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16. Abstract

The intensive lane change maneuvers at weaving sections often result in safety and operational problems. Various factors, including the design of ramp roadways, use of auxiliary lanes, and continuity of lanes will have significant effects on the level of service and safety performance of the weaving sections. This study investigated the safety performance of freeway weaving sections and developed a quantitative model for predicting the safety impacts of different types of geometric treatments for freeway weaving sections. The results of this study show that weaving sections with longer length will have lower crash frequency per 1000 ft., more required lane changes for diverge vehicles will result in more crashes in the freeway weaving section, increasing merge traffic in the weaving sections will slightly reduce the crash risk at this section, and increasing diverge traffic in the weaving sections will increase the crash risk at this section. In this study, Crash Modification Factors (CMFs) were also developed based on the developed crash prediction model for estimating the impacts of different safety treatments for the freeway weaving sections.

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Safety Performance for Freeway Weaving Segments

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DISCLAIMER

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EXECUTIVE SUMMARY

The performance of freeway weaving section has been an important subject since the late 1960s. Weaving is defined as the crossing of two streams traveling in the same direction along a significant length of the highway without the aid of traffic control devices. Both merge and diverge vehicles need to make one or more lane changes in limited space and time, which are confined by the length of the weaving section. The intensive lane change maneuvers combined with the heavy traffic volume and high speed conditions at weaving sections often result in safety and operational problems. In addition, various factors, including the design of ramp roadways, use of auxiliary lanes, and continuity of lanes have significant effects on the level of service and safety performance of the weaving sections.

The objective of this research is to investigate the safety performance of freeway weaving sections and to develop a quantitative model for predicting the safety impacts of different types of geometric treatments for freeway weaving sections. To this end, the research team performed the following primary tasks:

- Reviewed Literature on Safety Performance of Freeway Weaving Section
- Conducted Data Analysis to Investigate Contributing Factors to Crash Frequency for Freeway Weaving Sections
- Developed a Quantitative Model for Predicting Safety Impacts of Different Types of Geometric Treatments for Freeway Weaving Sections
- Provided Recommendations for Freeway Design

In this study, sixteen weaving sections with different geometric configurations -different numbers of auxiliary lanes and ramp arrangements- were selected in two major cities, Houston and El Paso, Texas. Field traffic data and historical crash data were collected at studied weaving sections. The Poisson regression model was used to investigate the impact of different factors on the crash that occurred in the freeway weaving section.

The statistical analysis results show that the crash frequency in the weaving section was significantly affected by the length of weaving section, minimum number of lane changes from

freeway to on-ramp, average daily on-ramp traffic, and average daily off-ramp traffic. In addition, it is also found that:

- Weaving sections with longer lengths will have lower crash frequency per 1000 ft. unit.
- More lane changes required for diverge vehicles will result in more crashes in the freeway weaving section.
- Increasing merge traffic in the weaving sections will slightly reduce the crash risk at this section.
- Increasing diverge traffic in the weaving sections will increase the crash risk at this section.

Crash Modification Factors (CMFs) were derived based on the developed crash prediction model for estimating the impacts of different geometric treatments for the freeway weaving sections. For demonstrating the use of the developed CMF, two case studies were conducted for two study weaving sections. The results of this study will help traffic engineers to better understand the safety performance of different weaving sections. It also provides them a guideline for quantitatively assessing the safe benefits of different geometric treatments for freeway weaving sections.

According to the results of this research, several design recommendations are presented to improve the safety performance of freeway weaving sections:

- The freeway designer should consider the required numbers of lane changes for weaving vehicles. Reducing required lane change to enter or exit freeway will decrease the crash risk in the freeway weaving sections.
- For weaving sections with short length and large volume, extending weaving length is strongly recommended. Thus, weaving vehicles can have more time to complete weaving maneuvers successfully.

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CHAPTER 1: INTRODUCTION

1.1 Background of Research

The performance of freeway weaving section has been an important subject since the late 1960s. Weaving is defined as the crossing of two streams traveling in the same direction along a significant length of the highway without the aid of traffic control devices *(Highway Capacity Manual, 2000)*. Freeway weaving sections are usually formed when a merge area is closely followed by a diverge area, or when an entrance ramp lane is closely followed by an exit ramp lane and they are connected by an auxiliary lane. Weaving sections require intense lane-changing maneuvers as merging and diverging vehicles usually need to make one or more lane changes. Figure 1 shows a typical weaving section. Flows A – D and B – C are the weaving flows. Vehicles traveling from Leg A to Leg D must cross the path of vehicles traveling from Leg B to Leg C.

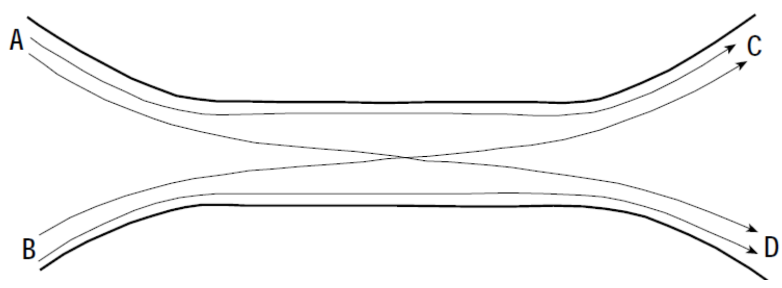


Figure 1 Formation of a weaving section *(Highway Capacity Manual, 2000)*

Both merge and diverge vehicles need to make one or more lane changes in limited space and time, which are confined by the length of the weaving section. Thus, the intensive lane change maneuvers combined with the heavy traffic volume and high speed conditions at weaving sections often result in safety and operational problems. In addition, various factors, including the design of ramp roadways, use of auxiliary lanes, and continuity of lanes have significant effects on the level of service and safety performance of the weaving sections. In implementing different types of weaving sections or applying different geometric treatments for weaving sections(such as adding an auxiliary lane), traffic engineers need guidelines on assessing the safety impacts of different types of designs and treatments for weaving sections.

Due to the great difficulty and cost of collecting comprehensive data on freeway weaving traffic operations, a limited number of studies have been conducted on the safety performance of weaving sections. The AASHTO Highway Safety Manual only provides CMFs for the on-ramp and off-ramp sections and no CMFs was provided for the safety performance of freeway weaving sections, leaving traffic engineers to make their decisions mainly relying on their judgment *(Highway Safety Manual, 2010)*.

For this purpose, historical crash-data based study was conducted at sixteen freeway weaving sections in Texas. Traffic data, geometric condition data, and historical crash data were collected to investigate the safety performance of freeway weaving sections. Conclusions and recommendations were made based on the findings of this study. The results of this research will help traffic engineers quantitatively assess the safety benefits of different geometric treatments for freeway weaving sections.

1.2 Objective of Research

According to the above discussion, the objective of this research is to investigate the safety performance of freeway weaving sections and to develop a quantitative model for predicting the safety impacts of different types of geometric treatments for freeway weaving sections.

1.3 Organization of Chapters

This report is organized in the following order of chapters which cover all work conducted for the research. First, Chapter 1 introduces the background and objective of this research. Secondly, Chapter 2 summarizes previous studies on safety analysis of freeway ramps and weaving sections. In Chapter 3, the design of the entire research is presented, including methodology, research procedure, data collection, and techniques and tools. Chapter 4 depicts the results and discussion of this research. Finally, Chapter 5 summarizes the procedure and the major results of this research, provides the conclusions, and recommends future research directions.

CHAPTER 2: LITERATURE REVIEW

In this chapter, literature review was conducted about the safety performance of freeway weaving sections, which includes four sections: 1) definition and types of freeway weaving sections; 2) Crash Modification Factors in Highway Safety Manual 2010; 3) studies on safety analysis of freeway ramps; and 4) studies on safety analysis of freeway weaving sections.

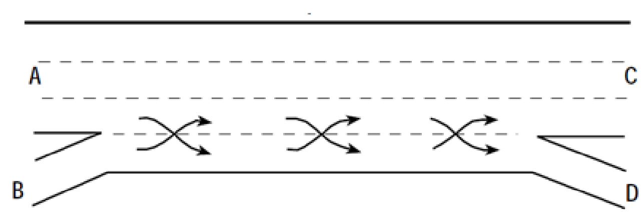
2.1 Definition and Types of Weaving Sections

Highway Capacity Manual 2000

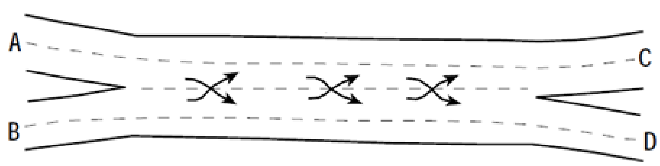
According to Highway Capacity Manual 2000 (HCM 2000), weaving section is defined as the crossing of two or more traffic streams traveling in the same general direction along a significant length of highway without the aid of traffic control devices. Weaving sections may exist on any type of facility: freeways, multilane highways, two-lane highways, interchange areas, urban streets, or collector-distributor roadways. Three geometric variables influence weaving section operations: configuration, length and width. Configuration of a weaving section indicates the way that entry and exit lanes are linked *(Highway Capacity Manual, 2000)*. The configuration determines how many lane changes a weaving vehicle needs to make to successfully complete the weaving maneuver. Length of a weaving section is the distance between the merge and diverge area. The weaving section length has a strong impact on lane-changing intensity, since weaving vehicles must execute required lane changes within the weaving section boundary. Weaving width is defined as the total number of lanes between the entry and exit gore areas. All of the three factors influence the lane-changing activities of the weaving traffic at freeway weaving sections.

