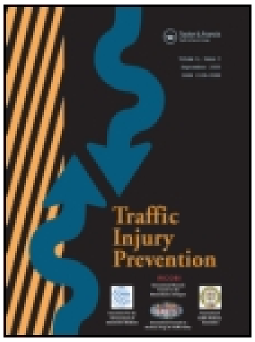

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Exploring the Impact of Access Designs on Crash Injury Severity on Multilane Highways

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Objective: Access design is a critical factor that influences the safety and mobility of urban/suburban multilane highways due to the interactions between access movements and through traffic. An effective way for improving the safety and mobility of multilane highways is to control access maneuvers by implementing appropriate access designs. Understanding the impact of access designs on crash injury severity is beneficial for implementing effective countermeasures to mitigate crash injury at access points. Thus, the objectives of this article are to investigate the impact of access designs on crash injury severity and identify contributing factors of crash injury severity at access points of multilane highways.

Methods: A total of 1830 crash records were collected at 149 access points with different access designs for a period of 3 years (2008–2010) in Florida. A heterogeneous logit model, relaxing the constraint of identical variances across observations in the traditional ordered choice models, was developed to evaluate the impact of access designs on crash injury severity and identify contributing factors. The marginal effects of the developed model were used to interpret the impact of access designs and other contributing factors.

Results: At 4-leg access points, given that a crash has occurred, replacing full median openings with closed medians will reduce the probability of severe injury (fatality, incapacitating injury, or nonincapacitating injury) by 9.73 percent; substituting full median openings with directional median openings will reduce the probability of severe injury by 11.02 percent. At 3-leg access points, given that a crash has occurred, closed medians significantly experience a lower risk of severe injury than full median openings; however, there is no evidence that directional median openings are similarly effective. Other contributing factors of crash injury severity at access points were identified as number of lanes, shoulder width, median width, driveway density, left-turn bay on major roads, speed limit, average annual daily traffic (AADT), high-density residential area, daylight, driver age, and truck involvement.

Conclusions: Installation of directional median openings is a reasonable safety treatment at 4-leg access points because this access design has better safety performance than full median openings in terms of crash injury severity; in addition, it provides fewer restrictions on accessibility than closed medians. Other effective treatments include installing left-turn storage bays at median openings and increasing the width of shoulders and medians.

Supplemental materials are available for this article. Go to the publisher's online edition of *Traffic Injury Prevention* to view the supplemental file.

Keywords: access management, access design, traffic safety, crash injury severity, heterogeneous choice model

Introduction

As described in roadway functional hierarchy (*Access Management Manual* 2003), the primary function of urban/suburban multilane highways is to deliver traffic (mobility), and the function of entering or leaving roadside properties (accessibility) is another important consideration in the geometric design and traffic management of multilane highways. In this article, access points are defined as generalized stop sign intersections that may consist of one or 2 driveways/minor roads with or without a median opening within a multilane highway section bounded by 2 consecutive signalized intersections. As shown in Figure 1, access designs, the combination of median types (closed, directional, and full) and number of legs at access points (3 legs or 4 legs), can be categorized into 6 types. In types I and IV, left-turn movements (departing or approaching driveways) and U-turn movements on major roads are fully restricted due to closed medians. Types II and V, which have directional median openings, allow U-turn movements on major roads and left-turn movements approaching driveways but left-turn movements departing driveways are restricted. Full

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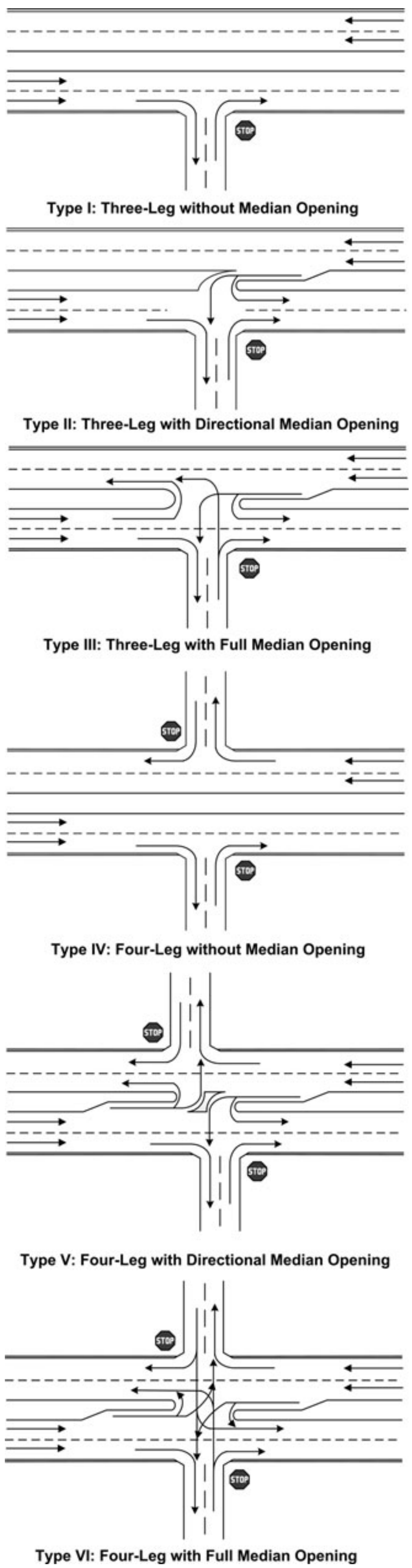
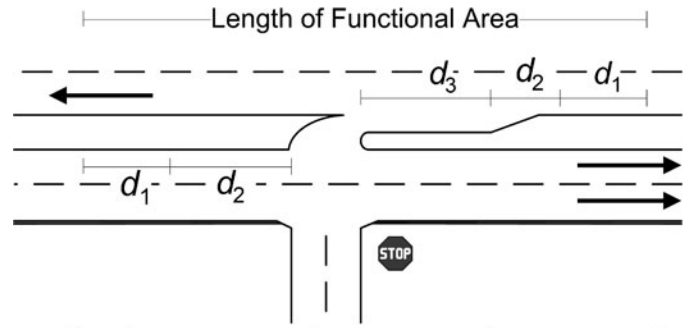


