Safety performance evaluation of left-side off-ramps at freeway diverge areas

Hongyun Chen a, *, Huaguo Zhou b,1, Jiguang Zhao b,2, Peter Hsu c,3

a Center for Urban Transportation Research, University of South Florida, 4202 E. Fowler Ave. CUT 110, Tampa, FL 33620, United States
b Department of Civil Engineering, Southern Illinois University Edwardsville, Edwardsville, IL 62026-1800, United States
c Florida Department of Transportation, 11201 N McKinley Dr., Tampa, FL 33612, United States

A R T I C L E   I N F O

Article history:
Received 10 February 2010
Received in revised form 14 August 2010
Accepted 18 August 2010

Keywords:
Freeway diverge area
Left-side off-ramp
Exit ramp type
Conflict study
Crash predictive model

A B S T R A C T

The safety performance of left-side off-ramps was evaluated by comparing that of right-side off-ramps at freeway diverge areas. Crash records at a total of 11 left-side and 63 similar right-side diverge areas in Florida were collected. Based on the data collected, the traffic conflict study and the cross-sectional comparison of crashes were conducted in this study. Four types of traffic conflicts were identified and counted. The average conflict rates near the ramp area were found to be approximately 10 per 1000 conflicting vehicles. Crash data were compared for the left-side off-ramps with right-side off-ramps by two exit ramp types: one-lane exit and two-lane exit with an optional lane, respectively. The comparisons indicate that the left-side off-ramp did have higher average crash counts, crash rate and percentage of severe crashes, but the difference is only statistically significant for the severe crashes at a 10% level.

1. Introduction

The abnormal left exits on freeways were commonly regarded to result in safety issues related to drivers’ expectancy. Recently, a major traffic incident on a left-side off-ramp along I-275 raised a great concern on the safety effects of off-ramps on this side of the freeway in Tampa, FL.

Although some studies evaluated the safety and operation effects of freeway off-ramps during the past several decades, none of them have focused on the safety performance of left-side off-ramps. To examine the impact of ramp locations on traffic safety, Cirillo et al. (1969) did a purely innovative investigation of the traffic study on the interstate system. The study found that a relationship between crash frequency and geometric elements could be established. About 30 years later, another research team (Garber and Fontaine, 1999) developed a guideline to search the operational and safety characteristics for the optimal ramp design. The newest guidelines for ramp design is the “Freeway and Interchange Geometric Design Handbook” (Leisch, 2006), published by the Institute of Transportation Engineers (ITE) in 2006. The handbook focuses on geometric and operational characteristics of freeways and interchanges, including on and off-ramps. It also recognizes that geometric design procedures for freeways and interchanges may vary. It is valued as a supplement of the AASHTO (Green book) (Policy on Geometric Design of Highways and Streets, 2004), the Highway Capacity Manual (HCM, 2000), and Traffic Engineering Handbook 5th Edition (Pline, 1999).

A few past studies were found to examine the factors that affect freeway off-ramp safety. Bared et al. (1999) found that the crash frequency on freeway ramps increased with freeway Annual Average Daily Traffic (AADT) volume. The results also indicated that off-ramps suffered from more crashes as compared to on-ramps. The statistical model, developed by Bauer and Harwood (1998), found that the ramp AADT explained most of the variability in the crash data report at selected sites. Other variables found to be significant were: contained freeway AADT, area types (rural, urban), ramp types (on, off), ramp configurations, ramp lengths, and speed-change lanes (deceleration lanes, acceleration lanes). However, no left-side off-ramps were included in these studies.

Maher and Summersgill (1996) established a mathematical method to compare the merging probability of the outside on-ramp with inside on-ramp on a Japanese urban expressway. Right-side merging lanes provided more comfortable merging traffic opera-
tions to drivers than the left-side ramp. It is suggested that the left-side ramp merging-lane length should be 50% longer than the right-side and additional attention should be given to operational countermeasures, such as speed regulation and ramp metering in order to maintain large gaps. Only on-ramps were examined in this study and no further conclusions for off-ramps were made. McCartt et al. (2004) examined 1150 crashes that occurred on heavily traveled urban interstate ramps in northern Virginia. About half of all these crashes occurred when at-fault drivers were in the process of exiting interstates, and the crash type most frequently associated with exiting ramp was run-off-the-road. It was also found that the run-off-the-road crashes frequently occurred when vehicles were exiting interstates at night, in bad weather, or on curved portions of ramps. No information about the location of the off-ramps, that is, left-side or right-side, was provided.

