Research Article

An Analysis of the Effects of Crash Factors and Precrash Actions on Side Impact Crashes at Unsignalized Intersections

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Annually, side impact crashes contribute to a significant proportion of road fatalities. These crashes typically occur as a result of traffic violations at intersections. This study contributes to efforts in addressing side impact crashes at unsignalized intersections by performing a path analysis to unravel some behavioral trajectories through which these crashes occur. The study further investigated how these behavioral pathways influence the severity of the crashes. Crashes that occurred at unsignalized four-way intersections and T-junctions in Alabama were used for model estimations. Three precrash actions, failed to yield right-of-way at the stop sign, failed to yield right-of-way at a turn, and running stop sign, were considered. The model estimation results reveal that some of the crash factors were more associated with certain precrash factors but not others at either four-way intersections or T-junctions or both. It was observed that side impact crashes that occurred under daylight conditions at four-way intersections, for instance, were less likely to involve running a stop sign but more likely to involve failure to yield at the stop sign and failure to yield right-of-way at a turn, but under dark and unlit roadway conditions, the at-fault drivers were more likely to run a stop sign or fail to yield at a stop sign but less likely to be involved in failure to yield right-of-way at a turn. This approach to injury severity analysis uncovers complex underlying relationships between precrash actions, other contributing factors, and crash outcomes.

1. Introduction

In 2018, side impact crashes accounted for about 23% of passenger vehicle occupant deaths in the U.S. Side impact crashes tend to cause serious injuries due to their possible effects on multiple body parts, including the head, neck, ribs, arms, hips, and legs [1]. Even at lower speeds, side impact crashes often lead to serious injuries. Studies have shown that side impact crashes, where the initial point is the driver side, are more likely to result in serious and fatal injuries than those that impact the far side. Side impact crashes often occur at intersections where one driver fails to yield the right-of-way. Efforts to reduce the occurrence of these crashes have led to the installation of various traffic control devices at intersections. While newer vehicle models have many safety features such as airbags, seatbelts, and bumpers, to protect occupants from frontal and rear-end collisions,

side impact car crashes leave occupants relatively unprotected. Presently, some vehicles have side curtain airbags, but most vehicles on the roads offer no protection from side impact crashes besides the car door.

Side impact crashes typically occur at intersections, and the frequency and severity of these crashes depend on the type of intersection [2, 3]. Generally, intersections are classified based on the number and configuration of the approaches (such as four-way (four-leg) intersections and T-junctions) and the type of traffic control (e.g., signalized and unsignalized). Studies have shown that the injury severity of crashes differs significantly across intersection types based on the traffic control present (e.g., stop/yield sign-controlled, traffic signals, and no traffic control) [4]. While traffic signals dictate the flow of traffic through signalized intersections, unsignalized intersections rely on traffic control signs and/or driver behavior to regulate the flow of traffic. As such, the

location, configuration, and type of traffic control at intersections affect stop/yield sign violation rates. Although these factors have been observed to be associated with crashes, driver and road user behaviors at intersections play even bigger roles in crash occurrence and crash outcomes. For instance, failure to stop or yield at unsignalized intersections (right-of-way violations) or running red light at signalized intersections increases the chances of a collision. These right-of-way violations are more likely to occur under certain roadway and traffic conditions and are often pronounced among certain driver populations [4, 5].

Previous studies have found some contributing factors to the injury severity of unsignalized intersection crashes. These crash contributing circumstances include crash-level factors: traffic volume, geometric characteristics, rural or urban, time, weather, lighting condition, and road grade; vehicle-level factors: vehicle type, model, and age; and person-level factors: driver gender and age, seatbelt usage, and drug-/alcohol-impaired. For instance, Pai [6] analyzed the injury severity of motorcyclists in angle crashes at T-junctions and found that the injuries of motorcyclists were greatest when the motorcycle from the major roads crashed into cars from the minor roads. Haleem and Abdel-Aty [7] examined the injury severity of crashes that occurred at unsignalized intersections and found that young and very young at-fault drivers were associated with the least fatal probability compared to other age groups. Wang et al. [8] observed that stop-controlled intersections, one-lane approaches, helmet usage, and lower speed limits are associated with decreased injury severity, whereas older (age >55) drivers and bicyclists, road users aged less than 16 years, bicyclists, foggy and rainy weather, inadequate use of lights in dark conditions, and wet road surfaces are associated with increased injury severity at uncontrolled intersections. Also, Haleem et al. [4] found that middle and very old pedestrians, at-fault pedestrians, vans, dark lighting condition, and higher speed limit are associated with higher pedestrian severity risk at unsignalized intersections. Li et al. [9] found that compared to intersections that have no traffic control devices, stop/yield sign-controlled intersections record decreased levels of injury severities and fatalities; however, the association was not as strong as that of the signal-controlled intersections. A study conducted by Wahi et al. [10] indicated that cyclists at stop/yield sign-controlled intersections were more severely injured if they were at fault in the crash occurrence. With respect to the intersection approach types, Wang et al. [11] found that compared to five-or-more-leg intersections, four-leg and T-junction intersections were both found to be associated with increased crash injury severity; and the estimated coefficients of these two intersection types indicate that the magnitude of association is higher for four-leg intersections.