Fig. 1. Access designs and allowed movements at mid-block segments of multilane highways.



Speed km/h (mph)	d_1 m (ft)	d_2 m (ft)	d_3 m (ft)
48 (30)	33.5 (110)	48.8 (160)	114.3 (375)
64 (40)	44.2 (145)	83.8 (275)	76.2 (250)
80 (50)	56.4 (185)	129.5 (425)	28.1 (125)

Fig. 2. Functional area of access points. Length of functional area is sum of perception reaction distance (d_1), maneuver distance (d_2), and storage length (d_3) for both directions. Source: *Access Management Manual* (2003; table 8-4).

opening medians in types III and VI allow left-turn movements, U-turn movements, and crossing movements between driveways (type VI only). Right-turn movements (departing or approaching driveways) are always allowed in the 6 access designs. For scaling the study range of an access point, a functional area, defined as the upstream section of an access point, consisting of perception reaction distance (d_1), maneuver distance (d_2), and storage length (d_3) in both directions, was calculated using the method defined in the *Access Management Manual* (2003) for each access point. If left-turn movements approaching driveways or U-turn movements are restricted on one side of an access point, the storage length (d_3) on that side is zero. The calculation process of functional areas is given in Figure 2.

Access points are the critical spots that influence the safety performance of multilane highways due to the interactions between accessing movements (approaching or departing driveways) and through movements on multilane highways. An inappropriate access design may increase the conflicts between accessing movements and through traffic (major roads) at access points and may even introduce severe traffic delays and traffic crashes. Therefore, implementation of appropriate access designs to control access maneuvers is an effective way to improve the safety and operational performance of multilane highways.

Several past studies have been conducted to evaluate the safety impacts of access designs in term of crash occurrence and/or traffic conflict. For example, Bonneson and McCoy (1997), Gluck et al. (1999), Parsonson et al. (2000), and Potts et al. (2004) explored the safety effectiveness of median treatments. Dissanayake et al. (2002) and Pirinccioglu et al. (2006) assessed the safety effectiveness of right-turn followed by U-turn as an alternative to direct left turn on arterials based on traffic conflicts. Other studies, including Sayed and Rodriguez (1999), Persaud et al. (2002), and Neuman et al. (2003), focused on the likelihood of a crash occurrence at unsignalized intersections on urban arterials.

Crash injury severity, another criterion to measure the safety performance of transportation facilities, is used to comprehend, given that a crash has occurred, the factors that may influence the degree of injury sustained by the road users involved in the crash. Limited previous studies were found to explore crash injury severity at access points or unsignalized intersections on multilane arterials. Das et al. (2009) identified traffic, highway design, and driver–vehicle information significantly related to fatal and severe crashes on urban arterials for different crash types using a random forests algorithm. They found that a restrictive median significantly influences injury severity in sideswipe, angle, and turning crashes. Haleem and Abdel-Aty (2010) examined crash injury severity at 3- and 4-leg unsignalized intersections. The authors found that left-turn movement on minor approaches has no significant impact on crash injury severity on both 3-leg and 4-leg unsignalized intersections. The significant factors affecting crash severity at unsignalized intersections were identified as traffic volume on major roads, number of through lanes on minor roads, upstream and downstream distance to the nearest signalized intersection, left and right shoulder width, number of left-turn movements on minor approaches, and number of left-turn and right-turn lanes on major approaches. Another important finding was that young and very young at-fault drivers were associated with the least fatal probability compared to other age groups.

