft	1250	20.7	21.4	22.2	22.9	23.6	24.4	25.1	25.8	26.6	27.3
	1500	24.6	25.3	26.1	26.8	27.5	28.3	29.0	29.7	30.5	31.2
	1750	28.5	29.2	30.0	30.7	31.4	32.2	32.9	33.6	34.4	35.1
	2000	32.4	33.1	33.9	34.6	35.3	36.1	36.8	37.5	38.3	39.0
With one auxiliary lane	v_F	v_R (pc/h/ln)									
	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	8.4	9.1	9.8	10.6	11.3	12.0	12.8	13.5	14.2	15.0
	750	12.3	13.0	13.7	14.5	15.2	15.9	16.7	17.4	18.1	18.9
	1000	16.2	16.9	17.6	18.4	19.1	19.8	20.6	21.3	22.0	22.8
L_A=900 ft	1250	20.1	20.8	21.5	22.3	23.0	23.7	24.5	25.2	25.9	26.7
	1500	24.0	24.7	25.4	26.2	26.9	27.6	28.4	29.1	29.8	30.6
	1750	27.9	28.6	29.3	30.1	30.8	31.5	32.3	33.0	33.7	34.5
	2000	31.8	32.5	33.2	34.0	34.7	35.4	36.2	36.9	37.6	38.4
With one auxiliary lane	v_F	v_R (pc/h/ln)									
	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	7.7	8.5	9.2	9.9	10.7	11.4	12.1	12.9	13.6	14.3
	750	11.6	12.4	13.1	13.8	14.6	15.3	16.0	16.8	17.5	18.2
	1000	15.5	16.3	17.0	17.7	18.5	19.2	19.9	20.7	21.4	22.1
L_A=1000 ft	1250	19.4	20.2	20.9	21.6	22.4	23.1	23.8	24.6	25.3	26.0
	1500	23.3	24.1	24.8	25.5	26.3	27.0	27.7	28.5	29.2	29.9
	1750	27.2	28.0	28.7	29.4	30.2	30.9	31.6	32.4	33.1	33.8
	2000	31.1	31.9	32.6	33.3	34.1	34.8	35.5	36.3	37.0	37.7
With one auxiliary lane	v_F	v_R (pc/h/ln)									
	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	7.1	7.8	8.6	9.3	10.0	10.8	11.5	12.3	13.0	13.7
	750	11.0	11.7	12.5	13.2	13.9	14.7	15.4	16.2	16.9	17.6
	1000	14.9	15.6	16.4	17.1	17.8	18.6	19.3	20.1	20.8	21.5
L_A=1100 ft	1250	18.8	19.5	20.3	21.0	21.7	22.5	23.2	24.0	24.7	25.4
	1500	22.7	23.4	24.2	24.9	25.6	26.4	27.1	27.9	28.6	29.3
	1750	26.6	27.3	28.1	28.8	29.5	30.3	31.0	31.8	32.5	33.2
	2000	30.5	31.2	32.0	32.7	33.4	34.2	34.9	35.7	36.4	37.1

Table B1. Density in the merge influence area under different length of acceleration lane length for four lane two way freeway. (Continued)

	Density in the merge influence area (pc/mi/ln)										
With one auxiliary lane	v_F					v_R (pc/h/ln)					
	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	6.5	7.2	8.0	8.7	9.4	10.2	10.9	11.6	12.4	13.1
	750	10.4	11.1	11.9	12.6	13.3	14.1	14.8	15.5	16.3	17.0
	1000	14.3	15.0	15.8	16.5	17.2	18.0	18.7	19.4	20.2	20.9
L_A=1200 ft	1250	18.2	18.9	19.7	20.4	21.1	21.9	22.6	23.3	24.1	24.8
	1500	22.1	22.8	23.6	24.3	25.0	25.8	26.5	27.2	28.0	28.7
	1750	26.0	26.7	27.5	28.2	28.9	29.7	30.4	31.1	31.9	32.6
	2000	29.9	30.6	31.4	32.1	32.8	33.6	34.3	35.0	35.8	36.5
With one auxiliary lane	v_F					v_R (pc/h/ln)					
	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	5.9	6.6	7.3	8.1	8.8	9.5	10.3	11.0	11.7	12.5
	750	9.8	10.5	11.2	12.0	12.7	13.4	14.2	14.9	15.6	16.4
	1000	13.7	14.4	15.1	15.9	16.6	17.3	18.1	18.8	19.5	20.3
L_A=1300 ft	1250	17.6	18.3	19.0	19.8	20.5	21.2	22.0	22.7	23.4	24.2
	1500	21.5	22.2	22.9	23.7	24.4	25.1	25.9	26.6	27.3	28.1
	1750	25.4	26.1	26.8	27.6	28.3	29.0	29.8	30.5	31.2	32.0
	2000	29.3	30.0	30.7	31.5	32.2	32.9	33.7	34.4	35.1	35.9
With one auxiliary lane	v_F					v_R (pc/h/ln)					
	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	5.2	6.0	6.7	7.4	8.2	8.9	9.6	10.4	11.1	11.8
	750	9.1	9.9	10.6	11.3	12.1	12.8	13.5	14.3	15.0	15.7
	1000	13.0	13.8	14.5	15.2	16.0	16.7	17.4	18.2	18.9	19.6
L_A=1400 ft	1250	16.9	17.7	18.4	19.1	19.9	20.6	21.3	22.1	22.8	23.5
	1500	20.8	21.6	22.3	23.0	23.8	24.5	25.2	26.0	26.7	27.4
	1750	24.7	25.5	26.2	26.9	27.7	28.4	29.1	29.9	30.6	31.3
	2000	28.6	29.4	30.1	30.8	31.6	32.3	33.0	33.8	34.5	35.2
With one auxiliary lane	v_F					v_R (pc/h/ln)					
	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	4.6	5.3	6.1	6.8	7.5	8.3	9.0	9.7	10.5	11.2
	750	8.5	9.2	10.0	10.7	11.4	12.2	12.9	13.6	14.4	15.1
	1000	12.4	13.1	13.9	14.6	15.3	16.1	16.8	17.5	18.3	19.0
L_A=1500 ft	1250	16.3	17.0	17.8	18.5	19.2	20.0	20.7	21.4	22.2	22.9
	1500	20.2	20.9	21.7	22.4	23.1	23.9	24.6	25.3	26.1	26.8
	1750	24.1	24.8	25.6	26.3	27.0	27.8	28.5	29.2	30.0	30.7
	2000	28.0	28.7	29.5	30.2	30.9	31.7	32.4	33.1	33.9	34.6

Table B2. Density in the merge influence area under different length of acceleration lane length for six lane two way freeway.