The latest study conducted by the research team in University of South Florida (Chen et al., 2009; Chen and Lu, 2009; Pan et al., 2010) is to explore the safety impacts of number and arrangement of lanes on freeways on the right-side off-ramps. The study evaluated different lane-design configurations and the results showed lane-balanced designs on the freeway diverge sections would improve safety performance by a 30% crash reduction. Another study (Wang et al., 2009) compared injury severity at freeway diverge areas by different design types. The results showed that the length of deceleration lanes, number of lanes on the freeways, freeway ADT, land type and light and weather conditions significantly influence severity crashes on the study area. However, they did not consider the left-side off-ramps in their studies.

After closely reviewing the literature, there are currently no conclusions on safety performance of left-side off-ramps. The left-side off-ramps are not the norm on most interstate highways, and their impacts on freeway safety are not clear. As a result, the project funded by FDOT evaluated the safety performances of the left-side off-ramps comparing to similar right-side off-ramps. This study aims to achieve the following objectives:

1. Examine the impacts of left-side off-ramps at the freeway diverge areas by the conflict study; and
2. Evaluate the safety performance of left-side off-ramps at freeway diverge areas with right-side off-ramps and identify the contributing factors to crashes at selected freeway segments.

2. Methodology

To evaluate the impact of left-side off-ramps on highway safety, a traffic conflict study was conducted at the three selected left-side off-ramps. A cross-sectional safety comparison was conducted at 11 left-side off-ramps and 63 right-side off-ramps. A crash prediction model was developed for the one-lane exit ramp at both the right-side and left-side freeway diverge areas.

2.1. Traffic conflict study

The deficiencies of motor vehicle accident records have long been recognized as an obstacle to a complete understanding of traffic safety problems at intersections. The Traffic Conflict Technique (TCT) was developed to provide additional information that could help make up for the deficiencies of accident records. A traffic conflict was defined as “an event involving two or more road users, in which the action of one user causes the other user to make an evasive maneuver to avoid a collision” (Upchurch et al., 2005). Evasive maneuvers, such as applying brakes, swerving, or noticeably decelerating in order to avoid a collision can be considered as conflicts. Since its introduction in the 1960s TCT has been widely used in the traffic safety studies. A study in west-central Florida area developed expected conflict value tables to estimate the expected number of crashes, relative safety effectiveness, and operational problems for unsignalized three-legged intersections (Weerasuriya and Pietrzyk, 1998). Sayed (1998) applied the traffic conflict technique to the estimation of safety at unsignalized intersections. Based on the method of additive conflict streams, a simplified theoretical approach was developed for the determination of capacities at unsignalized intersections (Brilon and Wu, 2007).

The purpose of the conflict study here is to determine if any safety problems exist at the three left-side off-ramps. The conflict rate, defined by the number of conflicts per 1000 total conflicting vehicles, was used to measure the safety performance of the research objects based on the assumption that the conflict numbers are correlated with the actual crash frequency.

Four basic types of conflicts are often used in traffic conflict studies, including diverging conflict, merging conflict, weaving conflict, and crossing conflict. For this study, a total of four types of traffic conflicts near the left-side off-ramps were defined. The first type of conflict is lane-change conflicts. These occur between the first vehicle changing from the exit lane to the through lane and the following vehicle on the through lane to where the first vehicle is changing. This type of conflict occurs when the through traffic stayed on the left-side exit lane erroneously. To keep moving on the highway, the vehicle needs to make a lane-change maneuver from the exit lane to the through lane. When the distance between the first vehicle and the following vehicle is too short for the lane-change maneuver, the following vehicle would have to slow down or swerve to avoid a crash. This lane-change conflict is defined as “Type 1” conflict in the study. The second type of conflict is also caused by a vehicle on the through lane weaving into the left-side exit lane. This type of conflict often happens when drivers assume that the off-ramps are located on the right side of the freeway. The Type 3 conflict is caused by an exit vehicle slowing down on an optional lane. This type of conflict occurs between two adjacent vehicles traveling on the same lane. When the first vehicle is diverging from the original direction, it might slow down to make the necessary maneuver. If the following distance was too close, a Type 3 traffic conflict would occur. The Type 4 conflict is the secondary conflict caused by the above three conflict situations. When the second vehicle makes an evasive maneuver, it may place another road user (a third vehicle) in danger of a collision. The secondary conflict will almost always look much like a slow-vehicle, same direction conflict or a lane-change conflict. The difference is that in a secondary conflict, the third vehicle responds to a second vehicle that is in a conflict situation itself.