Considering that side impact crashes occur primarily as a result of road user behaviors such as traffic law violations, this study performs a behavioral path analysis to understand what factors influence driver behaviors at unsignalized intersections and how these factors influence the severity of side impact crashes. As such, this paper quantifies the effects of various crash contributing factors, such as speeding,

through precrash traffic violation behaviors, such as failure to yield right-of-way at a stop sign, at unsignalized four-way intersections and T-junctions in Alabama. This would allow for the understanding of how direct crash contributing factors (such as speeding) influence crash outcomes under different precrash conditions (e.g., failure to yield or failure to stop) at unsignalized intersections. Unraveling the location type, association between direct crash contributing factors and the precrash actions that drivers engage in, and the driver populations that may be at increased risk of such behaviors would provide additional context to improve traffic safety. This approach provides an additional context to viewing the combined effects of crash factors and precrash actions on crash outcomes. The study outcomes are therefore expected to provide the necessary safety knowledge of driver behaviors and help to develop countermeasures that can reduce the incidence and severity of side impact crashes at unsignalized intersections.

2. Methodology

Previous crash injury severity studies have explored the associations between various factors, including precrash actions such as failure to yield right-of-way, and crash injury severities using various discrete-outcome modeling techniques (see [12, 13] for injury severity methodology reviews). These studies reveal the direct relationships between various crash factors and injury severity outcomes of different crash types. Beyond the direct relationships between crash contributing factors and crash outcomes, this study investigates indirect relationships among these contextual contributing factors and precrash actions to model behavioral pathways illustrated in Figure 1.

The behavioral pathways consist of two parts and are defined by two different models: association between crash contributing factors and precollision actions and the relationships between precrash actions and crash injury severity. The behavioral pathway analysis based on the precrash behaviors identified by primary contributing circumstances at either a four-way intersection or a T-junction involved a quantitative process of combining direct and indirect marginal effects from the injury severity model and the precrash behavior model.

This paper applies path analysis to quantify the behavioral pathways and quantitatively combine direct and indirect relationships among contextual contributing factors (X), precrash actions (Y_1), and crash injury severity (Y_2) as defined by equations (1) and (2) [14, 15]:

$$Y_1 = \alpha_1 + \beta_1 X, \quad (1)$$

$$Y_2 = \alpha_2 + \beta_2 X + \gamma Y_1. \quad (2)$$

Equations (1) and (2) represent linear-form models to estimate the nature of the relationship β_1 between crash contributing factors X and precrash action Y_1 and to express direct relationships β_2 between crash injury severity Y_2 and crash contributing factors X and precrash action Y_1 . This ensures that the direct effects of the contextual contributing

FIGURE 1: Conceptual workflow for the behavioral pathway of injury severity models.

factors on crash injury severity are captured together with their influence on precrash actions. The two are then connected by γ .

Equation (1) expresses the relationship between precrash action and crash contributing factors. Multinomial logistic (MNL) models were initially developed to estimate the correlates of precrash actions. To account for unobserved heterogeneity across observations, random-parameter models were further developed to allow estimates to vary across observations, which would improve the model performance [16–22]. The random-parameter MNL model is estimated by predicting the probability of one possible precrash action given a set of contributing factors:

$$\Pr(Y_1 = i) = \frac{\exp(\alpha_1^{(i)} + \beta_1^{(i)} + Z_1^{(i)}U)}{\sum_1^n \exp(\alpha_1^{(i)} + \beta_1^{(i)} + Z_1^{(i)}U)}, \quad (3)$$

where Y_1 is the response variable (i.e., precrash action); i is one of the three possible precrash actions; $\alpha_1^{(i)}$ is the constant term in estimates corresponding to precrash action i ; X

represents a vector of explanatory variables (i.e., contributing factors); $\beta_1^{(i)}$ is a set of fixed coefficients of X corresponding to precrash action i ; U is a vector of variables with a random parameter; and $Z_1^{(i)}$ is a set of random parameters of U corresponding to precrash action i .