	Density in the merge influence area (pc/mi/ln)										
Without auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	13.0	13.7	14.4	15.2	15.9	16.6	17.4	18.1	18.8	19.6
	750	16.3	17.1	17.8	18.5	19.3	20.0	20.7	21.5	22.2	23.0
	1000	19.7	20.5	21.2	21.9	22.7	23.4	24.1	24.9	25.6	26.3
L_A=0 ft	1250	23.1	23.8	24.6	25.3	26.0	26.8	27.5	28.2	29.0	29.7
	1500	26.5	27.2	27.9	28.7	29.4	30.1	30.9	31.6	32.4	33.1
	1750	29.9	30.6	31.3	32.1	32.8	33.5	34.3	35.0	35.7	36.5
	2000	33.2	34.0	34.7	35.4	36.2	36.9	37.6	38.4	39.1	39.8
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	12.4	13.1	13.8	14.6	15.3	16.0	16.8	17.5	18.2	19.0
	750	15.8	16.5	17.2	18.0	18.7	19.4	20.2	20.9	21.6	22.4
	1000	19.2	19.9	20.6	21.4	22.1	22.8	23.6	24.3	25.0	25.8
L_A=100 ft	1250	22.6	23.3	24.0	24.8	25.5	26.2	27.0	27.7	28.4	29.2
	1500	26.0	26.7	27.4	28.2	28.9	29.6	30.4	31.1	31.8	32.6
	1750	29.3	30.1	30.8	31.5	32.3	33.0	33.7	34.5	35.2	36.0
	2000	32.7	33.5	34.2	34.9	35.7	36.4	37.1	37.9	38.6	39.3
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	11.8	12.5	13.2	14.0	14.7	15.4	16.2	16.9	17.6	18.4
	750	15.2	15.9	16.7	17.4	18.1	18.9	19.6	20.3	21.1	21.8
	1000	18.6	19.3	20.1	20.8	21.5	22.3	23.0	23.7	24.5	25.2
L_A=200 ft	1250	22.0	22.7	23.5	24.2	24.9	25.7	26.4	27.1	27.9	28.6
	1500	25.4	26.2	26.9	27.6	28.4	29.1	29.8	30.6	31.3	32.0
	1750	28.8	29.6	30.3	31.0	31.8	32.5	33.2	34.0	34.7	35.4
	2000	32.2	33.0	33.7	34.4	35.2	35.9	36.6	37.4	38.1	38.9
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	11.2	11.9	12.7	13.4	14.1	14.9	15.6	16.3	17.1	17.8
	750	14.6	15.3	16.1	16.8	17.5	18.3	19.0	19.7	20.5	21.2
	1000	18.0	18.8	19.5	20.2	21.0	21.7	22.4	23.2	23.9	24.6
L_A=300 ft	1250	21.5	22.2	22.9	23.7	24.4	25.1	25.9	26.6	27.3	28.1
	1500	24.9	25.6	26.4	27.1	27.8	28.6	29.3	30.0	30.8	31.5
	1750	28.3	29.1	29.8	30.5	31.3	32.0	32.7	33.5	34.2	34.9
	2000	31.7	32.5	33.2	34.0	34.7	35.4	36.2	36.9	37.6	38.4

Table B2. Density in the merge influence area under different length of acceleration lane length for six lane two way freeway. (Continued)

	Density in the merge influence area (pc/mi/ln)										
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	10.6	11.3	12.1	12.8	13.5	14.3	15.0	15.7	16.5	17.2
	750	14.0	14.8	15.5	16.2	17.0	17.7	18.4	19.2	19.9	20.6
	1000	17.5	18.2	18.9	19.7	20.4	21.1	21.9	22.6	23.3	24.1
L_A=400 ft	1250	20.9	21.7	22.4	23.1	23.9	24.6	25.3	26.1	26.8	27.5
	1500	24.4	25.1	25.8	26.6	27.3	28.0	28.8	29.5	30.2	31.0
	1750	27.8	28.5	29.3	30.0	30.7	31.5	32.2	32.9	33.7	34.4
	2000	31.3	32.0	32.7	33.5	34.2	34.9	35.7	36.4	37.1	37.9
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	10.0	10.7	11.5	12.2	12.9	13.7	14.4	15.1	15.9	16.6
	750	13.5	14.2	14.9	15.7	16.4	17.1	17.9	18.6	19.3	20.1
	1000	16.9	17.6	18.4	19.1	19.9	20.6	21.3	22.1	22.8	23.5
L_A=500 ft	1250	20.4	21.1	21.8	22.6	23.3	24.0	24.8	25.5	26.2	27.0
	1500	23.8	24.6	25.3	26.0	26.8	27.5	28.2	29.0	29.7	30.4
	1750	27.3	28.0	28.8	29.5	30.2	31.0	31.7	32.4	33.2	33.9
	2000	30.8	31.5	32.2	33.0	33.7	34.4	35.2	35.9	36.6	37.4
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	9.4	10.1	10.9	11.6	12.3	13.1	13.8	14.5	15.3	16.0
	750	12.9	13.6	14.3	15.1	15.8	16.5	17.3	18.0	18.7	19.5
	1000	16.4	17.1	17.8	18.6	19.3	20.0	20.8	21.5	22.2	23.0
L_A=600 ft	1250	19.8	20.6	21.3	22.0	22.8	23.5	24.2	25.0	25.7	26.4
	1500	23.3	24.0	24.8	25.5	26.2	27.0	27.7	28.4	29.2	29.9
	1750	26.8	27.5	28.3	29.0	29.7	30.5	31.2	31.9	32.7	33.4
	2000	30.3	31.0	31.7	32.5	33.2	33.9	34.7	35.4	36.1	36.9
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	8.8	9.5	10.3	11.0	11.7	12.5	13.2	13.9	14.7	15.4
	750	12.3	13.0	13.8	14.5	15.2	16.0	16.7	17.4	18.2	18.9
	1000	15.8	16.5	17.3	18.0	18.7	19.5	20.2	20.9	21.7	22.4
L_A=700 ft	1250	19.3	20.0	20.8	21.5	22.2	23.0	23.7	24.4	25.2	25.9
	1500	22.8	23.5	24.2	25.0	25.7	26.4	27.2	27.9	28.7	29.4
	1750	26.3	27.0	27.7	28.5	29.2	29.9	30.7	31.4	32.1	32.9
	2000	29.8	30.5	31.2	32.0	32.7	33.4	34.2	34.9	35.6	36.4