HCM 2000 identifies three major categories of weaving configurations: Type A, Type B, and Type C. The HCM 2000 definition is mainly based on the minimum number of lane changes required for the weaving movements.

The characteristic of a Type A weaving section is that all weaving vehicles must make one lane change to complete their maneuver successfully. All of the lane changes occur across a lane line that connects from the entrance gore area directly to the exit gore area. Such a line is referred to as a crown line *(Highway Capacity Manual, 2000)*. Figure 2 shows the typical formation of Type A weaving sections. For Figure 2(a), the weaving section is formed by a one-lane on-ramp followed by a one-lane off-ramp with a continuous auxiliary lane connected. In this section, all merging vehicles must make a lane change from the auxiliary lane to main lanes of the freeway. All diverging vehicles must make a lane change from main lanes of the freeway to the auxiliary lane. This type of configuration is also referred to as a ramp-weave. A major weaving section is formed when at least three of the entry and exit legs have multiple lanes. The weaving section illustrated in Figure 2(b) is a Type A major weaving section.



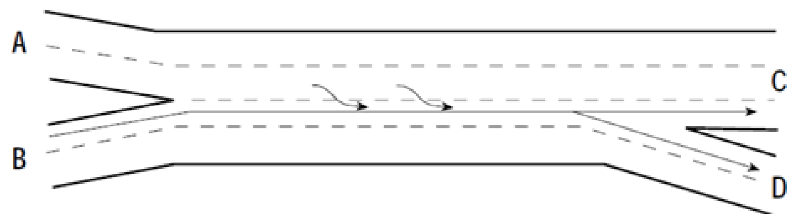
a. **Ramp- weave**: All weaving drivers must execute a lane change across the crown line



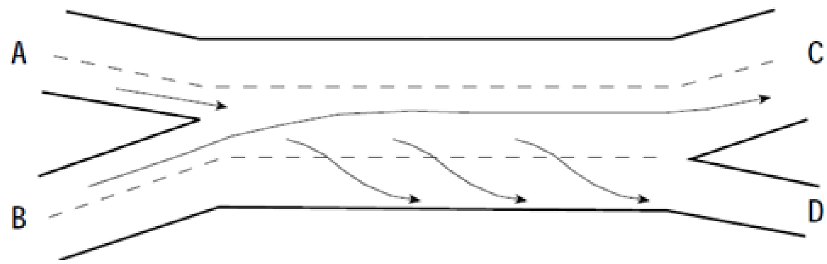
Major weave: Three or more entry/exit legs have multiple lanes

Figure 2 Type A weaving sections (*Highway Capacity Manual, 2000)*

The characteristic of Type B configuration is that: 1) one weaving movement can be made without making any lane changes and 2) the other weaving movement requires, at most, one lane change. All Type B weaving sections fall into the general category of major weaving sections in that such sections always have at least three entry and exit legs with multiple lanes (1). Figure 3 shows two Type B weaving sections. In both cases, weaving vehicles don't require lane changes from Leg B to Leg Cbut, from Leg A to Leg D, they must make one lane change.



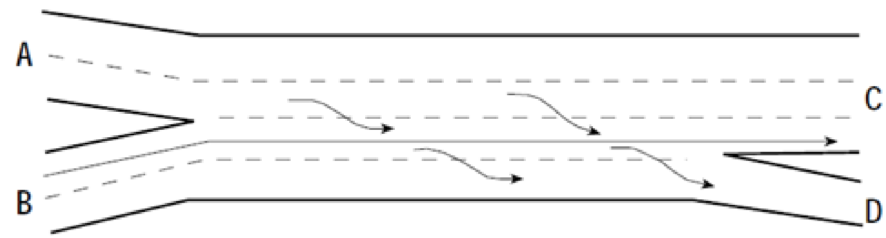
a. Major weave with dual off-ramp



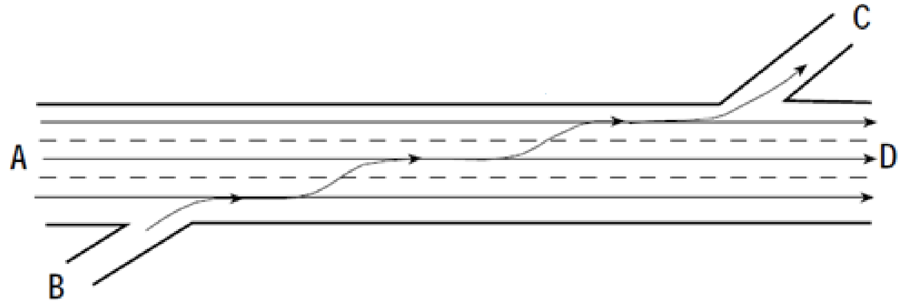
b. Major weave with single off-ramp

Figure 3 Type B weaving sections (*Highway Capacity Manual, 2000)*

The characteristic of Type C configuration is that: 1) one weaving movement can be made without making any lane changes and 2) the other weaving movement requires at least two lane changes. Figure 4 shows two types of Type C weaving sections. In Figure 4(a), movement B-C does not require lane change, while movement A-D requires two lane changes. Figure 4(b) shows a two-sided weaving section. In such cases, the ramp-to-ramp flow operates as a weaving flow. Weaving vehicles must cross all lanes of the freeway to complete their weaving maneuver.



a. One-sided weave

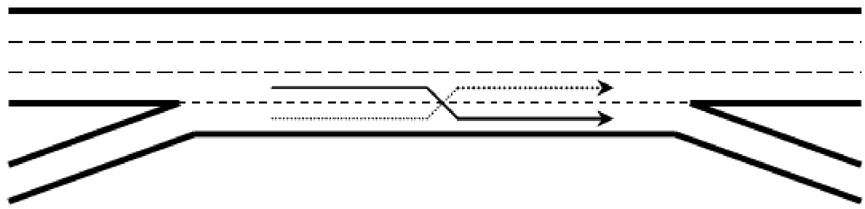


b. Two-sided weave

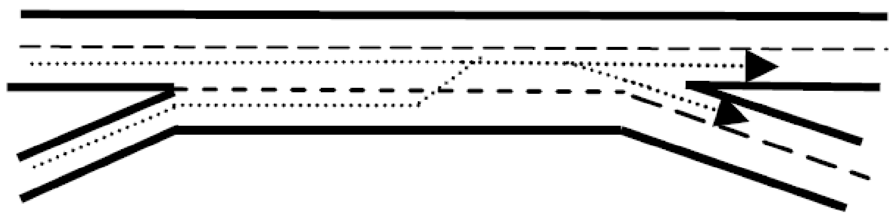
Figure 4 Type C weaving sections (*Highway Capacity Manual, 2000)*

Highway Capacity Manual 2010

According to Highway Capacity Manual 2010 (HCM 2010), there are two major categories of weaving sections: one-sided and two-sided weaving sections. A one-sided weaving section is one in which no weaving maneuvers require more than two lane changes to be successfully completed *(Highway Capacity Manual, 2010)*. A two-sided weaving section is one in which at least one weaving maneuver requires three or more lane changes to be successfully completed; or in which a single-lane on-ramp is closely followed by a single-lane off–ramp on the opposite side of the freeway *(Highway Capacity Manual, 2010)*. For weaving sections with on-ramp and off-ramp in opposite side, the ramp-to-ramp movement is considered as the weaving movement. Most weaving sections are one-sided. Figure 5 illustrates two examples of one-sided weaving sections.



