Exploring contributing factors to crash injury severity at freeway diverge areas using ordered probit model

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Abstract

Freeway diverge areas have long been considered crash prone locations. Research is needed to better understand the relationship between the severity consequences of crashes reported at freeway diverge areas and various contributing factors such as geometric layouts and traffic characteristics. The primary objective of this paper is to explore the impacts of contributing factors related to crash injury severity at freeway diverge areas. An ordered probit (OP) model was developed to relate the severity of crash to various explanatory variables using data collected at 326 freeway exit segments in Florida, United States. It is found that the factors significantly influencing crash severity at freeway diverge areas included the mainline lane number, length of ramp, difference of speed limits between mainline and ramp, light condition, weather condition, surrounding land type, alcohol/drug involvement, road surface condition, shoulder width, and crash types of rear-end and sideswipe. The two-lane exit ramps without optional lane were found to have minor crash injury as compared with single-lane exit ramps. The injury severity of crashes do not show significant difference between single-lane exit ramps and single-lane exit ramps with a taper and two-lane exit ramps with an optional lane. Marginal analysis was conducted to quantitatively interpret the marginal effects of contributing factors on each crash severity.

Keywords: crash severity; freeway diverge; OP models; SVM models

1. Introduction

The freeway diverge areas produce traffic conflicts between mainline traffic and exiting traffic due to the intensive lane changing maneuvers. As a consequence, crashes are likely to occur at freeway diverge...
areas. Previously, most of studies related to safety issues at freeway diverge areas focused on estimating the relationships between crash frequency reported at exit ramp areas and explanatory variables (Bauer and Harwood, 1998; Bared et al., 1999; McCartt et al., 2004; Bared et al., 2005; Lord and Bonneson, 2005; Golob et al., 2004; Garcia and Romero, 2006; Moon and Hummer, 2009; Chen et al., 2009; Liu et al., 2010; Chen et al., 2011a; Chen et al., 2011b; Wang et al. 2011). These studies aimed at exploring the factors that are likely to increase the crash counts at freeway diverge areas. Countermeasures were made based on these findings to reduce the number of crashes occurred at freeway off-ramp areas. However, individual information of crashes, such as weather condition, collision type and alcohol involvement, were lost due to aggregating individual crashes into crash frequencies.

In recent years, modeling the crash injury severity at freeway exit ramps has received the interests of transportation researchers (Wang et al., 2009; Wang et al., 2011; Chen et al., 2011a). The injury severity of crash is classified into several categories which have an inherent ordinal structure. Then statistical models such as ordered probit (OP) model were widely used to fit the ordinal structure of crash severity data (ODonnell and Connor, 1996; Kockelman and Kweon, 2002; Abdel-Aty, 2003; Zajac and Ivan, 2003; Abdel-Aty and Abdelwahab 2004; Lee and Abdel-Aty, 2005; Siddiqui et al., 2006). Exploring the relationships between crash injury severity and explanatory variables can help identifying the factors that will increase the severity level given a crash occur at freeway exit ramps. Countermeasures can be made to reduce the injury severity of crashes. As a consequence, the number of fatalities and severe injured ones at freeway exit ramps can be reduced and the property damage can also be reduced. The safety performance of freeway diverge areas can be improved.

Previously, Wang et al. (2009) first analyzed the crash injury severity issue at freeway diverge areas using a partial proportional odds model. The contributing factors to crash injury severity were identified in the model. An OP model were also developed for comparison purpose. It was found that the length of deceleration/ramp lanes, curve and grade, light and weather conditions, alcohol/drug and heavy vehicle involvement, lane number on mainline, mainline ADT, surface condition, land type, and crash types were related to crash injury severity at freeway diverge areas. Wang et al (2011) further developed an OP model to evaluate the impacts of factors on injury severity of truck related crashes at freeway diverge areas. The significant factors include deceleration lane length, number of through lanes, median/shoulder width, curvature and grade design, speed limit, AADT on mainline and ramp, and truck percentage. Moreover, proportionality tests were also used to test if the proportion of a particular severity between different freeway off-ramp types was statistically different (Chen et al., 2009; Chen et al., 2011a; Chen et al., 2011b).