Table B2. Density in the merge influence area under different length of acceleration lane length for six lane two way freeway. (Continued)

	Density in the merge influence area (pc/mi/ln)										
With an auxiliary lane	v_F	v_R (pc/h/ln)									
	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	8.2	8.9	9.7	10.4	11.1	11.9	12.6	13.3	14.1	14.8
	750	11.7	12.5	13.2	13.9	14.7	15.4	16.1	16.9	17.6	18.3
	1000	15.2	16.0	16.7	17.4	18.2	18.9	19.6	20.4	21.1	21.8
L_A=800 ft	1250	18.7	19.5	20.2	20.9	21.7	22.4	23.1	23.9	24.6	25.3
	1500	22.2	23.0	23.7	24.5	25.2	25.9	26.7	27.4	28.1	28.9
	1750	25.8	26.5	27.2	28.0	28.7	29.4	30.2	30.9	31.6	32.4
	2000	29.3	30.0	30.7	31.5	32.2	32.9	33.7	34.4	35.1	35.9
With one auxiliary lane	v_F	v_R (pc/h/ln)									
	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	7.6	8.4	9.1	9.8	10.6	11.3	12.0	12.8	13.5	14.2
	750	11.1	11.9	12.6	13.3	14.1	14.8	15.5	16.3	17.0	17.7
	1000	14.7	15.4	16.1	16.9	17.6	18.3	19.1	19.8	20.5	21.3
L_A=900 ft	1250	18.2	18.9	19.7	20.4	21.1	21.9	22.6	23.3	24.1	24.8
	1500	21.7	22.5	23.2	23.9	24.7	25.4	26.1	26.9	27.6	28.3
	1750	25.2	26.0	26.7	27.4	28.2	28.9	29.7	30.4	31.1	31.9
	2000	28.8	29.5	30.2	31.0	31.7	32.4	33.2	33.9	34.6	35.4
With one auxiliary lane	v_F	v_R (pc/h/ln)									
	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	7.0	7.8	8.5	9.2	10.0	10.7	11.4	12.2	12.9	13.6
	750	10.6	11.3	12.0	12.8	13.5	14.2	15.0	15.7	16.4	17.2
	1000	14.1	14.8	15.6	16.3	17.0	17.8	18.5	19.2	20.0	20.7
L_A=1000 ft	1250	17.6	18.4	19.1	19.9	20.6	21.3	22.1	22.8	23.5	24.3
	1500	21.2	21.9	22.7	23.4	24.1	24.9	25.6	26.3	27.1	27.8
	1750	24.7	25.5	26.2	26.9	27.7	28.4	29.1	29.9	30.6	31.3
	2000	28.3	29.0	29.7	30.5	31.2	31.9	32.7	33.4	34.1	34.9
With one auxiliary lane	v_F	v_R (pc/h/ln)									
	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	6.4	7.2	7.9	8.6	9.4	10.1	10.8	11.6	12.3	13.0
	750	10.0	10.7	11.5	12.2	12.9	13.7	14.4	15.1	15.9	16.6
	1000	13.5	14.3	15.0	15.7	16.5	17.2	18.0	18.7	19.4	20.2
L_A=1100 ft	1250	17.1	17.8	18.6	19.3	20.0	20.8	21.5	22.2	23.0	23.7
	1500	20.7	21.4	22.1	22.9	23.6	24.3	25.1	25.8	26.5	27.3
	1750	24.2	25.0	25.7	26.4	27.2	27.9	28.6	29.4	30.1	30.8
	2000	27.8	28.5	29.2	30.0	30.7	31.5	32.2	32.9	33.7	34.4

Table B2. Density in the merge influence area under different length of acceleration lane length for six lane two way freeway. (Continued)