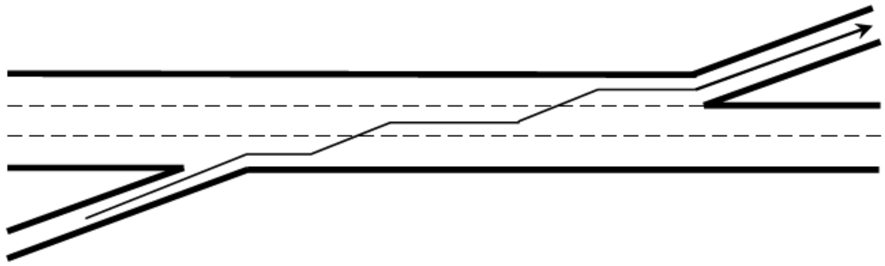
(a) **One-sided ramp weave**



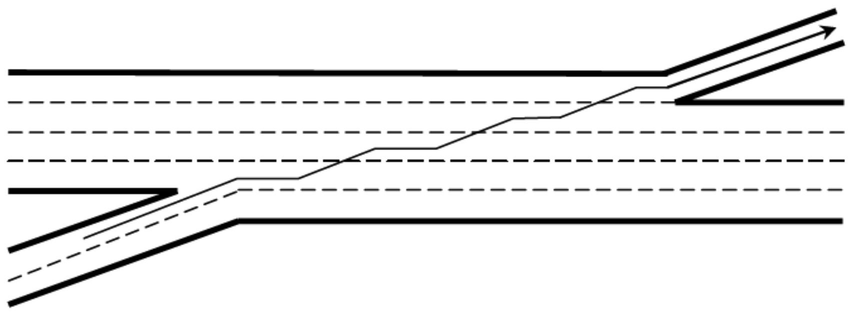
(b) One-sided major weave

Figure 5 One-sided weaving sections *(Highway Capacity Manual, 2010)*

Figure 6 illustrates two examples of two-sided weaving sections. Figure 6(a) shows a common form of two-sided weaving section. The ramp-to-ramp weaving movement requires two lane changes. Figure 6(b) shows a two-sided weaving section in which the on-ramp has multiple lanes. The ramp-to-ramp weaving movement requires three lane changes.



(a) Two-sided weaving section with single-lane ramps

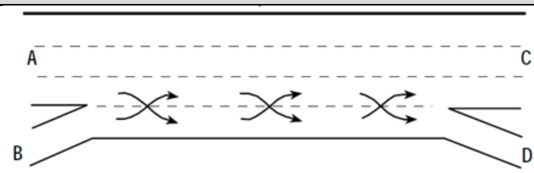
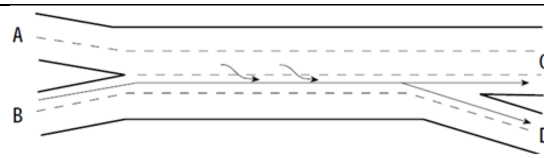
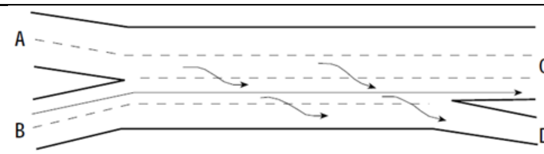
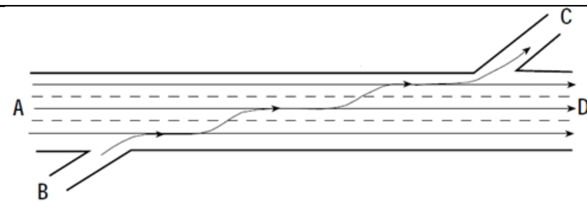


(b) Two-sided weaving section with three lane changes

Figure 6 Two-sided weaving sections *(Highway Capacity Manual, 2010)*

It can be seen that categories of freeway weaving section changed a lot from HCM 2000 to HCM 2010. Table 1 summarizes the relationship between the different categories defined in HCM 2000 and HCM 2010.

Table 1 Relationship between different categories in HCM 2000 and HCM 2010

Categories in HCM 2000	Weaving Section Layout	Categories in HCM 2010
Type A		One-Sided
Type B		One-Sided
Type C		One-Sided
		Two-Sided

Since HCM 2000 considers more details about the required number of lane changes for freeway weaving sections than HCM 2010, this study uses the definition and categories of weaving sections in HCM 2000 for analyzing the safety performance of freeway weaving sections.

2.2 Crash Modification Factors

The AASHTO Highway Safety Manual 2010 provides CMFs and summarizes the effects of various treatments such as geometric and operational modifications at a site. CMFs are the ratio of the crash frequency of a site under two different conditions and they represent the relative change in crash risk due to a change *(Gross et al., 2010).* Therefore, CMFs can be used to test alternative design options and they serve as the measures to quantify the effects of a particular geometric design or traffic control treatment. Thus, CMFs are generally used for the evaluation of the impacts of a particular treatment. Highway safety manuals provide CMFs to help transportation professionals or traffic engineers make safety decisions.

The values of CMFs in the HSM 2010 are determined for a specified set of base conditions. This allows comparison of treatment options against a specified reference condition. Under the base conditions (i.e., with no change in the conditions), the value of a CMF is 1.00. CMF values less than 1.00 indicate the alternative treatment reduces the average crash frequency in comparison to the base condition. CMF values greater than 1.00 indicate the alternative treatment increases the crash frequency in comparison to the base condition.

For treatments related to freeway design, HSM 2010 provides a function to calculate CMF for acceleration lane length, illustrated in Equation (1):

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

where L is the length of acceleration lane, as illustrated in Figure 7.

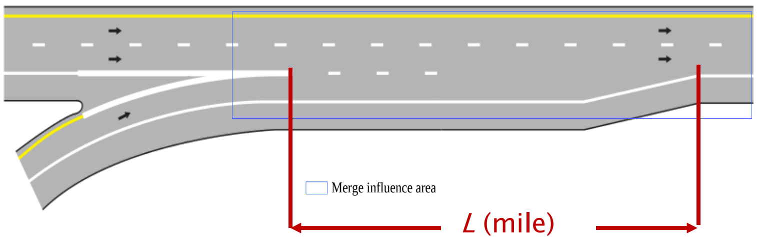


Figure 7 Acceleration lane

This means that, if extending the length of acceleration lane from 0.12 mile to 0.20 mile, the CMF for total accidents can be calculated as follows:

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

The result indicates that the crash frequency can reduce by 19% after extending the acceleration lane length from 0.12 mile to 0.20 mile.

Table 2 presents the crash effects and standard error associated with increasing the length of deceleration lane by 100ft. For existing deceleration lane that is less than 690 ft. in length, if the deceleration lane extends 100 ft. in length, the CMF can be calculated as follows:

CMF= 0.93± (2*0.06) = 0.81 to 1.05

The value suggests a possible increase, decrease, or no change in expected average crash frequency.

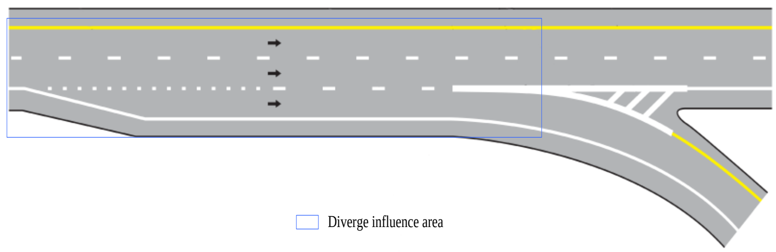


Figure 8 Deceleration lane

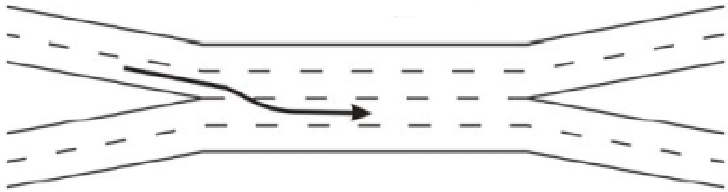
Table 2 Potential crash effects of extending deceleration lanes
(Highway Safety Manual, 2010)

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

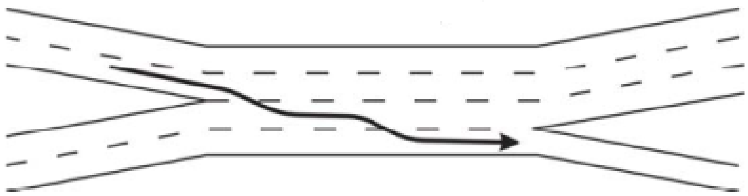
HCM 2000 also presents potential crash effects of modifying two-lane-change merge/diverge area to one-lane-change, as illustrated in Table 3. If the merge/diverge area is modified from two-lane-change to one-lane-change, the CMF can be calculated as follows:

CMF= 0.68± (2*0.04) = 0.60 to 0.76

The value suggests this treatment can decrease the crash frequency by 24% - 40%.



a. One lane change



b. Two lane change

Figure 9 Two-lane-change and one-lane-change merge/diverge area
(Highway Safety Manual, 2000)

Table 3 Potential crash effects of modifying two-lane-change merge/diverge area to one-lane-change *(Highway Safety Manual, 2000)*

Treatment	Setting	Traffic Volume	Crash Type	CMF	Std. Error
Modify two-lane to one-lane merge/diverge area	Unspecific	Unspecific	All	0.68	0.04
Base Condition: Merge/diverge area requiring two lane changes.					

Since quantitative information of potential treatments for freeway weaving sections was not sufficient to determine a CMF, Highway Safety Manual (2000) did not provide CMFs for the safety effects of different designs or treatments for freeway weaving sections, such as changing the weaving length, width and configuration. To fill this gap, the study calculates CMFs for geometric treatment for freeway weaving sections under the given traffic demand.