In summary, many previous studies evaluated the safety performance of access designs or unsignalized intersections in term of crash frequency/rate or traffic conflict, but few studies focused on the impact of access designs (or unsignalized intersections) on crash injury severity on multilane highways. The study conducted by Haleem and Abdel-Aty (2010) excluded the factors of median type, which are the basic elements of access designs, in the fitted models, although these factors were included in the variable list. Thus, a more in-depth study is necessary to (1) model the impact of access design on the injury severity of traffic crashes on urban/suburban multilane highways and (2) identify the significant factors contributing to the crash injury severity.

Methodology

Crash injury severity, usually represented by an ordinal categorical variable, is defined as the most severe injury level involved in a vehicle collision. Regression is the most popular method in modeling crash data and analysis of influencing factors, because it has a powerful ability in prediction, interpretation, and multivariate analysis in comparison with other methods, such as descriptive analysis, cross-tabulation, hypothesis testing, etc. Several statistic methodologies have been used to fit the severity data. Because of the ordinality of injury severity data, ordered choice regressions (ordered probit/logit) have been widely used to fit the data (Abdel-Aty 2003; Savolainen et al. 2011). In addition to the ordered probit/logit models, a wide range of statistic methodologies were used to assess the impact of vehicle, roadway, and human factors on injury severity data. These methodologies were reviewed and assessed comprehensively by Savolainen et al. (2011).

In this study, the heterogeneous choice regression—an extension of the traditional ordered choice models—was used to develop the prediction model for modeling crash injury severity at access points, because this method examines the violation of homoscedasticity that the error variances are assumed to be identical for all observations.

Model Structure

Let Y_i denote injury severity for the ith observed crash, the ordered choice model can be written in terms of cumulative probability as

$$\Pr(Y_i > m) = 1 - \sum_{j=1}^{m} \Pr(Y_i = j) = 1 - F(\tau_m - \mathbf{x_i}\boldsymbol{\beta}) \qquad j = 1, 2, 3, 4, \quad (1)$$

where $\Pr(Y_i > m)$ is the probability of the response variable Y_i associated with observed crash i being greater than a specific severity level m; $\mathbf{X}_i$ is a vector containing the values of observed crash i on a full set of explanatory variables; $\boldsymbol{\beta}$ is a vector of coefficients associated with the explanatory variables; τ_m is the threshold parameter (cutoff point) for injury severity m to be estimated, and F() represents the cumulative distribution function following the standard normal distribution (ordered probit model), the logistic distribution (ordered logit model), or the log-log distribution (ordered log-log model).

In traditional ordered choice models (Eq. (1)), an assumption that the error term (ε_i) is homoscedastic across individuals must be made. In other words, error variances ($\mathrm{Var}(\varepsilon_i)$) are the same for all observations. However, this assumption is often violated in actuality and results in biased, inconsistent, and inefficient parameter estimation in the ordered choice models (Williams 2009). The heterogeneous choice model, also known as the location-scale model, relaxes the constraint of identical variances across observations and adopts a cumulative probability form as

$$\Pr(Y_i > m) = 1 - \mathrm{F}\left(\frac{\tau_m - \mathbf{x_i}\boldsymbol{\beta}}{\sigma_i}\right). \quad (2)$$

And the adjustment factor for the error variance (σ_i) can be written as

$$\sigma_i = \exp(\mathbf{z_i}\boldsymbol{\gamma}) \text{ or } \ln(\sigma_i) = \mathbf{z_i}\boldsymbol{\gamma}, \quad (3)$$

where z_i is a vector of covariates of the ith observation that define groups with different error variances in the underlying latent variable; $\boldsymbol{\gamma}$ is a vector of parameters to be estimated. The heterogeneous choice model consists of two equations: the choice equation (Eq. (2)) and the variance equation (Eq. (3)). More detailed descriptions of the heterogeneous choice model can be found in a working paper (Williams 2010).

Identification of Assumption Violation

The variables in $\mathbf{z_i}$ may be different from those in $\mathbf{x_i}$. The explanatory variables that do not violate the assumption of identical variances across observations have no impacts on the variance of ε_i are excluded from $\mathbf{z_i}$; in other words, these variables. If the explanatory variables have significant influence on the variance of ε_i, indicating that these variables violate the assumption, they should be included in z_i. Williams (2010) proposed a stepwise method to select the variables that are significant to be added in $\mathbf{z_i}$ using the likelihood ratio test.