	Density in the merge influence area (pc/mi/ln)										
	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
With one auxiliary lane L_A=1200 ft	500	5.8	6.6	7.3	8.0	8.8	9.5	10.2	11.0	11.7	12.4
	750	9.4	10.1	10.9	11.6	12.3	13.1	13.8	14.5	15.3	16.0
	1000	13.0	13.7	14.5	15.2	15.9	16.7	17.4	18.1	18.9	19.6
	1250	16.6	17.3	18.0	18.8	19.5	20.2	21.0	21.7	22.4	23.2
	1500	20.1	20.9	21.6	22.3	23.1	23.8	24.5	25.3	26.0	26.7
	1750	23.7	24.4	25.2	25.9	26.6	27.4	28.1	28.8	29.6	30.3
	2000	27.3	28.0	28.8	29.5	30.2	31.0	31.7	32.4	33.2	33.9
With one auxiliary lane L_A=1300 ft	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	5.2	6.0	6.7	7.4	8.2	8.9	9.6	10.4	11.1	11.8
	750	8.8	9.6	10.3	11.0	11.8	12.5	13.2	14.0	14.7	15.4
	1000	12.4	13.2	13.9	14.6	15.4	16.1	16.8	17.6	18.3	19.0
	1250	16.0	16.7	17.5	18.2	19.0	19.7	20.4	21.2	21.9	22.6
	1500	19.6	20.3	21.1	21.8	22.5	23.3	24.0	24.7	25.5	26.2
	1750	23.2	23.9	24.7	25.4	26.1	26.9	27.6	28.3	29.1	29.8
	2000	26.8	27.5	28.3	29.0	29.7	30.5	31.2	31.9	32.7	33.4
With one auxiliary lane L_A=1400 ft	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	4.6	5.4	6.1	6.8	7.6	8.3	9.1	9.8	10.5	11.3
	750	8.3	9.0	9.7	10.5	11.2	11.9	12.7	13.4	14.1	14.9
	1000	11.9	12.6	13.3	14.1	14.8	15.5	16.3	17.0	17.7	18.5
	1250	15.5	16.2	16.9	17.7	18.4	19.1	19.9	20.6	21.3	22.1
	1500	19.1	19.8	20.5	21.3	22.0	22.7	23.5	24.2	24.9	25.7
	1750	22.7	23.4	24.2	24.9	25.6	26.4	27.1	27.8	28.6	29.3
	2000	26.3	27.0	27.8	28.5	29.2	30.0	30.7	31.4	32.2	32.9
With one auxiliary lane L_A=1500 ft	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	4.1	4.8	5.5	6.3	7.0	7.7	8.5	9.2	9.9	10.7
	750	7.7	8.4	9.1	9.9	10.6	11.3	12.1	12.8	13.5	14.3
	1000	11.3	12.0	12.8	13.5	14.2	15.0	15.7	16.4	17.2	17.9
	1250	14.9	15.7	16.4	17.1	17.9	18.6	19.3	20.1	20.8	21.5
	1500	18.5	19.3	20.0	20.8	21.5	22.2	23.0	23.7	24.4	25.2
	1750	22.2	22.9	23.6	24.4	25.1	25.8	26.6	27.3	28.0	28.8
	2000	25.8	26.5	27.3	28.0	28.7	29.5	30.2	30.9	31.7	32.4

Table B3. Density in the merge influence area under different length of acceleration lane length for eight lane two way freeway.

	Density in the merge influence area (pc/mi/ln)										
Without auxiliary lane	v_F	v_R (pc/h/ln)									
	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	12.4	13.2	13.9	14.7	15.4	16.1	16.9	17.6	18.3	19.1
	750	15.6	16.3	17.0	17.8	18.5	19.2	20.0	20.7	21.4	22.2
	1000	18.7	19.4	20.2	20.9	21.6	22.4	23.1	23.8	24.6	25.3
L_A=0 ft	1250	21.8	22.5	23.3	24.0	24.7	25.5	26.2	26.9	27.7	28.4
	1500	24.9	25.7	26.4	27.1	27.9	28.6	29.3	30.1	30.8	31.5
	1750	28.0	28.8	29.5	30.3	31.0	31.7	32.5	33.2	33.9	34.7
	2000	31.2	31.9	32.6	33.4	34.1	34.8	35.6	36.3	37.0	37.8
With one auxiliary lane	v_F	v_R (pc/h/ln)									
	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	11.8	12.6	13.3	14.0	14.8	15.5	16.2	17.0	17.7	18.4
	750	14.9	15.7	16.4	17.1	17.9	18.6	19.3	20.1	20.8	21.5
	1000	18.1	18.8	19.5	20.3	21.0	21.7	22.5	23.2	23.9	24.7
L_A=100 ft	1250	21.2	21.9	22.7	23.4	24.1	24.9	25.6	26.3	27.1	27.8
	1500	24.3	25.0	25.8	26.5	27.2	28.0	28.7	29.4	30.2	30.9
	1750	27.4	28.2	28.9	29.6	30.4	31.1	31.8	32.6	33.3	34.0
	2000	30.5	31.3	32.0	32.7	33.5	34.2	34.9	35.7	36.4	37.1
With one auxiliary lane	v_F	v_R (pc/h/ln)									
	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	11.2	11.9	12.7	13.4	14.1	14.9	15.6	16.3	17.1	17.8
	750	14.3	15.0	15.8	16.5	17.3	18.0	18.7	19.5	20.2	20.9
	1000	17.4	18.2	18.9	19.6	20.4	21.1	21.8	22.6	23.3	24.0
L_A=200 ft	1250	20.6	21.3	22.0	22.8	23.5	24.2	25.0	25.7	26.4	27.2
	1500	23.7	24.4	25.1	25.9	26.6	27.3	28.1	28.8	29.5	30.3
	1750	26.8	27.5	28.3	29.0	29.7	30.5	31.2	31.9	32.7	33.4
	2000	29.9	30.6	31.4	32.1	32.9	33.6	34.3	35.1	35.8	36.5
With one auxiliary lane	v_F	v_R (pc/h/ln)									
	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	10.6	11.3	12.0	12.8	13.5	14.2	15.0	15.7	16.4	17.2
	750	13.7	14.4	15.2	15.9	16.6	17.4	18.1	18.8	19.6	20.3
	1000	16.8	17.5	18.3	19.0	19.7	20.5	21.2	21.9	22.7	23.4
L_A=300 ft	1250	19.9	20.7	21.4	22.1	22.9	23.6	24.3	25.1	25.8	26.5
	1500	23.0	23.8	24.5	25.3	26.0	26.7	27.5	28.2	28.9	29.7
	1750	26.2	26.9	27.6	28.4	29.1	29.8	30.6	31.3	32.0	32.8
	2000	29.3	30.0	30.8	31.5	32.2	33.0	33.7	34.4	35.2	35.9

Table B3. Density in the merge influence area under different length of acceleration lane length for eight lane two way freeway. (Continued)