2.3 Studies on Safety Performance of Freeway Ramps

This section will present a summary of the existing studies on safety study of freeway ramps. Bared *et al.* (1999) conducted a study to investigate the relationship between the crash frequency and ramp Average Daily Traffic (ADT) and deceleration lane length. Bauer and Harwood (1998) focused on the relationship between traffic crashes and geometric design elements and traffic volumes.

Bared *et al.* (1999) studied the relationship between the crash frequency at freeway ramp areas and some influencing factors, including ramp ADT, freeway mainline ADT, deceleration lane length and geometric configuration. Based on the model developed by this study, it was found that the increase of ramp ADT and through ADT can increase crash frequency and the length of deceleration lane at off ramp has a positive impact on the safety performance of the ramp. Sensitivity analysis results indicate that a 100-ft increase in deceleration lane length can result in a 4.8% reduction in crash frequency.

Bauer and Harwood (1998) conducted a study to investigate the relationship between traffic crashes and highway geometric design elements and traffic volumes for interchange ramps and speed-change lanes. The study used Poisson and negative binomial (NB) regression modeling approaches to predict crashes on ramp sections and speed-change lanes. The explanatory variables included: mainline freeway annual average daily traffic (AADT), ramp AADT, area type (rural/urban), ramp type (on/off), ramp configuration, right shoulder width, and lengths of ramp and speed-change lane. For these explanatory variables, the statistical results showed that ramp AADT explained most of the variability in the accident data. Crash frequency increases with the increase of the ramp AADT.

Both of the results of the two studies indicate that ramp volume influences the crash frequency on freeway ramps. Bared *et al*. (1999) also presents that deceleration lane length has significant impacts on the safety performance of freeway ramps.

2.4 Studies on Safety Performance of Freeway Weaving Sections

Until recently, few previous studies have been conducted regarding the safety performance of freeway weaving sections. This section will present a summary of the limited number of existing studies on the safety performance of freeway weaving sections.

Liu *et al.* (2010) studies how lane arrangements on freeway mainlines and ramps affect safety of freeways weaving sections. Three different types of arrangements are studied to compare safety performance. The Type A arrangement has a one-lane entrance ramp followed by a one-lane exit ramp without auxiliary lane. Type B arrangement has a one-lane entrance ramp and a two-lane exit ramp with an auxiliary lane. The difference between Type C and Type B is that Type C has only a one-lane exit ramp. Crash prediction models were developed to indicate the relationship between the number of crashes and various contributing variables, including weaving section length, on-ramp ADT, type of lane arrangement, freeway mainline ADT, number of lanes and speed. This study found that length of weaving section, on-ramp ADT and speed have impacts on the safety of weaving section. In addition, it was found among three different types of lane arrangements, Type C has the lowest average crash frequency.

Le and Porter (2012) conducted a study that focuses on the relationship between ramp spacing and freeway safety by developing a negative binomial regression model. The results of this study indicate that crash frequency increased as ramp spacing decreased, and the safety benefits of using freeway auxiliary lanes decreased as ramp spacing increased.

Golob et al. (2004) analyzed accidents that occurred on three typical types of weaving sections as defined by HCM 2000. This study analyzed the frequency of different types of accidents, location of the accidents, the factors contributing to the accidents and the time period the accidents occurred. In addition, recommendations for improving the safety performance of each type of weaving sections were provided. For Type A weaving sections, improved signage and lighting could provide sufficient warning to change lanes. Effective speed control methods can improve the safety performance for Type B weaving sections. At Type C weaving sections, warning signs of potential hazards should be installed.

Batenhorst and Gerken (2000) studied the operational effects of the weaving sections created by auxiliary lanes between two successive interchanges. They compared the operational effects of two different lane arrangements based on traffic simulation analysis: (1) the auxiliary lane was terminated at a one-lane exit ramp, and (2) the auxiliary lane was terminated at a two-lane exit ramp. The research found that the two-lane exit ramp design resulted in higher total system delay than the one-lane exit ramp design. The increase in total system delay ranged from 0.4 to 39.9% and averaged 33.7%.

Park (2010) conducted a study to investigate the safety effects of important design elements for freeways. Negative binomial regression models were used to estimate the effects of independent variables on crashes. The final model for evaluation indicated that crashes on freeway segments were associated with ADT, on-ramp density, the number of lanes (for urban freeways), and whether the freeway is in an urban or rural area. Off-ramp density was not a statistically significant influencing factor. The statistical modeling results were geared into the development of CMFs for on-ramp density and horizontal curves for safety impacts prediction.

All of these studies conducted analysis on contributing factors to the crash frequency for freeway weaving sections. Both of the studies by Liu et al. (2010) and Le and Porter (2012) presented that shorter weaving length leads to higher crash frequency for freeway weaving sections. For the study, conducted by Batenhorst and Gerken (2000), the results showed that the two-lane exit ramp design resulted in higher total system delay than a one-lane exit ramp design. These studies also indicated that through ADT and on-ramp density could have impacts on safety performance for freeway weaving sections.

CHAPTER 3: DESIGN OF THE STUDY

In this chapter, the overall design of this research is presented in four aspects: 1) methodology, 2) research procedure, 3) data collection, and 4) techniques and tools.

3.1 Methodology

This research aims to investigate the safety performance of freeway weaving sections and develop a quantitative model for predicting the safety impacts of different types of geometric treatments for freeway weaving sections.

In order to achieve the objective of this research, a historical crash data based analysis was conducted to investigate the safety performance of freeway weaving sections. At first, a total of sixteen freeway weaving sections were selected for the field study. Field traffic data and historical crash data were collected at studied weaving sections. And then, an independent non-parametric test was conducted to investigate contributing factors on crashes occurred in the studied sites. A crash prediction model was developed from the safety analysis. In addition, CMFs were developed based on the developed crash prediction model for estimating the impacts of different safety treatments for the freeway weaving sections.

Poisson Regression and Negative Binomial (NB) regression models were used to identify factors that contribute to the crashes occurred in the freeway weaving sections. The following section introduces these two models and model selection methods.

Poisson Regression Model

The Poisson regression model is a classical model for counted data. The statistic software package SPSS was used for developing this model.

Critical events are randomly distributed and the frequency of critical events is discrete and positive numbers. The relationship between the expected number of critical events Y_i occurring at an intersection approach pair i (dependent variable Y_i) and a set of explanatory variables X_{i1}, X_{i2},…X_{in} that represent the features of intersections (i.e., intersection geometric, signal control, traffic volume conditions) could be modeled as Equation (2):

$$P(y_i|X_i) = \frac{\exp(-\mu_i)\mu_i^{y_i}}{y_i!} \ , \quad (2)$$

where y_i denotes the total number of critical events that occurred at intersection approach pair i, and μ_i is the conditional mean of y_i , which is a non-linear function of X_i and can be expressed as follows :

$$\text{In } \mu_i = \beta X_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_n X_{in} \ . \quad (3)$$

Then, the expected number of critical events at intersection approach pair i can be estimated by:

$$E(y_i|X_i) = \mu_i = e^{\beta X_i} \ , \quad (4)$$

where β is the vector of regression coefficients that can be estimated by the standard maximum likelihood method with the likelihood function given by:

$$L(\beta) = \prod_i \frac{\exp[-\exp(\beta X_i)][\exp(\beta X_i)]^{y_i}}{y_i!} \ , \quad (5)$$

Negative Binomial (NB) Regression Model

A limitation of the Poisson model is its implicit assumption that the dependent variance of y_i equals its mean. When critical event frequency data is over dispersed, which means that the variance of critical event frequency data is greater than its mean, the Poisson regression model cannot be employed. In order to relax the over dispersion constraint, a negative binomial regression model is commonly used. It generalizes the Poisson model by introducing an independently distributed error term into the conditional mean in Equation (1), such that

$$In\ \mu_i = \beta X_i + \varepsilon_i \quad (6)$$

where exp (ε_i) is a gamma-distributed error term with mean one and variance α. It can be derived that the conditional mean of the independent variable y_i follows a negative binomial distribution, which can be expressed as follows:

$$P(y_i|X_i) = \frac{\Gamma(1/\alpha + y_i)}{y_i! \cdot \Gamma(1/\alpha)} \cdot u_i^{1/\alpha}(1 - u_i)^{y_i} \quad (7)$$

where $u_i = 1/\alpha\,(1/\alpha + \mu_i)$. The mean of the negative binomial distribution remains the same as Poisson distribution, which is μ_i, and its variance can be expressed by following Equation

$$Var(y_i|X_i) = \mu_i + \alpha\mu_i^2 \tag{8}$$

where α is the variance of the gamma-distributed error term. From equation (8), it can be seen that the introduction of ε_i results in that the variance of y_i differs from the its mean. α is a measure of data dispersion and when $a \to 0$ the negative binomial becomes the Poisson distribution(it can be derived based on Equation (7)). Similar to the Poisson regression model, the value of parameter a and the coefficients of independent variables can be estimated by standard maximum log likelihood given by function:

$$\ln L' = \sum_{i=1}^{n}\left[\ln(\Gamma(y_i + 1/a)) - \ln(\Gamma(y_i + 1)) - \ln(\Gamma(1/a))\lambda_i + y_i \ln(a) + y_i\beta'\chi_i - (y_i + 1/a)\ln(1 + a\lambda_i)\right] \tag{9}$$

Model Selection

Cameron and Trivedi (1990) and Greene (2000) have developed a test that can be used to choose between the Poisson regression model and the negative binomial model. Their test is based on the following hypotheses:

$$H_0 : Var(y_i) = E(y_i) \tag{10}$$

$$H_1 : Var(y_i) = E(y_i) + ag(E(y_i)) \tag{11}$$

The test is conducted by regressing

$$Z_i = \frac{(y_i - \hat{\lambda}_i)^2 - y_i}{\lambda_i\sqrt{2}} \tag{12}$$

on λ_i and a constant term, which can be expressed as

$$Z_i = c_i + \beta_{\lambda i}\lambda_i \tag{13}$$

A simple *t* test for the coefficient λ_i is equivalent to a test of H_0 vs. H_1 .