Though some previous studies have focused on analyzing the crash injury severity at freeway diverge areas, the research on this issue was relatively few. More studies should be conducted to identify the factors that would produce more severe crashes at freeway diverge areas. And previous findings also need to be broadly validated or compared. The primary objective of this study is to explore the contributing factors that would influence the crash injury severity at freeway diverge areas and quantitatively evaluate their impacts. Based on the crash data collected at selected freeway exit segments in Florida, An OP model was proposed to explore the factors significantly influencing the crash injury severity at free diverge areas. Marginal effects of influencing factors were also computed in the OP model. This study also looked extensively at the safety performance of different lane arrangement types of exit ramps. Results of this study will be beneficial to transportation engineers to address safety problems and improve safety performances at freeway exit ramps.

2. DATA RESOURCES

The crash data used for injury severity analysis were collected at 326 freeway diverge areas in Florida,
United States. The freeway segment in this study contains a deceleration lane and a freeway exit. The influence areas in vicinity of the exit gore include a 457m (1500ft) upstream section and a 305m (1000ft) downstream section. A 3-year crash data, from 2004 to 2006 were collected at selected sites. A total of 5538 crashes were reported at selected freeway diverge areas. Roadway geometric designs as well as traffic data were also obtained to conduct the crash severity analysis. For more details regarding the data sources, please refer to Chen et al. (2009). Table 1 lists the description of dependent variables and explanatory variables for the data analysis. The crash injury severity was defined as five ordered levels ranked from one to five. Level 1 represents the no injury crashes which account for more than half of all crashes, while level 2 represents the possible/invisible injury with the proportion of 26.4%. Level 3 and level 4 denote no-capacitating injury and incapacitating injury, which account for 15.1% and 5.1% of all crashes, respectively. Level 5 is the fatal injury with the smallest proportion of 0.9%.

Four types of exit ramp widely used in Florida were identified in this study. Type 1 is the exit ramp parallel from a tangent single-lane, type 2 is the single-lane exit ramp without a taper, type 3 is the two-lane exit ramp with an optional lane, and type 4 the two-lane exit ramp without an optional lane. The final database includes 180 type 1 exit ramps, 68 type 2 exit ramps, 60 type 3 exit ramps, and 18 type 4 exit ramps. Exit ramp type 1 and type 3 were considered as lane-balanced designs and ramp type 2 and type 4 were considered as lane-unbalanced ones. The definition of each type of exit ramp is illustrated in Fig. 1.

![Illustrations of four types of exit ramps on freeways](image)

3. METHODOLOGY

The OP model has been widely used for fitting the data structure of an ordinal response. Based on the crash injury severity data that were defined as ordinal variables, an OP model was established to relate crash injury severity to various explanatory variables. The fundamental characteristic of OP model is briefly described in this section. Assuming that $Y$ represents the injury severity level, then a latent variable $Y^*$ is introduced as:

$$Y^* = X\beta + \epsilon$$

where $X$ is the vector containing the full set values of explanatory variables, $\beta$ is the vector of coefficients associated with the explanatory variables, and $\epsilon$ is a random error term following standard
Table 1. Description of Crash Characteristics and Variables for Analysis