Model Selection

To select the best model from the proposed models, pseudo R^2, Akaike's information criterion (AIC), and Bayesian information criterion (BIC) were used to evaluate the goodness-of-fit of the models. Pseudo R^2 is a logical analog to R^2 in ordinary least squares. The model with the higher pseudo R^2 value indicates a better model fit (Long 1996). AIC is an asymptotically efficient model selection criterion. The model with the smaller AIC value is considered as the better-fitting model (Long 1996). The BIC identifies the model that is more likely to have generated the observed data, assuming no prior preference for one model over the other. Similar to AIC, the model that has the smaller BIC value is preferred. Raftery (1995) proposed a guideline of model selection based on the magnitude of the BIC difference between 2 models: 0 to 2 = *weak*, 2 to 6 = *positive*, 6 to 10 = *strong*, and >10 = *very strong*.

Model Interpretation

The slope coefficients of the fitted model can be used to interpret the impacts of explanatory variables on crash injury severity. A positive coefficient indicates that increasing a variable by a unit value (changing from 0 to 1 for discrete variables) is more likely to increase the injury severity of traffic crashes; a negative coefficient means that a unit increase tends to decrease injury severity.

Another useful approach to interpret the model is marginal effects, more commonly defined as the slope of the probability curve relating the kth explanatory variable x_k to $\Pr(Y = j|\mathbf{x})$ at the mean values of all variables, holding all other explanatory variables constant. The equation is given as

$$\frac{\partial \Pr(Y = j|\mathbf{x})}{\partial x_k} = -\left[f\left(\frac{\tau_i - \bar{\mathbf{x}}\boldsymbol{\beta}}{\bar{\sigma}}\right) - f\left(\frac{\tau_{i-1} - \bar{\mathbf{x}}\boldsymbol{\beta}}{\bar{\sigma}}\right)\right] \cdot \frac{\beta_k}{\bar{\sigma}}, \tag{4}$$

where $f()$ is the probability density function; $\bar{\mathbf{x}}$ is the mean values of all variables; β_k is the slop coefficient of the kth variable; and $\bar{\sigma}$ is the mean variance across observations. For nominal/binary variables, the marginal effects are computed as the difference of probabilities due to the discrete change of the variables from 0 to 1, holding other explanatory variables constant.

Data

Data Collection

A total of 149 access points with different access designs were selected from Florida state roads (SR-60, SR-580, SR-582, SR-583, SR-50, SR-15, and SR-9). All of these access points are located in urban or suburban areas with at least 4 bidirectional lanes and speed limits of 56 km/h (35 mph), 64 km/h (40 mph), 72 km/h (45 mph), or 80 km/h (50 mph). The distribution of the number of access points over access types is: TYPE_I, 35 (23%); TYPE_II, 20 (12%); TYPE_III, 25 (17%); TYPE_IV, 19 (13%); TYPE_V, 13 (9%); and TYPE_VI, 37 (25%). For each access point, researchers calculated its functional area using the method described in Figure 2 and then they reviewed the Florida Department of Transportation (FDOT) GIS database, Google Earth, and FDOT straight-line diagrams to collect geometric design of access points, such as access type, left-turn storage bay, and driveway density. It is necessary to note that although an access point is defined by a combination of a median opening (may be closed) and one or 2 minor roads or driveways, more driveways may exist within the function area of the access point. These additional driveways have following characteristics: (1) short length; (2) not facing a median opening, if the opening exists; (3) very simple geometric design, usually without divided lanes; (4) serving very light traffic; (5) excluded from the FDOT GIS database. These driveways were treated as an influence factor (driveway density) rather than TYPE_I or TYPE_IV access points because of their slight impacts on through traffic. Traffic data and other geometric data were retrieved from the Florida Traffic Information CD and the Florida Roadway Characteristics Inventory database, respectively (both in the Florida Department of Transportation internal database). Finally, 1830 records of the crashes that occurred within the functional areas of the selected access points were collected from the Florida Crash Analysis Reporting system (CARs) for a period of 3 years (2008–2010). The functional areas of 2 consecutive access points may be overlapped. For these scenarios, the crashes that occurred within the overlapped area were assigned to the nearer access point because it was assumed that a crash was under a major influence of the access point that is closer to the crash location.

Geometry, traffic, environment, and crash data were merged based on the location information (roadway ID + mileposts). The data were organized at crash level: each row represented one crash observation with associated geometric, environmental, and traffic variables. All of the explanatory variables were aggregated as categorical variables. A descriptive summary of the dependent variable (crash injury severity) and explanatory variables is presented in Table A1 (see Appendix, online supplement).