Second, as mentioned before, when the parameter *a* in Equation (8) close to 0, negative binomial becomes Poisson distribution. So, by testing the hypothesis of $H_0 : a = 0$ vs. $H_1 : a \neq 0$, the appropriate model can be the selected for the critical events data used in this study. This test can be carried out by a t-test for the estimated *a*, a likelihood ratio test, or a Lagrange Multiple (LM) test.

The likelihood ratio test is a statistic test used to compare the fit of two models. The likelihood ratio or equivalently its logarithm can be used to compute a p-value to decide whether to reject the null model in favor of the alternative model. The likelihood ratio test is actually based on the ratio of likelihood function L and $L^{'}$ described in Equations (5) and (9). The ratio of likelihood λ can be written as:

$$\lambda = \frac{L}{L^{'}} \tag{14}$$

According to (Greene, 2000), the following variable Z^2 has a chi square distribution with one (1) degree of freedom:

$$Z^2 = -2\ln(\lambda) \tag{15}$$

Compared with likelihood ratio test, Lagrange Multiple Test is also based on likelihood function, but it only involves one model. The maximum log likelihood for NB regression is a function of parameter a as shown in Equation (9).The Lagrange Multiplier test is using the maximum likelihood function to generate a variable Lagrange Multiplier score. The Lagrange Multiplier score $\xi(a)$ can be written as:

$$\xi(a) = \frac{\partial(\ln L^{'})}{\partial a} \tag{16}$$

There we can get the first derivative of the Lagrange Multiplier score:

$$I(a) = \frac{\partial^2(\ln L^{'})}{\partial a^2} \tag{17}$$

So we obtain the Lagrange Multiplier test statistic *LM*, which can be expressed as:

$$LM = \frac{\xi(\alpha)^2}{I(\alpha)} \tag{18}$$

This Lagrange Multiplier test statistic *LM* follows a chi-square distribution and can used to compute a p-value to decide whether to reject the null model α=0 or accept the null model.

3.2 Research Procedure

According to the established objective and methodology of this research, the research procedure is divided into four steps. Step 1 is to conduct the literature review to summarize the results of the previous studies on safety analysis of freeway ramps and weaving sections. Step 2 is to collect detailed information and traffic data, as well as historical crash data for studied freeway weaving sections. Step 3 is to conduct safety analysis. Step 4 is to make conclusions and recommendations. The overall research procedure is shown as follows.

Step 1: Literature Review

Based on the review of previous research, the results of the previous studies on safety analysis of freeway ramps and weaving sections have been summarized.

Step 2: Data Collection

Traffic data and historical crash data were collected. At each weaving section, traffic data were collected during morning peak hours and afternoon peak hours .Historical crash data were collected for the studied sections over a five-year time period (from 2007 to 2011) from Texas Department of Transportation (TxDOT) Crash Record Information System (CRIS).

Step 3: Data Analysis

In this study, Poisson regression model is developed for analyzing the influencing factors on the safety performance of freeway weaving sections and to derive CMF for quantifying the impacts of different safety treatments.

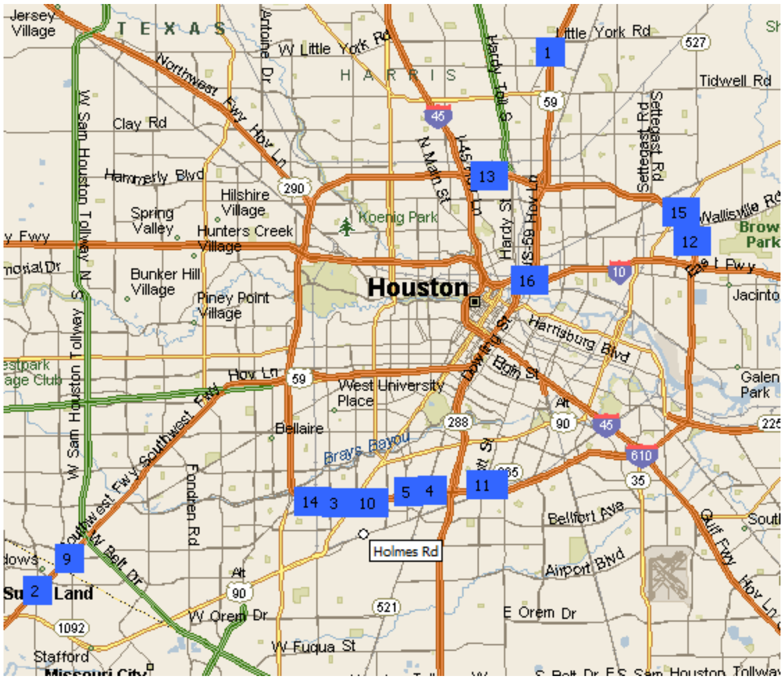
Step 4: Conclusions and Recommendations

Based on the results of data analysis, the key findings about the safety performance of freeway weaving sections were obtained.

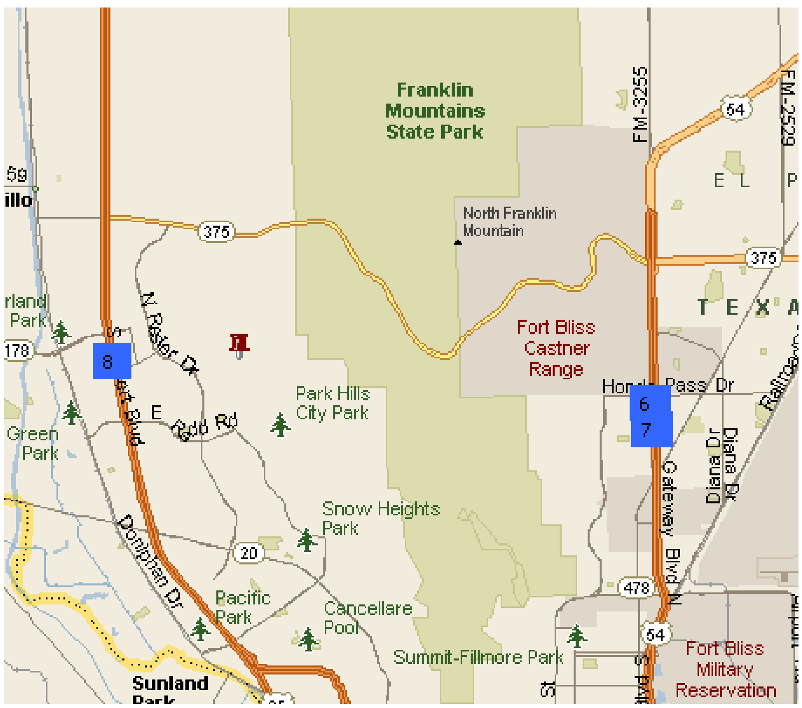
3.3 Data Collection

Selection of Study Freeway Weaving Sections

In this study, sixteen weaving sections with different geometric configurations (different number of auxiliary lanes and ramp arrangements) were selected in two major cities, Houston and El Paso, Texas. Among them, there are seven Type A weaving sections, three Type B weaving sections and six Type C weaving sections. Table 4 presents the detailed information about these selected freeway weaving sections. In this table, L_S is the weaving length which is measured from the merge gore area to the diverge gore area; N is the total number of lanes in the weaving area, which includes auxiliary lanes; LC_{RF} is the minimum number of required lane changes for a single weaving vehicle moving from on-ramp to freeway; and LC_{FR} is the minimum number of required lane changes for a single weaving vehicle moving from freeway to off-ramp. The detail locations of the study sites were presented in Figure 10.