| Variable                | Description                                                                 | Type       | Mean      | Std. | Frequency | Percent |
|-------------------------|-----------------------------------------------------------------------------|------------|-----------|------|-----------|---------|
| **Dependent Variable**  |                                                                             |            |           |      |           |         |
| Injury                  | 1 (No Injury)                                                               | Ordinal    | 2902      | 52.4 |           |         |
| Severity                | 2 (Possible/Invisible Injury)                                               |            | 1463      | 26.4 |           |         |
|                         | 3 (No-Capacitating Injury)                                                  |            | 837       | 15.1 |           |         |
|                         | 4 (Incapacitating Injury)                                                   |            | 285       | 5.1  |           |         |
|                         | 5 (Fatal Injury)                                                            |            | 51        | 0.9  |           |         |
| **Independent Variable**|                                                                             |            |           |      |           |         |
| Type 1                  | 1 (Type 1 Exit Ramp)                                                        | Dummy      | 948       | 17.1 |           |         |
| Type 2                  | 1 (Type 2 Exit Ramp)                                                        |            | 1848      | 33.4 |           |         |
| Type 3                  | 1 (Type 3 Exit Ramp)                                                        |            | 355       | 6.4  |           |         |
| MainLanes               | Number of lanes on freeway mainline                                         | Counts     | 4.11      | 1.21 | 5539      | -       |
| DeLength                | Length of deceleration lanes (mile)                                        | Continuous | 0.05      | 0.03 | 5539      | -       |
| RaLength                | Length of entire exit ramps (mile)                                          | Continuous | 0.31      | 0.17 | 5539      | -       |
| SurfacType              | 1 (Blacktop)                                                                | Binary     | 4390      | 79.3 |           |         |
|                         | 0 (Others)                                                                  |            |           |      |           |         |
| ShoulderType            | 1 (Paved)                                                                   | Binary     | 3840      | 69.3 |           |         |
|                         | 0 (Others)                                                                  |            |           |      |           |         |
| ShoulderWidth           | Right shoulder width (ft)                                                   | Continuous | 9.95      | 1.11 | 5539      | -       |
| MainSpeed               | Post speed limit on mainline (mi/h)                                         | Continuous | 61.25     | 6.37 | 5539      | -       |
| SpeedDiff               | Difference of speed limit between mainline and exit ramps (mi/h)           | Continuous | 25.41     | 8.32 | 5539      | -       |
| Light                   | 1 (Daylight)                                                                | Binary     | 3785      | 68.3 |           |         |
|                         | 0 (Others)                                                                  |            |           |      |           |         |
| Weather                 | 1 (Clear)                                                                   | Binary     | 3647      | 65.8 |           |         |
|                         | 0 (Others)                                                                  |            |           |      |           |         |
| Surface                 | 1 (Dry)                                                                     | Binary     | 4390      | 79.3 |           |         |
|                         | 0 (Wet)                                                                     |            |           |      |           |         |
| LandType                | 1 (Business)                                                                | Binary     | 3185      | 57.5 |           |         |
|                         | 0 (Residential)                                                             |            |           |      |           |         |
| MainADT                 | Mainline ADT per year in thousand                                          | Continuous | 15.77     | 7.38 | 5539      | -       |
| RampADT                 | Exit ramp ADT per year in thousand                                         | Continuous | 1.20      | 0.84 | 5539      | -       |
| AlcDrug                 | 1 (Alcohol/Drug involved)                                                   | Binary     | 223       | 0.4  |           |         |
|                         | 0 (No)                                                                      |            |           |      |           |         |
| RearEnd                 | 1 (Rear-end Crash)                                                          | Dummy      | 2347      | 42.4 |           |         |
| Sideswipe               | 1 (Sideswipe Crash)                                                         | Dummy      | 760       | 13.7 |           |         |
| Angle                   | 1 (Angle Crash)                                                             | Dummy      | 450       | 8.1  |           |         |

*Type 4 exit ramp is the reference category

Other collision type is the reference category

normal distribution. The value of the dependent variable is then determined as:

\[
Y = \begin{cases} 
1 & \text{if } Y < \tau_1 \\
 j & \text{if } \tau_{j-1} < Y < \tau_j \\
 J & \text{if } \tau_{J-1} < Y \end{cases}
\]

(2)

where \( J \) is the number of injury severity levels (in this case, \( J=5 \)), and \( \tau_j \) is the threshold parameter (cut-off points) to be estimated for each level. From the above, it can be determined that the probabilities of \( Y \) taking on each of the values \( j=1, \ldots, J \) are equal to:
\[ P(Y = 1) = \Phi(\tau_1 - \mathbf{X}\beta) \]
\[ P(Y = j) = \Phi(\tau_j - \mathbf{X}\beta) - \Phi(\tau_{j-1} - \mathbf{X}\beta) \]
\[ P(Y = J) = 1 - \Phi(\tau_{J-1} - \mathbf{X}\beta) \]

where \( P(Y=j) \) is the probability of response variable taking a specific severity level \( j \), and the threshold parameter satisfies the restriction \( \tau_1 < \tau_2 < \ldots < \tau_{J-1} \). For the classical OP model, the values of \( \mu \) and \( \beta \) can be determined by the Maximum Likelihood Estimate method.

Marginal effects were calculated in OP model to directly get the impacts of variables on probability of each injury severity. For continuous variables, the marginal effect of a variable for injury severity \( i \) is calculated as:

\[ \frac{\partial P(y = i)}{\partial \mathbf{X}} = \left[ \phi(\mu_{i-1} - \mathbf{X}\beta) - \phi(\mu_i - \mathbf{X}\beta) \right] \beta \]

where \( \phi(\cdot) \) is the standard normal density.