For the selected left-side off-ramps, the above four types of traffic conflicts were counted from video recorded in the field and the traffic conflict rates were calculated correspondingly.

2.2. Cross-sectional comparison

One of the main objectives is to compare the safety of the left-side off-ramps at freeway diverge areas with the right-side off-ramps. In this case, the safety performance of the entities in the “before” period when the off-ramps are located on the right sides is not available. The cross-sectional study can be implemented by comparing the safety performance of some entities with certain special features that of other entities without these special features. In this study, the special feature refers to the off-ramp location. For the cross-sectional comparison, two sets of sites should be identified with similar control factors aside from the treatment.

For each left-side off-ramp, several right-side off-ramps were selected as pairings. These right-side off-ramps should have similar characteristics with the left-side off-ramps. In this study, the geometric design types and traffic volumes were considered as the
criteria to select the similar right-side off-ramps. For each left-side off-ramp, the detailed criteria to select the paired right-side off-ramps are listed as follows:

1. For each left-side freeway segment, the basic number of lanes should be same as those of the paired right-side freeway segment, which range from 2 to 4 in this study;
2. The maximal speed limits for the left-side freeway segments are equal to those for the right-side segment, which is 112 km/h (70 mph) or 88 km/h (55 mph);
3. The range of AADT on the left-side segments and the selected right-side segment should be close;
4. The deceleration lane for the one-lane left-side off-ramp are all taped designs so that the right-side off-ramps should have the same design;
5. The deceleration lane length of the left-side segments range from 0.03 km (100 ft) to 0.25 km (825 ft) so that the selected right-side segments need meet this criterion as well.

Crash frequency, crash rate, and crash severity between different exit types by one-lane or two-lane were compared in this study. Crash frequency is the actual number of crashes that have happened at a certain location or segment in a particular time or time interval. Crash rate is defined as crashes per million vehicles per km. The R, for a particular freeway segment, can be calculated by using the following formula:

\[ R = \frac{1,000,000 \times A}{365 \times T \times V \times L} \]  

(1)

where \( R \) is the crash rate at a freeway segment (crashes per million vehicles per km); \( A \) is the number of report crashes (total crashes for the time frame), \( T \) is the number of years; \( V \) is the average daily traffic volume (vehicles per day); and \( L \) is the length of the freeway segment (km).

The \( t \)-tests were conducted to examine whether the crash rate of the left-side off-ramps is significantly different with that of the right-side off-ramps. The \( t \)-test is applied because the sample sizes are so small that using an assumption of normality and the associated \( z \)-test would lead to incorrect inferences. The null hypothesis for the \( t \)-test is that the crash rates of the left-side and right-side off-ramps are equal.

Crash severity is defined as two categories, Property-Damage-Only (PDO) and Injury/Fatal Crashes. A proportionality test is often used to test the significance of the difference between two proportions from two independent samples. Let \( p_1 \) and \( p_2 \) be the proportions of a particular type of crashes or a crash severity level associated with the left-side off-ramp and the right-side off-ramp. Assuming that the total number of crashes at selected sites for these two different types of exit ramps is \( m \) and \( n \), respectively, for testing the null hypothesis:

\[ H_0 : p_1 = p_2 \]  

versus

\[ H_1 : p_1 \neq p_2 \]  

(2)

\( H_0 \) can be rejected if:

\[ Z = \frac{p_2 - p_1}{\sqrt{((p_2(1 - p_2))/m)+(p_1(1 - p_1))/n}} \geq Z_{\alpha/2} \]  

(3)

2.3. Generalized linear models

Generalized linear models have been widely used for modeling crashes at a street segment. Generalized linear models are extensions of the classical linear regression models. Crashes are non-negative, random and discrete events in nature. Numerous previous studies have suggested the use of Poisson models and the negative binomial (NB) models for modeling crash data. Using a Poisson model, the probability that a particular freeway segment \( i \) experiences \( y_i \) crashes during a fixed time period is given by:

\[ p(Y_i = y_i) = p(y_i) = \frac{\mu_i^{y_i} e^{-\mu_i}}{y_i!}, \quad i = 1, 2, 3, \ldots, n \]  