	Density in the merge influence area (pc/mi/ln)										
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	9.9	10.7	11.4	12.1	12.9	13.6	14.3	15.1	15.8	16.5
	750	13.1	13.8	14.5	15.3	16.0	16.7	17.5	18.2	18.9	19.7
	1000	16.2	16.9	17.6	18.4	19.1	19.9	20.6	21.3	22.1	22.8
L_A=400 ft	1250	19.3	20.0	20.8	21.5	22.2	23.0	23.7	24.4	25.2	25.9
	1500	22.4	23.2	23.9	24.6	25.4	26.1	26.8	27.6	28.3	29.0
	1750	25.5	26.3	27.0	27.7	28.5	29.2	29.9	30.7	31.4	32.1
	2000	28.7	29.4	30.1	30.9	31.6	32.3	33.1	33.8	34.5	35.3
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	9.3	10.0	10.8	11.5	12.3	13.0	13.7	14.5	15.2	15.9
	750	12.4	13.2	13.9	14.6	15.4	16.1	16.8	17.6	18.3	19.0
	1000	15.6	16.3	17.0	17.8	18.5	19.2	20.0	20.7	21.4	22.2
L_A=500 ft	1250	18.7	19.4	20.1	20.9	21.6	22.3	23.1	23.8	24.5	25.3
	1500	21.8	22.5	23.3	24.0	24.7	25.5	26.2	26.9	27.7	28.4
	1750	24.9	25.6	26.4	27.1	27.9	28.6	29.3	30.1	30.8	31.5
	2000	28.0	28.8	29.5	30.2	31.0	31.7	32.4	33.2	33.9	34.6
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	8.7	9.4	10.2	10.9	11.6	12.4	13.1	13.8	14.6	15.3
	750	11.8	12.5	13.3	14.0	14.7	15.5	16.2	16.9	17.7	18.4
	1000	14.9	15.7	16.4	17.1	17.9	18.6	19.3	20.1	20.8	21.5
L_A=600 ft	1250	18.0	18.8	19.5	20.2	21.0	21.7	22.5	23.2	23.9	24.7
	1500	21.2	21.9	22.6	23.4	24.1	24.8	25.6	26.3	27.0	27.8
	1750	24.3	25.0	25.8	26.5	27.2	28.0	28.7	29.4	30.2	30.9
	2000	27.4	28.1	28.9	29.6	30.3	31.1	31.8	32.5	33.3	34.0
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	8.1	8.8	9.5	10.3	11.0	11.7	12.5	13.2	13.9	14.7
	750	11.2	11.9	12.6	13.4	14.1	14.9	15.6	16.3	17.1	17.8
	1000	14.3	15.0	15.8	16.5	17.2	18.0	18.7	19.4	20.2	20.9
L_A=700 ft	1250	17.4	18.2	18.9	19.6	20.4	21.1	21.8	22.6	23.3	24.0
	1500	20.5	21.3	22.0	22.7	23.5	24.2	24.9	25.7	26.4	27.1
	1750	23.7	24.4	25.1	25.9	26.6	27.3	28.1	28.8	29.5	30.3
	2000	26.8	27.5	28.2	29.0	29.7	30.5	31.2	31.9	32.7	33.4

Table B3. Density in the merge influence area under different length of acceleration lane length for eight lane two way freeway. (Continued)

	Density in the merge influence area (pc/mi/ln)										
	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
With an auxiliary lane	500	7.4	8.2	8.9	9.6	10.4	11.1	11.8	12.6	13.3	14.0
	750	10.6	11.3	12.0	12.8	13.5	14.2	15.0	15.7	16.4	17.2
	1000	13.7	14.4	15.1	15.9	16.6	17.3	18.1	18.8	19.5	20.3
L_A=800 ft	1250	16.8	17.5	18.3	19.0	19.7	20.5	21.2	21.9	22.7	23.4
	1500	19.9	20.6	21.4	22.1	22.8	23.6	24.3	25.1	25.8	26.5
	1750	23.0	23.8	24.5	25.2	26.0	26.7	27.4	28.2	28.9	29.6
	2000	26.2	26.9	27.6	28.4	29.1	29.8	30.6	31.3	32.0	32.8
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	6.8	7.5	8.3	9.0	9.7	10.5	11.2	11.9	12.7	13.4
	750	9.9	10.7	11.4	12.1	12.9	13.6	14.3	15.1	15.8	16.5
	1000	13.0	13.8	14.5	15.2	16.0	16.7	17.5	18.2	18.9	19.7
L_A=900 ft	1250	16.2	16.9	17.6	18.4	19.1	19.8	20.6	21.3	22.0	22.8
	1500	19.3	20.0	20.8	21.5	22.2	23.0	23.7	24.4	25.2	25.9
	1750	22.4	23.1	23.9	24.6	25.3	26.1	26.8	27.5	28.3	29.0
	2000	25.5	26.3	27.0	27.7	28.5	29.2	29.9	30.7	31.4	32.1
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	6.2	6.9	7.6	8.4	9.1	9.8	10.6	11.3	12.1	12.8
	750	9.3	10.0	10.8	11.5	12.2	13.0	13.7	14.4	15.2	15.9
	1000	12.4	13.2	13.9	14.6	15.4	16.1	16.8	17.6	18.3	19.0
L_A=1000 ft	1250	15.5	16.3	17.0	17.7	18.5	19.2	19.9	20.7	21.4	22.1
	1500	18.7	19.4	20.1	20.9	21.6	22.3	23.1	23.8	24.5	25.3
	1750	21.8	22.5	23.2	24.0	24.7	25.4	26.2	26.9	27.7	28.4
	2000	24.9	25.6	26.4	27.1	27.8	28.6	29.3	30.0	30.8	31.5
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	5.6	6.3	7.0	7.8	8.5	9.2	10.0	10.7	11.4	12.2
	750	8.7	9.4	10.1	10.9	11.6	12.3	13.1	13.8	14.5	15.3
	1000	11.8	12.5	13.3	14.0	14.7	15.5	16.2	16.9	17.7	18.4
L_A=1100 ft	1250	14.9	15.6	16.4	17.1	17.8	18.6	19.3	20.1	20.8	21.5
	1500	18.0	18.8	19.5	20.2	21.0	21.7	22.4	23.2	23.9	24.6
	1750	21.2	21.9	22.6	23.4	24.1	24.8	25.6	26.3	27.0	27.8
	2000	24.3	25.0	25.7	26.5	27.2	27.9	28.7	29.4	30.1	30.9