Model Estimation and Selection

The *oglm* command developed by Williams (2010) was used to develop the heterogeneous choice models using the STATA 12.0 (StataCorp LP). First, all of the variables listed in Table A1 were included in both equations (the choice equation and the variance equation) of an initial model, and the stepwise

Table 1. Comparison of goodness-of-fits for developed models

Model	df	Pseudo R^2	AIC	BIC[a]	Δ_{BIC}[b]
Heterogeneous logit[c]	32	0.1174	3837.88	4014.27	—
Heterogeneous probit	32	0.1149	3848.50	4024.89	10.62
Heterogeneous log-log	32	0.1023	3902.27	4078.65	64.38
Ordered probit	28	0.1029	3891.90	4046.24	31.97

[a]Support evidence based on the difference in BIC values: 0 to 2 = *weak*, 2 to 6 = *positive*, 6 to 10 = *strong*, and >10 = *very strong*. Lower BIC is preferred.
[b]ΔBIC = BICs of other models − BIC of the heterogeneous logit model.
[c]Best-fitted model.

method was used to select significant variables in $\mathbf{x_i}$ (the choice equation) at a confidence level of 90 percent. Second, the stepwise method was used again to identify significant variables in $\mathbf{z_i}$ (the variance equation) at a confidence level of 90 percent. Finally, the heterogeneous choice models were estimated with 3 link functions (logit, probit, and log-log, respectively) and compared by pseudo R^2, AIC, and BIC, as shown in Table 1. To assess the effectiveness of the heterogeneous choice models, the ordered probit model, the most popular method for modeling crash injury severity, was also estimated based on the same data set and compared with the heterogeneous models.

As shown in Table 1, the heterogeneous logit model has the highest value of pseudo R^2 and the lowest values of AIC and BIC. In particular, the absolute BIC differences between the heterogeneous logit model and the heterogeneous probit model, the heterogeneous log-log model, and the ordered probit model are 10.62, 64.38, and 31.97, respectively. The justification for selecting the heterogeneous logit model over the other 3 models is very strong (Raftery 1995). Based on the 3 criteria, the heterogeneous logit model was selected as the final model. Its estimation results and marginal effects are given in Table 2.

Table 2. Fitted heterogeneous logit model and marginal effects

Explanatory variable	Model		Marginal effects[a] (ACCSEV =)			
	Coefficient	*P* value	1	2	3	4
Choice equation (Eq. (2))						
Access type						
TYPE_I	−0.4882	.0990	0.1193	−0.0474	−0.0563	−0.0156
TYPE_II	0.2147	.4160	−0.0535	0.0175	0.0277	0.0083
TYPE_III	0.0858	.6970	−0.0213	0.0074	0.0108	0.0032
TYPE_IV	−0.7044	.0180	0.1687	−0.0713	−0.0767	−0.0206
TYPE_V	−0.8268	.0000	0.1953	−0.0851	−0.0871	−0.0231
TYPE_VI			(Baseline)			
Geometric design						
NOLANE8	0.4783	.0110	−0.1188	0.0350	0.0638	0.0200
SLDWDH2	−1.0975	.0000	0.2445	−0.1171	−0.1018	−0.0257
MEDWDH	−0.5771	.0020	0.1555	−0.0843	−0.0683	−0.0029
LTSPACE1	−0.5826	.0190	0.1406	−0.0587	−0.0645	−0.0174
LTSPACE2	−0.5019	.0870	0.1235	−0.0464	−0.0600	−0.0170
DRVWYDEN1	0.5976	.0000	−0.1476	0.0387	0.0820	0.0269
DRVWYDEN2	0.2651	.0110	−0.0658	0.0233	0.0329	0.0096
SPEED45	0.7341	.0000	−0.1801	0.0651	0.0891	0.0259
SPEED50	0.6656	.0030	−0.1640	0.0419	0.0916	0.0304
Traffic and land use						
AADT1	0.3514	.0210	−0.0869	0.0322	0.0425	0.0121
HIRESIDENT	−0.9442	.0000	0.2186	−0.0989	−0.0949	−0.0247
Crash type						
REAREND	1.7363	.0000	−0.4320	0.1775	0.2287	0.0259
ANGLE	1.7259	.0000	−0.4250	0.0797	0.2750	0.0703
LEFTTURN	1.7547	.0000	−0.3844	0.0100	0.2477	0.1267
PEDBKE	3.9603	.0000	−0.5577	−0.1875	0.1558	0.5894
HEADON	2.3052	.0000	−0.4410	−0.0691	0.2809	0.2293
OTHER	1.3019	.0000	−0.2789	0.0013	0.1636	0.1140
Miscellaneous factors						
DAYLIGHT	−0.1992	.0460	0.0496	−0.0171	−0.0251	−0.0074
TRUCKINV	−0.9330	.0230	0.2116	−0.1001	−0.0890	−0.0226
YONG	−0.3704	.0000	0.0916	−0.0338	−0.0449	−0.0129
Variance equation (Eq. (3))						
REAREND	−0.3861	.0000	—	—	—	—
ANGLE	−0.2080	.0350	—	—	—	—
OTHER	0.2291	.0370	—	—	—	—
MEDWDH	0.1656	.0600	—	—	—	—
Cut points						
/cut1	1.1438	.0040	—	—	—	—
/cut2	2.4064	.0000	—	—	—	—
/cut3	4.2751	.0000	—	—	—	—
Statistics						
Sample size		1830	—	—	—	—
Log likelihood		−1886.94	—	—	—	—

[a]Probability difference at an injury level j ($Y = j$) due to the discrete change in an explanatory variable (X_k) from 0 to 1, holding other variables (X) constant. Marginal effect = $\Pr(Y = j \mid X, X_k = 1) - \Pr(Y = j \mid X, X_k = 0)$.