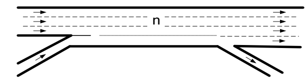
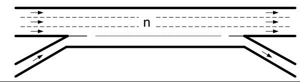
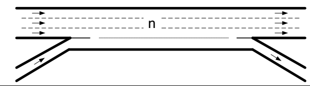
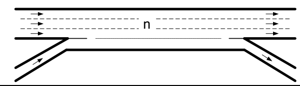
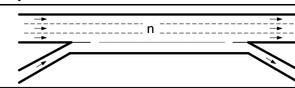
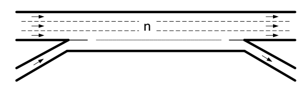
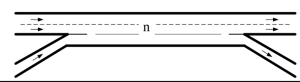
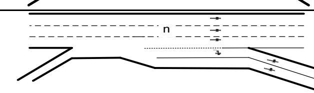
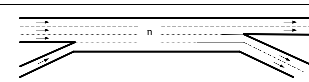
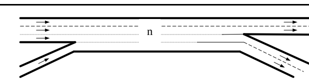
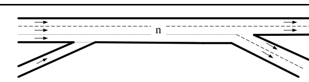
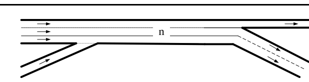
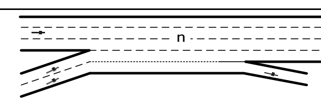
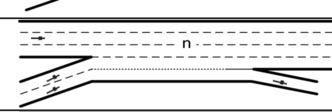
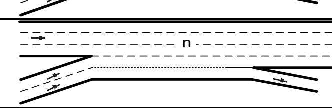
a **Studied weaving sections in Houston, Texas.**



b **Studied weaving sections in El Paso, Texas.**

Figure 10 Studied weaving sections

Table 4 Information for all the studied weaving sections

ID	Cities	Freeway	*L_S(ft)	**N	***LC_{RF}	****LC_{FR}	Type	Layout
1	Houston	US 59	2370	5	0	1	B	
2	Houston	US 59	2851	5	1	1	A	
3	Houston	I-610	1130	6	1	1	A	
4	Houston	I-610	432	6	1	1	A	
5	Houston	I-610	423	6	1	1	A	
6	El Paso	US 54	752	4	1	1	A	
7	El Paso	US 54	680	3	1	0	B	
8	El Paso	I-10	697	3	1	1	A	
9	Houston	US 59	2787	6	1	1	A	
10	Houston	I-610	1325	6	2	0	C	
11	Houston	I-610	1107	5	2	0	C	
12	Houston	I-610	1640	4	1	0	B	
13	Houston	I-610	1285	6	2	0	C	
14	Houston	I-610	1540	6	0	2	C	
15	Houston	I-610	957	5	0	2	C	
16	Houston	US 59	2020	5	0	2	C	

* L_S: weaving length that is measured from the merge gore area to the diverge gore area; **N: is the total number of lanes in the weaving section; *** LC_{RF}: minimum number of lane changes from on-ramp to freeway; **** LC_{FR}: Minimum number of lane changes from freeway to off-ramp

Historical Crash Data Collection

Historical crash data were collected for the sixteen studied sections over a five-year time period (from 2007 to 2011) from TxDOT Crash Record Information System (CRIS). Each data sample contains longitude and latitude of crash locations, which enables a spatial distribution analysis. Using ArcGIS software, the locations of crashes can be displayed on the maps of cities where the candidate study sites are located. Based on the crash spatial location information and the crash information in the CRIS database, crashes that occurred within the area of study weaving sections can be identified and selected. As an example, Figure 11 shows the crashes occurred and recorded in Texas in 2007.

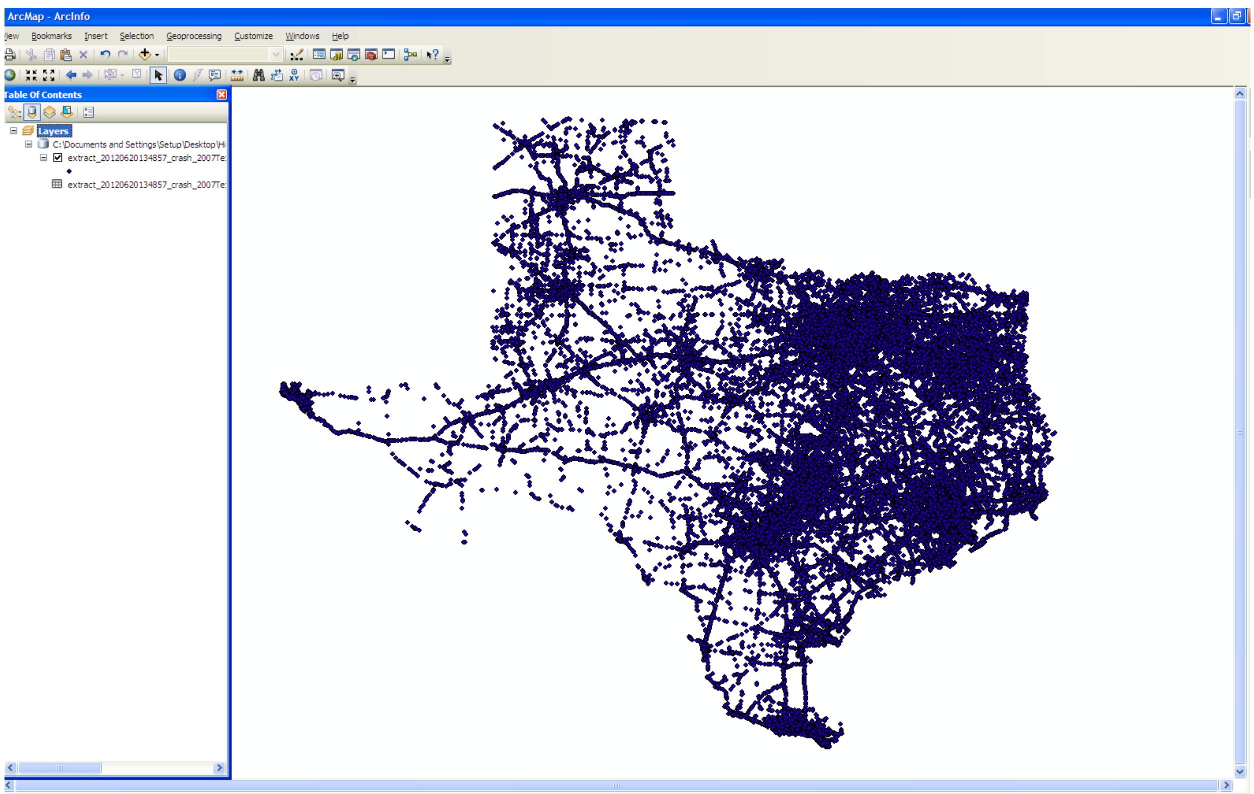


Figure 11 Crash Map in Texas

Data Collected from the Field

To collect data at these selected weaving sections, traffic video was recorded from surveillance cameras installed at each freeway section during both morning and afternoon peak hours of a weekday. As an example, a screen shoot of the video of Interstate 610 @ Wallisville Rd. is shown in Figure 12. Table 5 shows the volume and crash data for all the study weaving section. The volume data collected for each location included:

- $V_{THR:}$ Through volume (pc/h)
- V_{ON}: On-ramp volume (pc/h)
- V_{OFF}: Off-ramp volume (pc/h)
-

Figure 12 Sample of traffic video

Table 5 Volume and crash data for all the studied weaving sections

ID	Time of video recording	V_{ON} (pc/h)	V_{OFF} (pc/h)	V_{THR} (pc/h)	Number of Crashes (crash/1000 ft)
1	AM Peak Hours	1016	478	4763	1
	PM Peak Hours	854	646	4813	
2	AM Peak Hours	399	1112	3647	2
	PM Peak Hours	1375	1715	6124	
3	AM Peak Hours	617	766	4572	2
	PM Peak Hours	528	749	5554	
4	AM Peak Hours	942	1142	5393	9
	PM Peak Hours	1028	992	4813	
5	AM Peak Hours	232	1200	5193	31
	PM Peak Hours	486	1526	4849	
6	AM Peak Hours	586	274	4351	4
	PM Peak Hours	419	242	2235	
7	AM Peak Hours	126	221	1217	7
	PM Peak Hours	319	618	2980	
8	AM Peak Hours	1036	127	993	9
	PM Peak Hours	808	397	1903	
9	AM Peak Hours	848	1486	4285	3
	PM Peak Hours	931	1716	6909	
10	AM Peak Hours	591	1347	5825	4
	PM Peak Hours	349	1925	7422	
11	AM Peak Hours	372	2515	7404	1
	PM Peak Hours	427	1876	6376	
12	AM Peak Hours	315	2978	4217	7
	PM Peak Hours	738	3330	4717	
13	AM Peak Hours	449	1799	6637	9
	PM Peak Hours	364	1564	5658	
14	AM Peak Hours	1486	319	4593	3
	PM Peak Hours	1036	479	5844	
15	AM Peak Hours	1929	673	3179	5
	PM Peak Hours	1890	578	3432	
16	AM Peak Hours	243	162	3209	6
	PM Peak Hours	264	192	1122	

3.4 Techniques and Tools

In this research, several statistical techniques and transportation software will be used, including Microsoft Excel, SPSS and GIS, etc.