(5)

where \( \mu_i \) is the expected number of crashes for freeway segment \( i \). A logarithm link function connects \( \mu \) to a linear predictor \( \eta \). The negative binomial model assumes that crash counts are Poisson-gamma distributed. The probability density function of a Poisson-gamma structure is given by:

\[ p(Y_i = y_i) = \frac{\Gamma(y_i + \alpha^{-1})}{\Gamma(\alpha^{-1})} \left( \frac{\alpha \mu_i}{1 + \alpha \mu_i} \right)^{y_i} \left( \frac{1}{1 + \alpha \mu_i} \right)^{\alpha^{-1}} \]  

(6)

where \( \alpha \) is the dispersion parameter which determines the variance of the Poisson-gamma distribution. However, using the Poisson-gamma models can significantly misestimate the crash characteristics if the sample size is limited and the mean value is low. In order to reduce the bias, the Poisson regression must be used under this situation (Lord, 2006; Park and Lord, 2008). The link function and the linear predictor determine the functional forms of the crash prediction model. If the linear predictor is a linear function of the explanatory variables, the fitted crash prediction model takes the functional form of \( \mu_i = \exp(\beta_0 + \beta_1 x_{i1} + \cdots + \beta_k x_{ik}) \), where \( \beta_0, \beta_1, \ldots, \beta_k \) are coefficients and \( x_{1}, x_{2}, \ldots, x_{k} \) are explanatory variables.

If the linear predictor is a linear function of the logarithm of the explanatory variables, the functional form is \( \mu_i = \beta_0 x_{1i}^1 x_{2i}^2 \cdots x_{ki}^k \).

Two parameters are often used for evaluating the goodness-of-fit of a generalized linear model. These two parameters are the scaled deviance (SD) and the Pearson’s \( \chi^2 \) statistic. The scaled deviance equals twice the difference between the log-likelihood under the maximum model and the log-likelihood under the reduced model. The scaled deviance can be calculated as:

\[ SD = -2(\log(L_p) - \log(L_r)) \]  

(7)

where \( L_r \) is the likelihood under the maximum model and \( L_p \) is the likelihood under the reduced model. The Pearson’s \( \chi^2 \) statistic can be calculated as:

\[ Pearson’s \chi^2 = \sum_{i=1}^{n} \left( \frac{y_i - \mu_i}{\sigma_i} \right)^2 \]  

(8)

where \( y_i \) is the crash count at segment \( i \), \( \mu_i \) is the expected number of crashes for segment \( i \), and \( \sigma_i \) is the estimation error for segment \( i \). The scaled deviance SD and Pearson’s \( \chi^2 \) statistic for an adequate model should be approximately chi-square distributed with \( (N-p) \) degrees of freedom, where \( N \) is the number of observations and \( p \) is the number of parameters in the model (Dobson, 1990). If the values of both SD and Pearson’s \( \chi^2 \) statistic are close to \( (N-p) \), it can be taken as an indication that the model is adequately fitted (Maher and Summersgill, 1996). However, due to the limited sample size, the additional Akaike Information Criteria (AIC) was also used to measure the goodness of model. In a general sense, the model for which AIC is smallest represents the best approximation to the true model.

3. Data collection

3.1. Traffic conflict data

In order to collect the conflict data, three sites around Tampa Bay area were selected by the research team. There are two types of geometric designs for conflict study: two exit lanes with an inside
optional lane and two exclusive exit lanes. The two left-side exit lanes with an optional lane have two exit lanes with the one outside lane becoming exclusively off-ramp and the inside lane being an optional lane. On the inside lane, vehicles can make a left exit or continue on the freeway. The off-ramps of I-275/I-375 and I-4/50th Street belong to this type of geometric design. Another type of left-side exit lane configurations has two exclusive exit lanes. The off-ramp of I-275/31st Street is this type of design.

1. I-275/I-375: The first left-side off-ramp is located at the interchange from I-275 to I-375 in Pinellas County, near the intersection of North 5th Street and North 20th Street. There are three through lanes on I-275 and two left-side exit lanes with an optional lane.

2. I-4/50th Street: The left-side off-ramp of I-4/50th Street is located near the intersection of East Columbus Driveway and North 50th Street in Hillsborough County. There are two left-side exit lanes with an optional lane and three through lanes at this location.

3. I-275/31st Street: The northbound left-side off-ramp of I-275/31st Street is located near the intersection of South 15th Street and 31st Street in Pinellas County. The difference between the site and the above two sites is that there are two exclusive left-side exit lanes with no optional lane.