For binary (dummy) variables, the marginal effect of a variable for injury severity \( i \) is analyzed by comparing the outcome when the variable takes one value with that when the variable takes zero value, while all other variables remain constant, which is:

\[ \Delta(Y = j \mid x_n) = \Pr(Y = j \mid x_n = 1) - \Pr(Y = j \mid x_n = 0) \]

3. DATA ANALYSIS RESULTS

3.1 Estimations of the OP Model

The ordered probit model was specified using the STATA software package. Factors significantly influence crash injury severity were carefully identified from initially considered variables in Table 1. Twelve variables were identified as contributing factors which significantly impact the injury severity of crashes at freeway diverge areas. The fitted ordered probit model is given in Table 2. A positive coefficient of a variable implies that the increase of the variable would increase the severity of crashes. On the contrary, a negative coefficient of a variable means that the crash injury severity would be reduced by the increase of the variable.

| Variables    | Coef.   | Std.Err. | z     | P>|z| | 95%Conf.Interval |
|--------------|---------|----------|-------|------|-----------------|
| Type4        | -0.121622 | 0.06697  | -1.82   | 0.069 | -0.25289, 0.00964 |
| SpeedDiff'   | 0.003008  | 0.00199  | 1.51   | 0.132 | -0.00091, 0.00692 |
| Mainlanes    | 0.053603  | 0.01321  | 4.06   | 0.000 | 0.02769, 0.07950 |
| RaLength     | 0.178303  | 0.09594  | 1.86   | 0.063 | -0.00974, 0.36634 |
| LandType     | 0.119946  | 0.03262  | 3.68   | 0.000 | 0.05601, 0.18388 |
| ShoulderWidth| 0.065255  | 0.01498  | 4.36   | 0.000 | 0.03589, 0.09461 |
| Light        | -0.085596 | 0.03389  | -2.53  | 0.012 | -0.15203, -0.01916 |
| Surface      | -0.102001 | 0.05062  | -2.02  | 0.044 | -0.20122, -0.00278 |
| Weather      | -0.083198 | 0.04007  | -2.08  | 0.038 | -0.16174, -0.00466 |
| AlcDrug      | 0.374733  | 0.07642  | 4.9    | 0    | 0.22494, 0.52452 |
| /cut1        | 0.901336  | 0.16915  | 5.36   | 0    | 0.56979, 1.23287 |
| /cut2        | 1.662236  | 0.16979  | 9.94   | 0    | 1.32944, 1.99502 |
| /cut3        | 2.429173  | 0.17118  | 14.34  | 0    | 2.09364, 2.76469 |
| /cut4        | 3.260813  | 0.17745  | 18.14  | 0    | 2.91301, 3.60861 |
As estimated in OP model, the type 4 exit ramp has a better safety performance in terms of less severely injured crashes, as compared with type 1 exit ramp. In other words, crashes occurred at type 4 exit ramps are more likely to have minor injured consequence than type 1 exit ramps. The type 2 and type 3 exit ramps do not have significant impact on injury severity. The coefficient of the number of lane on freeway mainline is positive, implying the fact that more lanes on freeway mainline tends to increase the probability of severer crash injuries at freeway diverge areas. The increase of difference between speed limit on freeway mainline and exit ramp will increase the injury severity of crash. Good light conditions, good weather conditions and diverge areas located in residential zones will decrease the probability of severe injuries. Alcohol/drug involvement is highly significant to cause a more severely injured crash. A wet road surface is also likely to raise the injury severity. In addition, rear-end and sideswipe crashes are related to minor crashes.

Severe crashes are likely to occur at longer exit ramps which is a little counter-intuitive. One possible reason for this phenomenon may be that vehicles tend to travel faster on longer exit ramps which increase the injury severity of crashes. The probability of severe injury increases with the increase of the shoulder width since the coefficient is positive. Possible reason may be that drivers tend to pay less attention and increase speed under wider shoulder conditions.

Several variables were not found to be significantly related to crash severity at freeway diverge areas and were excluded from the model. These variables include the type 2 and type 3 exit ramps, length of deceleration lane, grade, surface type, shoulder type, post speed limit on mainline, ADT on mainline, ADT on ramp, and angle collision type. It was noticed that the length of deceleration lane and ADT on mainline and ramp were positively correlated to the crash counts at freeway exit ramps, according to previous studies based on the same dataset. However, the length of deceleration lane was not found to have significant impact on the crash injury severity. The mainline ADT and the ramp ADT also do not significantly impact the injury severity of crashes at freeway off-ramp areas.

3.2 Marginal Analysis of the OP Model

The coefficients of variables estimated in OP model do not directly reflect the impacts of contributing factors on each crash injury severity level. The marginal effects of factors identified in OP model were computed. The estimate results were listed in Table 3. The marginal coefficients illustrate the change of occurrence probability of injury severity by one unit increase of the input variable, keeping other factors at their mean values. A positive marginal coefficient of a variable for a particular injury severity level means that the probability of this severity level will increase by a value equals the coefficient, as the one unit increase of this input variable, and vice versa.