Microsoft Excel is an electronic spreadsheet program that can be used for storing, calculating and analyzing data. In this research, it was used to calculate Average Daily Through Traffic (ADT_{THR}), Average Daily On-Ramp Traffic (ADT_{ON}), and Average Daily Off-Ramp Traffic (ADT_{OFF}).

SPSS (Statistical Package for the Social Sciences) is a computer program used for survey authoring and deployment (IBM SPSS Data Collection), data mining (IBM SPSS Modeler), text analytics, statistical analysis, and collaboration and deployment (batch and automated scoring services). In this research, it was used to investigate the influencing factors on the safety performance of freeway weaving sections.

GIS (Geographic Information System) is a system designed to capture, store, manipulate, analyze, manage, and present all types of geographical data. In this study, it was used to collect the historical crash data for the studied freeway weaving sections.

CHAPTER 4: RESULTS AND DISCUSSION

In this chapter, a quantitative model for predicting safety impacts of different types of geometric treatments for freeway weaving sections was developed. The modeling results were discussed and based on the developed model, CMFs were derived for estimating the safety impacts of different geometric treatments for the freeway weaving sections.

4.1 Development of Statistical Model for Safety Impacts Analysis

In this study, a regression model was developed for analyzing the influencing factors on the safety performance of freeway weaving sections. The crash frequency was standardized by weaving section length because the length will not only affect the intensive level of lane changes at the weaving section, but also affect the traffic exposure level (the longer length means high traffic exposure level). Therefore, the crash frequency needs to be standardized by the length to control the effect of traffic exposure due to the length. In this study, the dependent variable is defined as the number of crashes per 1000 ft. occurred during five years. The candidate independent variables include "Length of Weaving Sections" (L_S), "Minimum Number of Lane Changes from On-Ramp to Freeway" (LC_{RF}), "Minimum Number of Lane Changes from Freeway to Off-Ramp" (LC_{FR}), "Average Daily Through Traffic" (ADT_{THR}), "Average Daily On-Ramp Traffic" (ADT_{ON}), and "Average Daily Off-Ramp Traffic" (ADT_{OFF}). Among these variables, the variable of "Average Daily Traffic Volume" was estimated by multiplying the collected average peak hour volume with 10 because the *K* factor (proportion of daily traffic occurring in the peak hour of the day) provided by HCM 2000 is between 0.09 and 0.10 (1). Table 6 shows all dependent and independent variables used for the analysis in this study and their descriptions.

Table 6 Candidate independent and dependent variables with descriptions

Dependent Variables	Description
Crashes (crash/1000 ft)	Number of crashes per 1000 ft occurred during five years
Independent Variables	**Description**
Weaving Section Geometry Characteristics	
$L_S(ft)$	Length of weaving section
LC_{RF}	Minimum number of lane changes from on-ramp to freeway
LC_{FR}	Minimum number of lane changes from freeway to off-ramp
Traffic Flow Characteristics	
ADT_{THR}	Average Daily Through Traffic
ADT_{ON}	Average Daily On-ramp Traffic
ADT_{OFF}	Average Daily Off-ramp Traffic

Likelihood ratio tests will be used to select the appropriate regression model. The log likelihood for the Poisson model and negative binomial model is -40.01150 and -38.71968. The likelihood ratio can be calculated according to equation (15): 2*(-38.71968-(-40.01150)) =2.58, which follows chi-square distribution with 1 freedom and p-value is 0.10797314. The p-value is larger than 0.05. Therefore, a Poisson regression model is selected for this study.

The results, of the Poisson regression model, are presented in Table 7. The statistical analysis results in Table 7 show that the number of crashes on the freeway were significantly affected by the following variables: "Length of Weaving Section" (L_S), "Minimum Number of Lane Changes from Freeway to On-Ramp" (LC_{FR}), "Average Daily On-Ramp Traffic" (ADT_{ON}), and "Average Daily Off-Ramp Traffic" (ADT_{OFF}) at the confidence level of 95%.

Table 7 Results of Poisson regression analysis

Model		Dependent Variable: Crashes	
Regression Results	Independent Variables	Estimated Coefficients	p-value
	Constant	2.3797	0.000
	L_S	-0.00104	0.000
	LC_{FR}	0.86022	0.002
	ADT_{ON}	-0.00010	0.004
	ADT_{OFF}	0.000056	0.009
	Sample Size	16	
	Log likelihood	-40.01150	

4.2 Findings for Statistically Significant Impacting Factors

The length of weaving section (L_S) and average daily on-ramp traffic (ADT_{ON}) have positive impacts on safety performance for weaving sections, while minimum number of lane changes from freeway to off-Ramp (LC_{FR}) and average daily off-ramp traffic (ADT_{OFF}) could increase the crash risk for weaving sections. The impact of length of weaving sections was consistent with the literature findings. Following are the discussions for the impacts of individual factors that have significant impacts on the safety performance of weaving section.

Length of Weaving Section

The length of weaving section has positive impacts on its safety performance (its coefficient is negative), which means weaving sections with longer lengths will have lower crash frequency per 1000 ft. This is reasonable because weaving vehicles need to make required lane changes in the space and time limited by the length of the weaving section. Longer lengths mean weaving vehicles have more time and more moving distance to find safe gaps to make lane changes.

Minimum Number of Lane Changes from Freeway to Off-Ramp (LC_{FR})

Minimum Number of Lane Changes from Freeway to Off-Ramp (LC_{FR}) has negative impacts on the safety of weaving section (its coefficient is positive). It means that as LC_{FR} increases, the crash risk at the weaving section will increase too. A larger value of LC_{FR} means more lane changes are required for the vehicles diverge from the freeway, which can lead to increased crash risk.

Average Daily Traffic for On-ramp (ADT_{ON})

According to the results, ADT_{ON} has a slight positive impact on the safety of weaving section (its coefficient is -0.00010), which means more merge traffic in the weaving sections will lead to less crash risk. This may be different with our expectation. However, after observing the collected traffic video, it was found that the weaving sections with high merge traffic volume tend to have slow traffic flow. In addition, drivers may become more cautious to other vehicles when they see high merge volume from the ramp. Both of these factors may explain the decrease of the crash possibility in the weaving sections with high merge volume.

Average Daily Traffic for off-ramp (ADT_{OFF})

Since the coefficient of ADT_{OFF} is positive, it means increasing diverge traffic in the weaving sections will increase the crash frequency at this section. This is easy to understand because more diverge traffic will result in more lane change maneuvers and diverge vehicles tend to slow down before entering the exit ramp, which will cause more turbulence in the traffic flow and lead to increased crash risk.

4.3 Crash Modification Factors (CMFs) and Case Study

A CMF is a quantitative measure of the change in expected average crash at a site caused by implementing a particular treatment. The developed crash prediction model can be used to quantify the impacts of different safety treatments for freeway weaving sections under different traffic conditions. Based on the results from Poisson regression analysis, the expected crash frequency (per 1000 ft.) can be estimated by following equation:

$$Y = e^{\left(2.3797 - 0.00104 \times L_S + 0.86022 \times LC_{FR} - 0.0001 \times ADT_{ON} + 0.000056 \times ADT_{OFF}\right)} \tag{19}$$

Where, Y is the expected crash frequency for a freeway weaving section within five years (crashes/1000ft);

L_S is the length of the weaving section (ft);

LC_{FR} is the minimum number of lane changes from freeway to off-ramp;

ADT_{ON} is the average daily on-ramp traffic;

ADT_{OFF} is the average daily off-ramp traffic.

Therefore, the percentage of change in crash frequency at a weaving section after implementing a particular geometric treatment, such as adding an auxiliary lane or a lane on the ramp, can be estimated as follows:

$$CMF = \frac{e^{\left(2.3797-0.00104\times L_S{}^{after}+0.86022\times LC_{FR}{}^{after}-0.0001\times ADT_{ON}{}^{after}+0.000056\times ADT_{OFF}{}^{after}\right)}}{e^{\left(2.3797-0.00104\times L_S{}^{before}+0.86022\times LC_{FR}{}^{before}-0.0001\times ADT_{ON}{}^{before}+0.000056\times ADT_{OFF}{}^{before}\right)}} \qquad (20)$$

The developed CMF can be used to estimate the impacts of different safety treatments for a freeway weaving section as demonstrated by the two case studies for the two selected locations listed in Table 4: and 1) 16th weaving section. 2) 4th and 5th weaving sections