To obtain the traffic conflict for each freeway segment, 2 h of traffic flow just before the off-ramps was recorded on video during peak hours in the morning (7–9 A.M.) or in the afternoon (4–6 P.M.) on weekdays. Traffic conflicts were identified and manually counted afterward in the lab. Since a safe place from which to observe and record the traffic could be found at the site southbound I-275@I-175, conflict data on the following three left-side off-ramps were collected: southbound I-275@I-375, northbound I-275@31st Street, and eastbound I-4@50th Street. For all of the three off-ramps, cameras were set up approximately 305 m (1000 ft) away from the beginning of the gore area. Fig. 1 exhibits the camera location used in this study. The speeds of different traffic movements were recorded and the exit and through traffic volumes were counted with electronic traffic counters as well.

3.2. Traffic crash data

Crash data were collected at 74 freeway segments in Florida, with 11 sites for left-side off-ramps and 63 sites for the right-side off-ramps. The sites were defined as Type 1, Type 2, Type 3 and Type 4, respectively, based on the number of exit lanes and exit directions. Type 1 is a one-lane right-side off-ramp while Type 2 represents a one-lane left-side off-ramp. Similarly, Type 3 is a two-lane right-side off-ramp with an optional lane while Type 4 is a two-lane left-side off-ramps. Fig. 2 presents the configurations and number of sites by each exit type. The study area contains three subsections, the diverging area and two influence segments, upstream 457 m (1500 ft) of the diverge area and 305 m (1000 ft) downstream the diverge area. The selection of influential areas mainly based on current design guidelines (HCM, 2000; MUTCD, 2010) past research experiences (Bared et al., 1999; Bauer and Harwood, 1998), and field observations from the research team. Highway Capacity Manual (HCM, 2000) presents that the influential area is within 457 m (1500 ft) of the diverge sections. Current Manual on Uniform Traffic Control Devices (MUTCD, 2010) suggests the guide sign for an interchange should be put 402 m (1320 ft) upstream of the exit to assist drivers leaving or continuing on the freeway mainlines. Previous studies selected 305 m (1000 ft) to 457 m (1500 ft) as the influential areas from the diverge areas.
Table 1
Number of conflicts at different off-ramps.

<table>
<thead>
<tr>
<th>Off-ramp</th>
<th>Conflict type</th>
<th>Total conflicts</th>
<th>Traffic volume</th>
<th>Conflict rate a</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type 1</td>
<td>Type 2</td>
<td>Type 3</td>
<td>Type 4</td>
</tr>
<tr>
<td>1-275@31st Street</td>
<td>16</td>
<td>23</td>
<td>3</td>
<td>43</td>
</tr>
<tr>
<td>1-275@31st Street</td>
<td>40</td>
<td>10</td>
<td>5</td>
<td>59</td>
</tr>
<tr>
<td>1-275@31st Street</td>
<td>61</td>
<td>27</td>
<td>4</td>
<td>3,494</td>
</tr>
<tr>
<td>1-275@31st Street</td>
<td>4,545</td>
<td>12.3</td>
<td>10.5</td>
<td>11.9</td>
</tr>
</tbody>
</table>

a Conflict rate refers to total conflicts per 1000 vehicles.

(Bared et al., 1999; Bauer and Harwood, 1998). Also the field observation showed that there is no significant influence 457 m (1500 ft) upstream the diverge section and 305 m (1000 ft) downstream the diverge section. So crashes were collected for each site based on the selected segment mentioned above. Crash data were obtained from the Florida Crash Analysis Reporting (CAR) System which is maintained by the FDOT. In 2003, the FDOT renamed all the freeways' exit ramps for the whole state. Accordingly, the crash database updated the exit ramp numbers for the entire database. Due to this reason, crash data for freeway exit ramps before 2004 include a lot of missing information and, as a result, cannot be used in this study.

A three-year time frame, from 2004 through 2006, was selected to obtain crash data. Eighty-six variables are enclosed in the FDOT crash database including: site identification, time of crashes, traffic conditions, geometric conditions, crash detailed information as location, direction, severity and related information. The selection of each crash record is determined by the milepost, which ranged from 455 m (1500 ft) upstream and 305 m (1000 ft) downstream of the painted nose. A total of 352 crashes were observed within the study area at the left-side freeway diverge areas.

4. Data analysis result

4.1. Conflict study

Based on the definition of the four conflict types, the numbers of conflicts at the three left-side off-ramps recorded in the videotape were counted, as listed in Table 1. The results indicated that Type 1 and Type 3 conflicts were the main conflict types on the off-ramp area, while there were relatively small occurrences of Type 2 and Type 4 conflicts between vehicles.