Discussion of Estimation Results

Variance Equation

The crash type factors of REAREND, ANGLE, and OTHER were identified to significantly violate the assumption that the error term (ε_i) is homoscedastic across individuals. Thus, they were included in the variance equation (Table 2). It seems that the crash types REAREND and ANGLE experience less variance in crash injury severities at access points than other crash types due to their negative coefficients in the variance equation, whereas the crash type OTHER experiences more variance in crash injury severities at access points than other crash types because of its positive coefficient.

The median width is another factor violating the assumption of homogeneous variance. If median width is greater than 4.57 m (15 ft, MEDWDH = 1), the dispersion of injury severity in crashes at access points is more likely to be larger than the one with a narrow median with of 4.57 m (15 ft) or less.

Access Type

Compared to the access design of full median openings at 4-leg access points (TYPE_VI), the designs of closed medians at 3-leg access points (TYPE_I) and 4-leg access points (TYPE_IV) significantly affect crash injury severity because their *P* values (.099 and .018, respectively) are less than .1, as shown in Table 2. Furthermore, due to their negative coefficients (−0.4882 and −0.7044, respectively), the 2 designs are more likely to experience slight injury than the design of full median openings at 4-leg access points (TYPE_VI). A possible reason, as shown in Figure 3B, is that the design of closed medians that fully restricts left-turn, U-turn, and crossing movements is more likely to decrease the likelihood of crash types associated with severe injury, such as angle, turning, head-on, pedestrian–bicycle crashes, etc. According to the

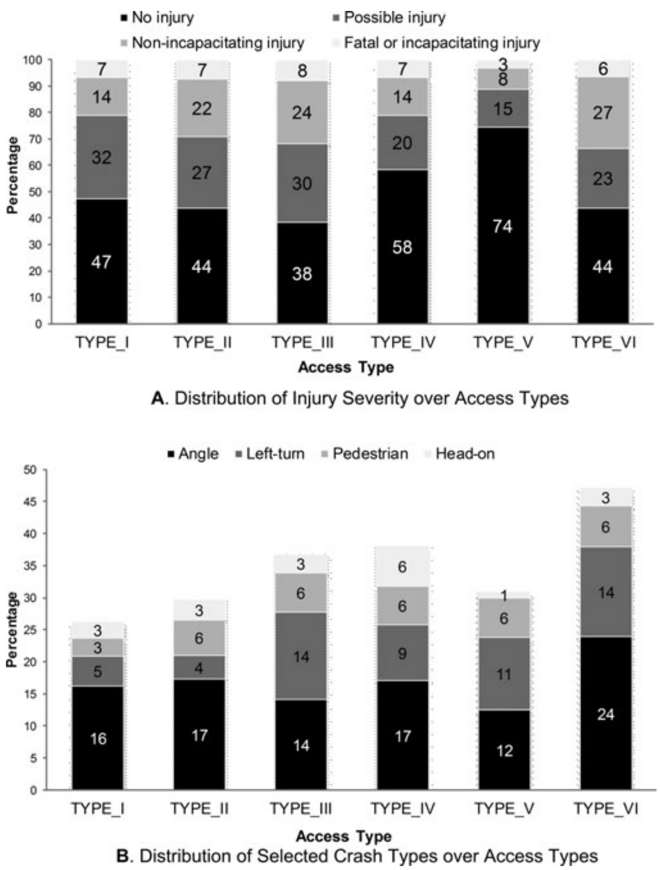


Fig. 3. Distributions of crash injury severity and selected crash types over 6 access types.

marginal effects, as shown in Table 2, given that a crash has occurred, and holding all other factors constant, changing the access design from full median openings at 4-leg access points (type VI) to closed medians at 4-leg access points (type IV) will reduce the probability of severe injury (fatal, incapacitating, and nonincapacitating injury) by 9.73 percent (=7.67% for nonincapacitating injury + 2.06% for fatal and incapacitating injury).

As shown in Table 2, it can also be concluded that directional median openings at 4-leg access points (TYPE_V) experience significantly lower injury severity than full median openings at 4-leg access points (TYPE_VI) due to the negative coefficient and small *P* value. According to the marginal effects (Table 2), replacement of full median openings with directional median openings at 4-leg access points will decrease the probability of severe injury by 11.02 percent (= 8.71% + 2.31%), holding other factors constant.