Case Study A – 16th study location

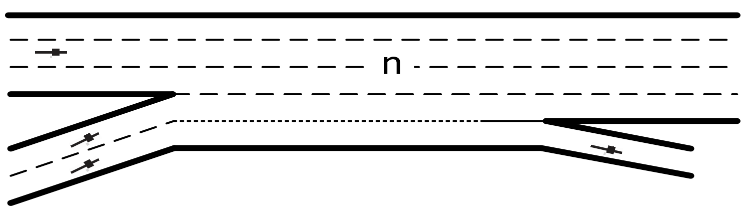
Figure 13 shows the lane configuration of this location. In this location, diverge vehicles need to make at least two lane changes in order to exit the freeway. According to the crash prediction model, the value of variable LC_{FR} (minimum number of lane changes from freeway to off-ramp) will affect the safety performance of the weaving section. More lane changes from freeway to off-ramp will result in more crashes. Therefore, to reduce the value of LC_{FR}, in this case study, the two-lane on ramp at this location was converted to a one-lane ramp and an auxiliary lane was converted to a main through lane as shown in the Figure 13(b). By this change, the diverge traffic only needs to make one lane change to exit the freeway, which will improve the safety at this location. By calculating CMF, it is easy to quantify the safety benefits of this treatment. In the original configuration, LC_{FR} is equal to 2. After this treatment, $\mathrm{LC_{FR}}$ become 1. According to Equation (20), CMF can be calculated.

$$CMF = \frac{e^{\left(2.3797-0.00104\times L_S{}^{after}+0.86022\times LC_{FR}{}^{after}-0.0001\times ADT_{ON}{}^{after}+0.000056\times ADT_{OFF}{}^{after}\right)}}{e^{\left(2.3797-0.00104\times L_S{}^{before}+0.86022\times LC_{FR}{}^{before}-0.0001\times ADT_{ON}{}^{before}+0.000056\times ADT_{OFF}{}^{before}\right)}}$$

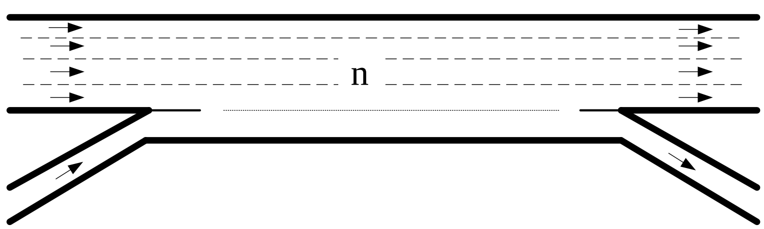
$$= \frac{e^{(2.3797-0.00104\times 2020+0.86022\times 1-0.0001\times 2540+0.000056\times 1770)}}{e^{(2.3797-0.00104\times 2020+0.86022\times 2-0.0001\times 2540+0.000056\times 1770)}}$$

$$= 42.31\%$$

Compared with the CMF for modifying two-lane-change to one-lane-change in HCM 2000, the result of the case study is relatively smaller. The result indicates that the expected crash frequency after changing the freeway configuration will reduce by 57.69%.



a. Existing geometric configuration.



b. Geometric configuration after treatment.

Figure 13 Geometric treatment for 16th studied weaving section

Case Study B – 4th and 5th weaving sections

Figure 14 show the geometric configuration of 4th and 5th study weaving section. These two weaving sections are adjacent with short distance in the same direction. As shown in Table 5, both have highest crash frequency during the recent five years. The major problem for this location is the extremely short weaving length (432 ft. and 423 ft.), which results in high density of weaving conflicts. One potential solution for improving the safety performance of this location is to combine these two weaving sections to a big weaving section by extending the auxiliary lane to connect both sections and closing the current off ramp in the 4th section and on ramp in the 5th section (as shown in Figure 14). Therefore, after this treatment, the total length of the weaving section will increase to 3457 ft. In addition, since the off-ramp in the 4th section and on-ramp in the 5th section are closed, all merge traffic will use on-ramp in the 4th section and all diverge traffic will use off-ramp in the 5th section. According to traffic volume data in Table 5, the on-ramp ADT for the location after the treatment will be 13440, and the off-ramp ADT after the treatment will be 24300. Based on the Equation (19), the expected crash frequencies for the original 4th and 5th weaving sections and the combined weaving section after the treatment can be obtained as follows.

Crash frequency for 4th weaving section is

$$e^{(2.3797-0.00104\times432+0.86022\times1-0.0001\times9850+0.000056\times10670)}=11.06$$

Crash frequency for 5th weaving section is

$$e^{(2.3797-0.00104\times423+0.86022\times1-0.0001\times3590+0.000056\times13630)}=24.63$$

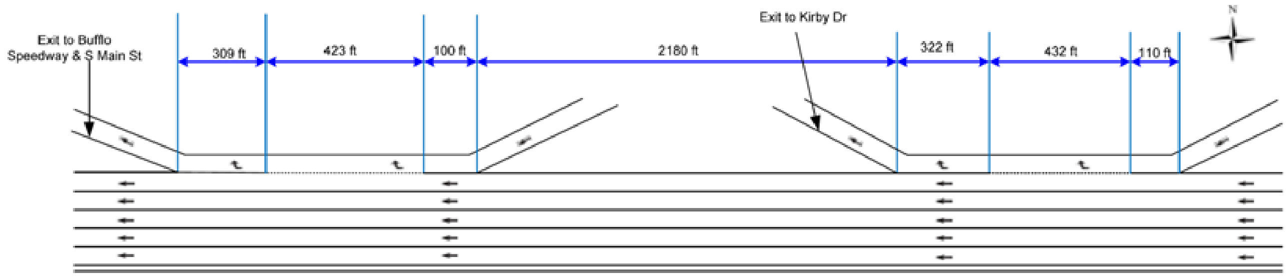
Crash frequency for combined weaving section after the treatment is

$$e^{(2.3797-0.00104\times3457+0.86022\times1-0.0001\times13440+0.000056\times24300)}=0.71$$

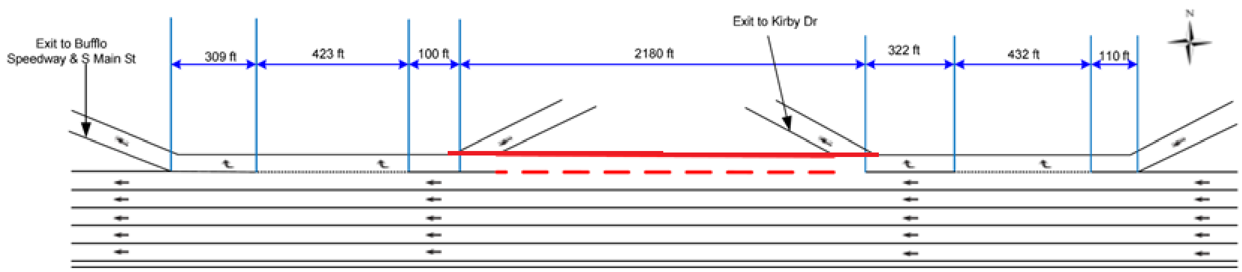
Then CMF for this location can be estimated by considering the length of weaving sections.

$$CMF=\frac{0.71\times3.457}{11.06\times0.432+24.63\times0.423}=16.15\%$$

The result indicates that the proposed geometric treatment for this location can reduce crash frequency by 83.85%.



a. Existing geometric configuration.



b. Geometric configuration after treatments.

Figure 14 Geometric treatment for 4th and 5th studied weaving section

CHAPTER 5: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The research investigated the safety performance of freeway weaving sections and developed a quantitative model for predicting the safety impacts of different types of geometric treatments for freeway weaving sections. In this study, Poisson regression model is developed for analyzing the influencing factors on the safety performance of freeway weaving sections and to derive CMF for quantifying the safety impacts of different geometric treatments. The statistical analysis results show that the crash frequency in the weaving section was significantly affected by the length of the weaving section, minimum number of required lane changes from freeway to on-ramp, average daily on-ramp traffic, and average daily off-ramp traffic. In addition, it is also found that:

- Weaving sections with longer lengths will have lower crash frequency per 1000 ft.
- More lane changes are needed for diverge vehicles which will result in more crashes in the freeway weaving section.
- Increasing merge traffic in the weaving sections will slightly reduce the crash risk at this section.
- Increasing diverge traffic in the weaving sections will increase the crash risk at this section.

CMFs were derived based on the developed crash prediction model for estimating the impacts of different geometric treatments for the freeway weaving sections. For demonstrating the use of the developed CMF, two case studies were conducted for two study weaving sections. The results of this study will help traffic engineers to better understand the safety performance of different weaving sections. It also provides them a guideline for quantitatively assessing the safe benefits of different geometric treatments for freeway weaving sections.

According to the results of this research, several design recommendations are presented as follows to improve the safety performance of weaving sections:

- Reducing required lane change to enter or exit freeway will decrease the crash risk in the freeway weaving sections. The freeway designer should consider the required numbers of lane changes for weaving vehicles.

- For weaving sections with short length and large volume, extending weaving length is strongly recommended. For existing freeway weaving sections, extending length can be completed by combining two adjacent weaving sections. Thus, weaving vehicles can have more time to complete weaving maneuvers successfully.

The study still has limitations. First, the sample size is small and all of the crash data were collected in Texas. In the future, more field data in different locations should be collected to obtain more accurate results. Second, in this study, the safety analysis is solely based on police-reported crashes. The information about crashes is often insufficient. Researchers cannot fully control some external factors, such as the factors related to human behaviors where it is usually hard to measure their impacts on crash analysis. In the future, driving simulator based study can be conducted to further test the effect of human behavior related factors.

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