The conflict rate here is defined as the number of conflicts per 1000 vehicles. As previously mentioned, the left-side off-ramps 1-275@31st Street was a two-lane off-ramp without an optional lane, while the other two were two-lane off-ramps with an optional lane. A previous cross-sectional safety study (Chen et al., 2009) showed that replacing two-lane exit ramps that have an optional lane with two-lane exit ramps without an optional lane may increase crash counts at areas freeways diverge by 11.7%. The conflict study here indicated that the conflict rates at the location with the two exclusive off-ramps are slightly higher than the location with an optional lane.

4.2. Crash data analysis

4.2.1. Crash frequency and crash rate

Cross-sectional comparisons were conducted in the study to compare the average crash frequency and crash rate by the four exit types defined above. Crash frequency at selected sites varies from 0 to 20 crashes per year for all the sites. The collected crash data were divided into four different groups based on the types of exit ramps. Summary statistics of crash counts for different types of freeway exit ramps were given in Table 2. On average, Type 1, Type 2, Type 3 and Type 4 exit ramps reported 5.14, 8.29, 5.93, 6.00 crashes per year at selected freeway segments, respectively. The Type 2 ramp (left-side off-ramps with one-lane exit) has 60% more crashes than the Type 1 (right-side off-ramp with one-lane exit). Also Type 2 (one-lane exit on the left-side off-ramp) has the highest average crash frequency (8.29 crashes per year per site), followed by the Type 4 (two-lane exit on the left-side off-ramps). Type 1 exit ramps have the best safety performance in terms of the lowest average crash frequency reported at freeway diverge areas. In general, the right-side off-ramps were found to be safer as compared to those on the left-side off-ramps, especially for one-lane exit. For two-lane exit ramps, the average crash frequency on the left-side (Type 4) is 1.2% more than Type 3 (right-side off-ramps). Descriptive statistics for crash rates were given in Table 2 as well. The comparison of two different crash rates yields similar results. Again, Type 1 exit ramps have the best safety performance in terms of the lowest crash rates at freeway diverge areas. And Type 2 ramp has the highest crash rates. The crash rates for Type 3 and Type 4 ramps are similar.

4.2.2. Crash severity

Crash severity was compared for different types of exit ramps by comparing the percentages of PDO crashes and injury plus fatal crashes. The exit ramps with lower percentages of injury plus fatal crashes were considered to be safer. Fig. 3 compares the percentage of PDO and injury plus fatal crashes by each type. On average, the percentage of fatal plus injury crashes was found to be 36.18%, 67.62%, 37.98%, and 68.13% for Type 1, Type 2, Type 3, and Type 4 exit ramps, respectively. It is obvious that both Type 2 and Type 4 exit ramps have relatively high percentage of severe crashes as compared to Type 1 and Type 3. Proportionality tests were...
conducted to evaluate if the difference in crash severity between different types of exit ramps was statistically significant. The null hypothesis of the proportionality test is that the percentages of fatal plus injury crashes for left-side and right-side exit ramps are equal. The test results are given in Table 3. It is noticed that the left-side off-ramps have a relative higher percentage of fatal plus injury crashes than the right-side off-ramps so that the signs are positive for the comparison; however it is contrary for the PDO crashes. With a 10% level, Type 2 (one-lane exit on the left-side) was found to have statistically significantly higher severe crashes than Type 1 (one-lane exit on the right-side). But for two-lane exits, the difference is not significant. This might be because of the limited number of available sites for the study. Also it is noticed that two-lane exits have higher percentage of injury plus fatal crashes comparing to one-lane exit, it could be one of the reason that increasing the number of exit lanes would cause an increasing in severe crashes for both right-side and left-side exits.

The results suggest that even though the average crash frequency and crash rate did not appear significantly different for left-side and right-side off-ramps, the one-lane left-side off-ramps did affect crash severity in a significant way than one-lane right-side off-ramps at freeway diverging areas. One possible reason might be the high approaching speed which relates to severe crashes. When vehicle approach the diverge area, drivers used to maintain a high speed on the left lane as compared to those traveling on the right lane. The probability of fatal injury crashes increases rapidly by the increment of speeds (Elvik et al., 2004). Another possible reason could be the speed differential for these two exit types. From field observation, exiting vehicle speeds decrease gradually for the right-side off-ramp. However, when traffic approaches left-side off-ramp, the exiting vehicles are traveling at a lower speed since drivers might have the confusion of the exit location. So the speed difference between the exiting traffic and traffic on the left-side freeway segments is larger than those at the left-side freeway diverge area. The higher percentage of severe crashes is the main reason that left-side off-ramps can only be allowed under new constructions and should be evaluated carefully.