Table B3. Density in the merge influence area under different length of acceleration lane length for eight lane two way freeway. (Continued)

Density in the merge influence area (pc/mi/ln)

With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
L_A=1200 ft	500	4.9	5.7	6.4	7.1	7.9	8.6	9.3	10.1	10.8	11.5
	750	8.0	8.8	9.5	10.2	11.0	11.7	12.4	13.2	13.9	14.7
	1000	11.2	11.9	12.6	13.4	14.1	14.8	15.6	16.3	17.0	17.8
	1250	14.3	15.0	15.8	16.5	17.2	18.0	18.7	19.4	20.2	20.9
	1500	17.4	18.1	18.9	19.6	20.3	21.1	21.8	22.5	23.3	24.0
	1750	20.5	21.3	22.0	22.7	23.5	24.2	24.9	25.7	26.4	27.1
	2000	23.6	24.4	25.1	25.8	26.6	27.3	28.0	28.8	29.5	30.3

With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
L_A=1300 ft	500	4.3	5.0	5.8	6.5	7.2	8.0	8.7	9.4	10.2	10.9
	750	7.4	8.2	8.9	9.6	10.4	11.1	11.8	12.6	13.3	14.0
	1000	10.5	11.3	12.0	12.7	13.5	14.2	14.9	15.7	16.4	17.1
	1250	13.7	14.4	15.1	15.9	16.6	17.3	18.1	18.8	19.5	20.3
	1500	16.8	17.5	18.2	19.0	19.7	20.4	21.2	21.9	22.7	23.4
	1750	19.9	20.6	21.4	22.1	22.8	23.6	24.3	25.0	25.8	26.5
	2000	23.0	23.8	24.5	25.2	26.0	26.7	27.4	28.2	28.9	29.6

With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
L_A=1400 ft	500	3.7	4.4	5.1	5.9	6.6	7.3	8.1	8.8	9.5	10.3
	750	6.8	7.5	8.3	9.0	9.7	10.5	11.2	11.9	12.7	13.4
	1000	9.9	10.6	11.4	12.1	12.8	13.6	14.3	15.0	15.8	16.5
	1250	13.0	13.8	14.5	15.2	16.0	16.7	17.4	18.2	18.9	19.6
	1500	16.2	16.9	17.6	18.4	19.1	19.8	20.6	21.3	22.0	22.8
	1750	19.3	20.0	20.7	21.5	22.2	22.9	23.7	24.4	25.1	25.9
	2000	22.4	23.1	23.9	24.6	25.3	26.1	26.8	27.5	28.3	29.0

With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
L_A=1500 ft	500	3.0	3.8	4.5	5.2	6.0	6.7	7.4	8.2	8.9	9.7
	750	6.2	6.9	7.6	8.4	9.1	9.8	10.6	11.3	12.0	12.8
	1000	9.3	10.0	10.8	11.5	12.2	13.0	13.7	14.4	15.2	15.9
	1250	12.4	13.1	13.9	14.6	15.3	16.1	16.8	17.5	18.3	19.0
	1500	15.5	16.3	17.0	17.7	18.5	19.2	19.9	20.7	21.4	22.1
	1750	18.6	19.4	20.1	20.8	21.6	22.3	23.0	23.8	24.5	25.3
	2000	21.8	22.5	23.2	24.0	24.7	25.4	26.2	26.9	27.6	28.4

Appendix C

Density In the Diverge Influence Area under Different Length of Deceleration Lane Length

Table C1. Density in the diverge influence area under different length of deceleration lane length for six lane two way freeway.

	Density in the diverge influence area (pc/mi/ln)										
Without auxiliary lane	v_F	v_R (pc/h/ln)									
	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	13.8	13.9	14.1	14.4	14.6	14.8	15.0	15.3	15.5	15.8
	750	18.0	18.2	18.4	18.6	18.8	19.0	19.2	19.4	19.7	19.9
	1000	22.1	22.2	22.4	22.6	22.8	23.0	23.2	23.4	23.6	23.8
L_D=0 ft	1250	25.9	26.0	26.2	26.4	26.5	26.7	26.9	27.1	27.3	27.5
	1500	29.4	29.6	29.7	29.9	30.0	30.2	30.4	30.6	30.8	31.0
	1750	32.8	32.9	33.0	33.1	33.3	33.5	33.6	33.8	34.0	34.2
	2000	35.8	35.9	36.1	36.2	36.3	36.5	36.6	36.8	36.9	37.1
With one auxiliary lane	v_F	v_R (pc/h/ln)									
	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	12.9	13.0	13.2	13.5	13.7	13.9	14.1	14.4	14.6	14.9
	750	17.1	17.3	17.5	17.7	17.9	18.1	18.3	18.5	18.8	19.0
	1000	21.2	21.3	21.5	21.7	21.9	22.1	22.3	22.5	22.7	22.9
L_D=100 ft	1250	25.0	25.1	25.3	25.5	25.6	25.8	26.0	26.2	26.4	26.6
	1500	28.5	28.7	28.8	29.0	29.1	29.3	29.5	29.7	29.9	30.1
	1750	31.9	32.0	32.1	32.2	32.4	32.6	32.7	32.9	33.1	33.3
	2000	34.9	35.0	35.2	35.3	35.4	35.6	35.7	35.9	36.0	36.2
With one auxiliary lane	v_F	v_R (pc/h/ln)									
	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	12.0	12.1	12.3	12.6	12.8	13.0	13.2	13.5	13.7	14.0
	750	16.2	16.4	16.6	16.8	17.0	17.2	17.4	17.6	17.9	18.1
	1000	20.3	20.4	20.6	20.8	21.0	21.2	21.4	21.6	21.8	22.0
L_D=200 ft	1250	24.1	24.2	24.4	24.6	24.7	24.9	25.1	25.3	25.5	25.7
	1500	27.6	27.8	27.9	28.1	28.2	28.4	28.6	28.8	29.0	29.2
	1750	31.0	31.1	31.2	31.3	31.5	31.7	31.8	32.0	32.2	32.4
	2000	34.0	34.1	34.3	34.4	34.5	34.7	34.8	35.0	35.1	35.3
With one auxiliary lane	v_F	v_R (pc/h/ln)									
	(pc/h/ln)	100	200	300	400	500	600	700	800	900	1000
	500	11.1	11.2	11.4	11.7	11.9	12.1	12.3	12.6	12.8	13.1
	750	15.3	15.5	15.7	15.9	16.1	16.3	16.5	16.7	17.0	17.2
	1000	19.4	19.5	19.7	19.9	20.1	20.3	20.5	20.7	20.9	21.1
L_D=300 ft	1250	23.2	23.3	23.5	23.7	23.8	24.0	24.2	24.4	24.6	24.8
	1500	26.7	26.9	27.0	27.2	27.3	27.5	27.7	27.9	28.1	28.3
	1750	30.1	30.2	30.3	30.4	30.6	30.8	30.9	31.1	31.3	31.5
	2000	33.1	33.2	33.4	33.5	33.6	33.8	33.9	34.1	34.2	34.4