Comparing directional median openings (TYPE_V) and closed medians (TYPE_IV) at 4-leg access points, it can be found that the 2 access designs have similar marginal effects (Table 2): 2.31 vs. 2.06 percent of reduction in fatal and incapacitating injury, 8.71 vs. 7.67 percent of reduction in noncapacitating injury, and 11.02 vs. 9.73 percent of reduction in total severe injury. In other words, directional median openings have similar safety performance compared to closed medians at 4-leg access points in terms of injury severity. Considering that directional median openings partially allow left-turn and U-turn movements, installing directional median openings at 4-leg access points is a reasonable alternative to closed medians and full median openings.

There is no evidence that directional and full median openings at 3-leg access points (TYPE_II and TYPE_III, respectively) have significant impacts on injury severity, compared to full median openings at 4-leg access points (TYPE_VI).

Geometric Design

As shown in Table 2, the significant geometric factors influencing injury severity at access points include number of through lanes, outside shoulder width, median width, speed limit, left-turn storage, and driveway density. Based on their coefficients and marginal effects, the impacts of the factors can be interpreted as follows:

1. If the number of through lanes is equal to 8 (bidirectional), the likelihood of severe injury in a crash tends to increase by 8.38 percent (= 6.38% + 2%), compared to 4 or 6 through lanes. The design of 8 through lanes increases exposure duration of accessing movements in the through traffic on major roads when they are making left turns or crossing major roads. Because left-turning or crossing vehicles reveal their "fragile" parts (sides or heads) to through traffic, the longer exposure duration tends to increase the risk of serious injury crashes at access points. In addition, more lanes increase the risk for pedestrians or bicyclists when they are crossing major roads at access points.
2. Compared to narrow shoulders (≤1.83 m, 6 ft) or wide shoulders (>3.05 m, 10 ft), if shoulder width is between 1.83 m (6 ft) and 3.05 m (10 ft, SLDWDH2 = 1), the probability of severe injury will be reduced by 12.75 percent (= 10.18% + 2.57%).
3. If the median width at access points is greater than 4.57 m (15 ft, MEDWDH = 1), the probability of severe injury is more likely to decrease by 6.67 percent (= 6.38% + 0.29%).
4. An increase in driveway density within the functional area of an access point is more likely to increase the probability of severe injury in a crash. Compared to the driveway density of 0.24 m (0.8 ft) or less, if driveway density is between 0.8 per 30.48 m (100 ft) and 2.0 per 30.48 m (100 ft, DRVWYDEN1 = 1), the probability of severe injury tends to be increased by 10.89 percent (= 8.2% + 2.69%); if driveway density is greater than 2.0 per 30.48 m (100 ft, DRVWYDEN2 = 1), the probability tends to be increased by 4.25 percent (= 3.29% + 0.96%).
5. Speed limit is a significant factor contributing to injury severity at access points. Compared to a low speed limit of 64 km/h (40 mph) or less, increasing the speed limit to 72 km/h (45 mph, SPDLMT45 = 1) is more likely to raise the probability of severe injury by 11.5 percent (= 8.91% + 2.59%); increasing to 80 km/h (50 mph) or higher (SPDLMT50 = 1), the probability tends to increase by 12.2 percent (= 9.16% + 3.04%).
6. Installing left-turn bays on medians is more likely to decrease the injury severity in a traffic crash at access points. A one-side left-turn bay (LTSPACE1 = 1) will decrease the

probability of severe injury by 8.19 percent (= 6.45% + 1.74%), and a 2-side left-turn bay (LTSPACE2 = 1) will decrease the probability by 7.7 percent (= 6% + 1.7%).

Traffic and Land Use

High traffic volumes on major roads increase the likelihood of crash occurrence (Bonneson and McCoy 1997; Eisele and Frawley 2005; Gluck et al. 1999; Parsonson et al. 2000; Potts et al. 2004; Schultz et al. 2007) but show a complicated impact on injury severity at access points. Compared to low traffic volume (25,000 vehicles per day or less, AADT0 = 1) and high traffic volume (49,000 vehicles per day or higher, AADT2 = 1), middle traffic volume (between 25,000 vehicles per day and 49,000 vehicles per day, AADT1 = 1) is more likely to increase the probability of severe injury by 5.46 percent (= 4.25% + 1.21%). A possible explanation is that, compared to middle traffic conditions, high traffic volume raises traffic density and slows down travel speed; low speed is a critical factor that reduces the likelihood of severe injury. On the other hand, low traffic conditions can provide simple traffic conditions and better perception conditions for drivers to evade "dangerous" events, although its associated travel speed is high. Thus, crashes occurring in middle traffic volume experiences more severe injury severity because of the joint impact of high travel speed (compared to high traffic volume) and worse perception conditions (compared to low traffic volume) in middle traffic conditions.