4.2.3. Crash predictive regression models

A crash prediction model was developed to identify factors that contribute to the crashes reported at selected freeway segments and to quantify the safety impacts of left-side off-ramps and right-side off-ramps at the freeway diverge areas. In this study, only one-lane exits would be considered since the site number for two-lane exits is not adequate enough to develop a generalized linear regression. A total of 60 sites are included in the final model. The dependent variable of the model is the average number of crashes per year reported at selected freeway segments. Seven variables were initially considered in the model as listed in Table 4, including number of lanes on freeway mainlines, speed limit, length of deceleration lanes, ramp length, freewayAADT, ramp AADT and one dummy variable. The dummy variable has two values, 0 represents the one-lane right-side off-ramps while 1 represents the one-lane left-side off-ramps. Poisson models were applied. For an adequate model, the scaled deviance divided by the degrees of freedom shall be close to one. These statistics are used to detect overdispersion or underdispersion in the Poisson regression model. Values greater than 1 indicate overdispersion, while values smaller than 1 indicate underdispersion. Step-wise regression was used to select the independent variables at a 5% level.

Two variables, number of lanes and speed limit, were not found to be statistically significant. The final model contains five variables which are given in Table 5. The scaled deviance divided by the degrees of freedom is found to be 0.99. The statistics are reasonably close to one, indicating the fact that the model is adequately fitted. The final equations of the crash models are given as follows:

$$Y_1 = (X_1)^{0.5060}(X_2)^{0.7412} \exp(-1.7518 + 0.1817X_3 + 0.8401X_4 - 0.7575X_5)$$

where $Y_1$ is the expected average crash frequency in a freeway segment with one-lane exit ramp (crashes/year); $X_1$ is the logarithm of mainline freeway AADT for the direction of travel in which the ramp is located (vehicles in thousands per day); $X_2$ is the logarithm of ramp AADT (vehicles in thousands per day); $X_3$ is the 1 if the exit ramp is left-side off-ramp, 0 if the exit ramp is right-side off-ramp; $X_4$ is the length of the deceleration lane (km); and $X_5$ is the ramp length (km).

The coefficients for both freeway AADT and ramp AADT are positive, indicating the fact that the number of crashes increases with the increase of freeway and ramp AADT. The impact of deceleration lane length is contradictory to the results of Bared et al.’s study. They found that increasing deceleration lane length will reduce crash frequency. In fact, the results of past studies regarding the

**Table 3** Proportionality test of crash severity.

<table>
<thead>
<tr>
<th>Crash severity</th>
<th>Type 1 versus Type 2</th>
<th>Type 3 versus Type 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDO</td>
<td>−1.70</td>
<td>−1.10</td>
</tr>
<tr>
<td>Injury/fatal</td>
<td>1.70</td>
<td>1.10</td>
</tr>
</tbody>
</table>

The bold values indicate there is significant differences in crash severity between one-lane left-side off-ramps and one-lane right-side off-ramps.

**Table 4** Descriptive statistics of variables.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean</th>
<th>Max.</th>
<th>Min.</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total crash counts per year for one-lane exit ramp</td>
<td>5.5</td>
<td>19.67</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>Basic number of lanes on freeway</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>60</td>
</tr>
<tr>
<td>Deceleration lane length (km)</td>
<td>0.07</td>
<td>0.25</td>
<td>0.03</td>
<td>60</td>
</tr>
<tr>
<td>Logarithm of AADT in thousands on freeway sections</td>
<td>4.58</td>
<td>5.28</td>
<td>4.01</td>
<td>60</td>
</tr>
<tr>
<td>Logarithm of AADT in thousands on exit ramp sections</td>
<td>2.10</td>
<td>3.23</td>
<td>0.44</td>
<td>60</td>
</tr>
<tr>
<td>Posted speed limit on freeway sections (km/h)</td>
<td>108.61</td>
<td>112.61</td>
<td>88.03</td>
<td>60</td>
</tr>
<tr>
<td>Ramp length (km)</td>
<td>0.61</td>
<td>1.69</td>
<td>0.30</td>
<td>60</td>
</tr>
<tr>
<td>Exit ramp location</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 (Type 1-right-side off-ramp)</td>
<td></td>
<td></td>
<td></td>
<td>53(88.33%)</td>
</tr>
<tr>
<td>1 (Type 2-left-side off-ramp)</td>
<td></td>
<td></td>
<td></td>
<td>7(11.67%)</td>
</tr>
</tbody>
</table>
safety impacts of the deceleration lane length are not quite consistent. For example, some recent studies (Chen et al., 2009; Garcia and Romero, 2006; Wang et al., 2009) found that using long deceleration lane creates more weaving maneuvers at freeway diverge areas. Another possible explanation is that drivers might accelerate speeds before they exit the main roads if the distance is too long. Thus, it has the potential to increase crash risks at freeway diverge areas. However, further studies are needed to investigate the impact of various deceleration lane lengths on safety. The only negative sign is the ramp length. It indicates fewer crashes would occur at longer ramp length while all other situations remain same. The conclusion is consistent with previous study findings (Bauer and Harwood, 1998; Bared et al., 1999; Chen et al., 2009; Garcia and Romero, 2006; Wang et al., 2009). The possible reason is might be longer of the length, the less of the distributions from off-ramp traffics.