Table C1. Density in the diverge influence area under different length of deceleration lane length for six lane two way freeway. (Continued)

	Density in the diverge influence area (pc/mi/ln)										
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln)									
		100	200	300	400	500	600	700	800	900	1000
	500	10.2	10.3	10.5	10.8	11.0	11.2	11.4	11.7	11.9	12.2
	750	14.4	14.6	14.8	15.0	15.2	15.4	15.6	15.8	16.1	16.3
	1000	18.5	18.6	18.8	19.0	19.2	19.4	19.6	19.8	20.0	20.2
L_D=400 ft	1250	22.3	22.4	22.6	22.8	22.9	23.1	23.3	23.5	23.7	23.9
	1500	25.8	26.0	26.1	26.3	26.4	26.6	26.8	27.0	27.2	27.4
	1750	29.2	29.3	29.4	29.5	29.7	29.9	30.0	30.2	30.4	30.6
	2000	32.2	32.3	32.5	32.6	32.7	32.9	33.0	33.2	33.3	33.5
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln)									
		100	200	300	400	500	600	700	800	900	1000
	500	9.3	9.4	9.6	9.9	10.1	10.3	10.5	10.8	11.0	11.3
	750	13.5	13.7	13.9	14.1	14.3	14.5	14.7	14.9	15.2	15.4
	1000	17.6	17.7	17.9	18.1	18.3	18.5	18.7	18.9	19.1	19.3
L_D=500 ft	1250	21.4	21.5	21.7	21.9	22.0	22.2	22.4	22.6	22.8	23.0
	1500	24.9	25.1	25.2	25.4	25.5	25.7	25.9	26.1	26.3	26.5
	1750	28.3	28.4	28.5	28.6	28.8	29.0	29.1	29.3	29.5	29.7
	2000	31.3	31.4	31.6	31.7	31.8	32.0	32.1	32.3	32.4	32.6
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln)									
		100	200	300	400	500	600	700	800	900	1000
	500	8.4	8.5	8.7	9.0	9.2	9.4	9.6	9.9	10.1	10.4
	750	12.6	12.8	13.0	13.2	13.4	13.6	13.8	14.0	14.3	14.5
	1000	16.7	16.8	17.0	17.2	17.4	17.6	17.8	18.0	18.2	18.4
L_D=600 ft	1250	20.5	20.6	20.8	21.0	21.1	21.3	21.5	21.7	21.9	22.1
	1500	24.0	24.2	24.3	24.5	24.6	24.8	25.0	25.2	25.4	25.6
	1750	27.4	27.5	27.6	27.7	27.9	28.1	28.2	28.4	28.6	28.8
	2000	30.4	30.5	30.7	30.8	30.9	31.1	31.2	31.4	31.5	31.7
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln)									
		100	200	300	400	500	600	700	800	900	1000
	500	7.5	7.6	7.8	8.1	8.3	8.5	8.7	9.0	9.2	9.5
	750	11.7	11.9	12.1	12.3	12.5	12.7	12.9	13.1	13.4	13.6
	1000	15.8	15.9	16.1	16.3	16.5	16.7	16.9	17.1	17.3	17.5
L_D=700 ft	1250	19.6	19.7	19.9	20.1	20.2	20.4	20.6	20.8	21.0	21.2
	1500	23.1	23.3	23.4	23.6	23.7	23.9	24.1	24.3	24.5	24.7
	1750	26.5	26.6	26.7	26.8	27.0	27.2	27.3	27.5	27.7	27.9
	2000	29.5	29.6	29.8	29.9	30.0	30.2	30.3	30.5	30.6	30.8

Table C1. Density in the diverge influence area under different length of deceleration lane length for six lane two way freeway. (Continued)