It was concluded from the table that the type 4 exit ramp will reduce the fatal crashes by 0.2 percent, decrease the probabilities of incapacitating, no-capacitating and possible/invisible injuries by 1.0, 2.1 and 1.5 percentage respectively, as compared with type 1 exit ramp. The probability of no injury crash at type 4 exit ramp is 4.8 percent higher than type 1 ramp. One additional lane on mainline will decrease the proportion of no injury crash by 2.1% and increase the proportion of at least incapacitating injuries by 0.6%. In the same manner, good light and weather condition will increase the probability of no injury by 3.4% and 3.3%, respectively, while increase the probabilities of severe injuries. The alcohol involvement increases the probability of injured crash by 14.8%. The quantitative impacts of each contributing factors on the injury severity level can be found in the table and were not listed here. The marginal analysis of this study provides more intuitive findings towards the impacts of contributing factors on each injury severity level.
Table 3. Marginal Effects of Ordered Probit Model

| Variable     | Level 1        | Level 2        | Level 3        | Level 4        | Level 5        |
|--------------|----------------|----------------|----------------|----------------|----------------|
| Type4        | 0.0481562      | -0.0151765     | -0.0204365     | -0.0102794     | -0.0022637     |
| SpeedDiff    | -0.0011978     | 0.0003441      | 0.0005159      | 0.0002742      | 0.0000636      |
| Mainlanes    | -0.0213399     | 0.0061308      | 0.0091918      | 0.0048848      | 0.0011325      |
| RaLength     | -0.0709839     | 0.0203932      | 0.0305750      | 0.0162485      | 0.0037671      |
| LandType     | -0.0476933     | 0.0139194      | 0.0204884      | 0.0107987      | 0.0024869      |
| ShoulderWidth| -0.0259785     | 0.0074635      | 0.0111898      | 0.0059466      | 0.0013787      |
| Light        | 0.0340967      | -0.0094989     | -0.0147426     | -0.0079741     | -0.0018811     |
| Surface      | 0.0404800      | -0.0123462     | -0.0172761     | -0.0088674     | -0.0019904     |
| Weather      | 0.0331379      | -0.0092777     | -0.0143192     | -0.0077238     | -0.0018172     |
| AlcDrug      | -0.1477788     | 0.0274130      | 0.0655133      | 0.0427263      | 0.0121262      |
| RearEnd      | 0.0254164      | -0.0073669     | -0.0109328     | -0.0057819     | -0.0013348     |
| Sideswipe    | 0.2286018      | -0.0862258     | -0.0916256     | -0.0403465     | -0.0080039     |

* dy/dx is for discrete change of dummy variable from 0 to 1

4. CONCLUSIONS

This study explored the impacts of contributing factors on crash injury severity at freeway diverge areas. The data were collected at 326 freeway exit ramps and an OP model was proposed to identify the relationships between injury severity and explanatory variables. Based on the data analysis results, it was found that the factors significantly impact injury severity of crashes include the mainline lane number, length of ramp, difference of speed limits between mainline and ramp, light condition, weather condition, surrounding land type, alcohol/drug involvement, road surface condition, shoulder width, and crash types of rear-end and sideswipe. As compared with type 1 exit ramps (single-lane exit ramps), crashes occurred at type 4 exit ramps (two-lane exit ramps without optional lane) have minor injury consequences. Type 2 (single-lane exit ramps with a taper) and type 3 exit ramps (two-lane exit ramps with an optional lane) do not have significant impact on crash injury severity compared with type 1 ramps. Marginal analysis was conducted to quantitatively interpret the marginal effects of contributing factors on each crash severity.

The analysis of crash injury severity can help prevent severe crashes and increase safety of roadway facilities. This study explored the contributing factors to crash injury severity, and the findings will be beneficial to transportation engineers to address safety problems and improve safety performances at freeway diverge areas. However, this study does suffer from several limitations. To begin with, the OP model assumes that input variables were independent among each other. The potential correlations between variables were not considered in this study which would produce inaccurate estimates. Then, this study did not address the impacts of lane-balanced design on injury severity which would be a potential significant factor. In addition, the findings of this study needs to be validated or compared with other datasets. The authors recommend that future studies could focus on these issues.

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