The coefficient for the indicator variables for left-side off-ramp is positive. It indicates the fact that left-side off-ramps have a higher crash frequency as compared to right-side off-ramps. This conclusion is consistent with the results of our cross-sectional comparisons.

5. Conclusions and recommendations

To evaluate the safety effects of left-side off-ramp, a traffic conflict study was conducted based on the field data collected at the three sites. Four types of traffic conflicts were observed. The average conflict rate near the ramp area is about 10 per 1000 vehicles. Conflict study results showed that conflict rates at the location with the two exclusive off-ramps are slightly higher than the location with an optional lane. Crash records were analyzed at 74 sites on freeways, including 7 sites for one-lane left-side off-ramp, 53 sites for one-lane right-side off-ramp, 4 sites for two-lane left-side off-ramp, and 10 sites for two-lane right-side off-ramp. Cross-sectional comparisons were conducted to evaluate the safety performance of left-side off-ramps at freeway diverge areas. The results show that the left-side off-ramps have higher average crash counts, crash rate and percentage of severe crashes. A further t-test indicates that only crash severity for left-side exit ramps is significantly different with the right-side diverge areas at selected freeway segments.

A crash prediction model for one-lane exit was developed to identify the factors that contribute to the crashes that have been reported for selected freeway segments. It was found that increasing the freeway AADT, ramp AADT or length of deceleration lane, would increase the overall crash counts while increasing the ramp length would reduce the potential crash counts for both left-side and right-side diverge areas. The study result also explained why the left-side off-ramps are always critical issues on the highway geometric design and only can be allowed under new construction. One of main reasons is the potential higher percentage of severe injury and fatal crashes. It is expected that this study could help engineers design practical left-side off-ramps and select the appropriate countermeasures include but are not limited to the following three aspects:

- Advanced sign implementation and improvements: improvement of advanced warning sign by location and design could be the possible countermeasure when traffic approaches the freeway diverge areas.
- The results of this study indicate that geometric improvements, and optimal design guidelines have the potential to improve the safety performance at the freeway diverge area.
- Highway safety workshops: enhancement of drivers’ knowledge of the left-side off-ramp is an effective way to improve safety by raising the drivers’ awareness.

Acknowledgment

This research was sponsored by the Florida Department of Transportation.

References


Table 5

<table>
<thead>
<tr>
<th>Variables</th>
<th>Coefficient</th>
<th>Std. error</th>
<th>Pr &gt;</th>
<th>x²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>−1.7518</td>
<td>0.7456</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>Left-side off-ramp</td>
<td>0.5060</td>
<td>0.1677</td>
<td>0.0026</td>
<td></td>
</tr>
<tr>
<td>Logarithm of AADT in thousands on freeways in thousands</td>
<td>0.7412</td>
<td>0.1723</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>Logarithm of AADT in thousands on ramp</td>
<td>0.1817</td>
<td>0.1222</td>
<td>0.0017</td>
<td></td>
</tr>
<tr>
<td>Ramp length (km)</td>
<td>0.8401</td>
<td>0.2676</td>
<td>0.0137</td>
<td></td>
</tr>
<tr>
<td>AIC</td>
<td>−0.7575</td>
<td>0.2320</td>
<td>0.0011</td>
<td></td>
</tr>
<tr>
<td>Pearson-χ²</td>
<td>2.77</td>
<td>52.327</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SD</td>
<td>53.449</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pearson-χ²/DF</td>
<td>0.97</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SD/DF</td>
<td>0.99</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