	Density in the diverge influence area (pc/mi/ln)										
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	6.6	6.7	6.9	7.2	7.4	7.6	7.8	8.1	8.3	8.6
	750	10.8	11.0	11.2	11.4	11.6	11.8	12.0	12.2	12.5	12.7
	1000	14.9	15.0	15.2	15.4	15.6	15.8	16.0	16.2	16.4	16.6
L_D=800 ft	1250	18.7	18.8	19.0	19.2	19.3	19.5	19.7	19.9	20.1	20.3
	1500	22.2	22.4	22.5	22.7	22.8	23.0	23.2	23.4	23.6	23.8
	1750	25.6	25.7	25.8	25.9	26.1	26.3	26.4	26.6	26.8	27.0
	2000	28.6	28.7	28.9	29.0	29.1	29.3	29.4	29.6	29.7	29.9
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	5.7	5.8	6.0	6.3	6.5	6.7	6.9	7.2	7.4	7.7
	750	9.9	10.1	10.3	10.5	10.7	10.9	11.1	11.3	11.6	11.8
	1000	14.0	14.1	14.3	14.5	14.7	14.9	15.1	15.3	15.5	15.7
L_D=900 ft	1250	17.8	17.9	18.1	18.3	18.4	18.6	18.8	19.0	19.2	19.4
	1500	21.3	21.5	21.6	21.8	21.9	22.1	22.3	22.5	22.7	22.9
	1750	24.7	24.8	24.9	25.0	25.2	25.4	25.5	25.7	25.9	26.1
	2000	27.7	27.8	28.0	28.1	28.2	28.4	28.5	28.7	28.8	29.0
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	4.8	4.9	5.1	5.4	5.6	5.8	6.0	6.3	6.5	6.8
	750	9.0	9.2	9.4	9.6	9.8	10.0	10.2	10.4	10.7	10.9
	1000	13.1	13.2	13.4	13.6	13.8	14.0	14.2	14.4	14.6	14.8
L_D=1000 ft	1250	16.9	17.0	17.2	17.4	17.5	17.7	17.9	18.1	18.3	18.5
	1500	20.4	20.6	20.7	20.9	21.0	21.2	21.4	21.6	21.8	22.0
	1750	23.8	23.9	24.0	24.1	24.3	24.5	24.6	24.8	25.0	25.2
	2000	26.8	26.9	27.1	27.2	27.3	27.5	27.6	27.8	27.9	28.1
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	3.9	4.0	4.2	4.5	4.7	4.9	5.1	5.4	5.6	5.9
	750	8.1	8.3	8.5	8.7	8.9	9.1	9.3	9.5	9.8	10.0
	1000	12.2	12.3	12.5	12.7	12.9	13.1	13.3	13.5	13.7	13.9
L_D=1100 ft	1250	16.0	16.1	16.3	16.5	16.6	16.8	17.0	17.2	17.4	17.6
	1500	19.5	19.7	19.8	20.0	20.1	20.3	20.5	20.7	20.9	21.1
	1750	22.9	23.0	23.1	23.2	23.4	23.6	23.7	23.9	24.1	24.3
	2000	25.9	26.0	26.2	26.3	26.4	26.6	26.7	26.9	27.0	27.2

Table C1. Density in the diverge influence area under different length of deceleration lane length for six lane two way freeway. (Continued)

	Density in the diverge influence area (pc/mi/ln)										
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	3.0	3.1	3.3	3.6	3.8	4.0	4.2	4.5	4.7	5.0
	750	7.2	7.4	7.6	7.8	8.0	8.2	8.4	8.6	8.9	9.1
	1000	11.3	11.4	11.6	11.8	12.0	12.2	12.4	12.6	12.8	13.0
L_D=1200 ft	1250	15.1	15.2	15.4	15.6	15.7	15.9	16.1	16.3	16.5	16.7
	1500	18.6	18.8	18.9	19.1	19.2	19.4	19.6	19.8	20.0	20.2
	1750	22.0	22.1	22.2	22.3	22.5	22.7	22.8	23.0	23.2	23.4
	2000	25.0	25.1	25.3	25.4	25.5	25.7	25.8	26.0	26.1	26.3
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	2.1	2.2	2.4	2.7	2.9	3.1	3.3	3.6	3.8	4.1
	750	6.3	6.5	6.7	6.9	7.1	7.3	7.5	7.7	8.0	8.2
	1000	10.4	10.5	10.7	10.9	11.1	11.3	11.5	11.7	11.9	12.1
L_D=1300 ft	1250	14.2	14.3	14.5	14.7	14.8	15.0	15.2	15.4	15.6	15.8
	1500	17.7	17.9	18.0	18.2	18.3	18.5	18.7	18.9	19.1	19.3
	1750	21.1	21.2	21.3	21.4	21.6	21.8	21.9	22.1	22.3	22.5
	2000	24.1	24.2	24.4	24.5	24.6	24.8	24.9	25.1	25.2	25.4
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	1.2	1.3	1.5	1.8	2.0	2.2	2.4	2.7	2.9	3.2
	750	5.4	5.6	5.8	6.0	6.2	6.4	6.6	6.8	7.1	7.3
	1000	9.5	9.6	9.8	10.0	10.2	10.4	10.6	10.8	11.0	11.2
L_D=1400 ft	1250	13.3	13.4	13.6	13.8	13.9	14.1	14.3	14.5	14.7	14.9
	1500	16.8	17.0	17.1	17.3	17.4	17.6	17.8	18.0	18.2	18.4
	1750	20.2	20.3	20.4	20.5	20.7	20.9	21.0	21.2	21.4	21.6
	2000	23.2	23.3	23.5	23.6	23.7	23.9	24.0	24.2	24.3	24.5
With one auxiliary lane	v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
	500	0.3	0.4	0.6	0.9	1.1	1.3	1.5	1.8	2.0	2.3
	750	4.5	4.7	4.9	5.1	5.3	5.5	5.7	5.9	6.2	6.4
	1000	8.6	8.7	8.9	9.1	9.3	9.5	9.7	9.9	10.1	10.3
L_D=1500 ft	1250	12.4	12.5	12.7	12.9	13.0	13.2	13.4	13.6	13.8	14.0
	1500	15.9	16.1	16.2	16.4	16.5	16.7	16.9	17.1	17.3	17.5
	1750	19.3	19.4	19.5	19.6	19.8	20.0	20.1	20.3	20.5	20.7
	2000	22.3	22.4	22.6	22.7	22.8	23.0	23.1	23.3	23.4	23.6

Curriculum Vita

Yubian Wang was born in Shanxi, China in 1984. Yubian attended Harbin Institute of Technology, which is in the City of Harbin in China, and received her Bachelor degree in Mathematics. In September 2008, Yubian came to U.S. and started her graduate study in transportation planning and management in Texas Southern University in Houston, Texas. In September 2011, Yubian came to The University of Texas at El Paso to pursue her PhD degree in the Department of Civil Engineering.

Yubian also worked as a Ph.D. research associate in the Department of Civil Engineering at the University of Texas at El Paso. Her research interests include traffic operation and safety. She has been involved in several research projects that investigated the operational and safety impacts of different roadway designs and signal designs.

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