A high-density residential area is more likely to experience a lower injury severity of traffic crashes at access points due to a low operating speed in this area. Compared to other area types, high-density residential areas (HIRESIDENT = 1) tend to decrease the probability of severe injury by 11.96 percent (= 9.49% + 2.47%).

Crash Type

Crash type is defined as the first harmful event involved in a crash. Different crash types may result in different harmful patterns to drivers or passengers. Usually, angle, left-turn, and head-on crashes are more likely to result in serious injuries because the impact points of these crashes are located on vehicle sides and drivers or passengers tend to receive the impacts more directly than rear-end and sideswipe crashes. In particular, pedestrians and cyclists are more fragile if they are involved in a traffic crash. Thus, these crash types are more dangerous than other types. It is worth noting that there are significant connections among crash injury severity, crash type, and access design. As an intermediate factor, crash type affects crash injury severity and is simultaneously impacted by access designs. However, this connecting process is complicated. In addition to crash type, many factors may directly contribute to crash injury severity, such as vehicle velocity, impact point, human conditions, and so on. Figure 3 gives the distributions of injury crash severity and crash types over access designs, and a detailed discussion of the interactions among crash injury severity, crash type, and access design is given in the Appendix.

Compared to SIDESWIPE, as shown in Table 2, the types REAREND, ANGLE, LEFTTURN, PEDBIKE, HEADON, and OTHER are all more likely to increase crash injury severity at access points. According to the marginal effects (Table 2), the percentages of increasing the probability of crash severe injury at access points are given as follows (in descending order): PEDBKE (74.52% = 15.58% + 58.94%), HEADON (45.82% = 28.09% + 22.93%), LEFTTURN (37.44% = 24.77% + 12.67%), ANGLE (34.53% = 27.5% + 7.03%), OTHER (27.76% = 16.36% + 11.4%), and REAREND (25.46% = 22.87% + 2.59%). It can be found that involvement of pedestrians or bicyclists in a crash at access points is the most dangerous factor resulting in a serious injury. Thus, protection of nonmotorists at access points should be an important consideration in access design and management.

Miscellaneous Factors

Daylight can provide good light conditions for drivers to decrease the injury severity at access points. Compared to the light conditions of night, dawn, and dusk, daylight tends to reduce the probability of severe injury of traffic crashes by 3.25 percent (= 2.51% + 0.74%).

A young driver who is at fault (YOUNG = 1) is more likely to experience lower injury severity in a crash at access points because itscoefficient in the developed model is negative. A possible interpretation is that young drivers have stronger bodies and better perception than drivers of other age groups.

Truck involvement in a crash (TRUCKINV = 1) at an access point tends to reduce the probability of severe injury due to its negative coefficient in Table 2. A similar phenomenon was also found in a previous study (Wang et al. 2009)—truck involvement will decrease injury severity at diverging areas of freeways. A possible explanation is that drivers are likely to pay more attention and decrease their speed when they are close to a truck.

In this study, a heterogeneous logit model was developed to assess the safety impact of access design in terms of crash injury severity and identify the significant factors contributing to crash injury severity at access points at urban/suburban multilane highways. Based on the model, the following conclusions can be obtained:

- At 4-leg access points, substitution of full median openings with directional median openings is more likely to decrease the probability of severe injuries (fatal, incapacitating injuries, or nonincapacitating injuries) by 11.02 percent. Closing median openings at 4-leg access points has similar effectiveness (9.73%). Considering that directional median openings can provide partial accessibility for left-turn and U-turn movements, this access design (TYPE_V) is a reasonable alternative to closed medians or full median openings at 4-leg access points.
- At 3-leg access points, replacing full median openings with directional median openings does not significantly influence crash injury severity in statistics; closing median openings tends to reduce the probability compared to full median openings.

- Installation of left-turn storage bays at access points is an effective treatment to decrease the risk of severe injury by 8.19 percent (one side) and 7.7 percent (two sides).
- Increasing shoulder width to more than 1.83 m (6 ft) or median width to more than 4.57 m (15 ft) is also an effective way to reduce injury severity.
- Middle traffic volume (between 25,000 and 49,000) experiences a higher likelihood of severe injury than low traffic volume and high traffic volume.
- Young drivers (age $\leq$ 25) tend to decrease the probability of severe injury severity.
- Other significant factors contributing to crash injury severity include speed limit, high-density residential area, daylight, and truck involvement.
- Crash type, as an intermediate factor, significantly affects crash injury severity; in addition it is impacted by access designs. Involvement of pedestrians or bicyclists in a crash at access points is the most dangerous factor resulting in a serious injury. Thus, protection of nonmotorists at access points should be an important consideration in access design and management.
- The heterogeneous logit model has better goodness-of-fit than the ordered probit model and provides more information with its variance equation.

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