The estimation of a MNL model produces -1 sets of coefficients, where -1 is the number of discrete choices. Each set of coefficients can be used to predict the probability of one corresponding pre-crash action, and to indicate the relationship between contextual contributing factors and a specific pre-crash action.

Equation (2) models the correlates of crash injury severity, similar to traditional injury severity analyses. Given the ordinal nature of injury severity, this study used ordered logistic modeling techniques to show how contributing factors (plus precrash behavior) are associated with crash injury severity. Again, to account for unobserved heterogeneity across crash observations, random-parameter ordered logistic models were estimated as

$$\Pr(Y_2 = c) = \frac{1}{1 + \exp(-k_c + \beta_2 X + \gamma Y_1 + Z_2 U)} - \frac{1}{1 + \exp(-k_{c-1} + \beta_2 X + \gamma Y_1 + Z_2 U)}, \quad (4)$$

where Y_2 is the crash injury severity; c is the specific level of injury severity, $c = 1 \sim 5$ possible levels of injury severity (fatal injury, incapacitating injury, nonincapacitating injury, possible injury, and no injury); k_c is the threshold value for injury severity level c , $k_0 = -\infty$ and $k_5 = +\infty$; X is a vector of contributing factors excluding precrash action; β_2 is a set of coefficients corresponding to X ; Y_1 is the precrash action, treated as an explanatory variable; γ is the coefficient of Y_1 ; U is a vector of variables with a random parameter; and Z_2 is a set of random parameters of U .

The model parameters are estimated by maximizing the likelihood. A likelihood-ratio test is performed to compare the random-parameter model with the regular logistic model that does not account for the unobserved heterogeneity. The test is done by calculating the ratio of log likelihoods of two models:

$$LR = -2 \ln \frac{LL_{\text{regular}}}{LL_{\text{random-parameter}}}, \quad (5)$$

where LL_{regular} is the estimated log likelihood of the regular model and $LL_{\text{random-parameter}}$ is the log likelihood of the

random-parameter model. The ratio is assumed to have an approximate χ^2 distribution with k degrees of freedom. k is the number of model parameters. If χ^2 is larger than the 95-percentile value in the χ^2 distribution table with k degrees of freedom, a p value is given to indicate how the random-parameter models perform in comparison with the fixed-effect models.

The unit of coefficients in both multinomial and ordered logistic models is log of the odds, showing the change of log

of the odds of one response with one unit change in one explanatory variable if other variables are held constant. To quantify the behavioral pathway (i.e., combining β_1 and γ), the marginal effects of explanatory variables are estimated based on the model coefficients. Marginal effects show the probability change of one response with one unit change in one explanatory variable if the other variables are held constant. For multinomial logistic models, marginal effects are computed as

$$\frac{\partial \Pr(Y_1 = i)}{\partial X} = \frac{\exp(f^{(i)}(X, U))(\beta_1^{(i)})' + \exp(f^{(i)}(X, U))(\sum_{j=1}^n \exp(f^{(j)}(X, U))((\beta_1^{(j)})' - (\beta_1^{(i)})'))}{[1 + \sum_{j=1}^n \exp(f^{(j)}(X, U))]^2}, \quad (6)$$

where $f^{(i)}(X, U) = \alpha_1^{(i)} + \beta_1^{(i)}X + Z_1^{(i)}U$ and $f^{(j)}(X, U) = \alpha_1^{(j)} + \beta_1^{(j)}X + Z_1^{(j)}U$. For ordered logistic models, marginal effects can be estimated as

$$\frac{\partial \Pr(Y_2 \leq c)}{\partial X} = \frac{\exp(-k_c + \beta_2 X + \gamma Y_1 + Z_2 U)}{[1 + \exp(-k_c + \beta_2 X + \gamma Y_1 + Z_2 U)]^2} \beta_2'. \quad (7)$$

The marginal effects of correlates of precrash actions and their relationships with crash injury severity can be combined as the indirect relationship between contributing factors and injury severity through precrash actions as

$$\text{indirect ME of } X \text{ on } Y_2 = (\mu_X + \text{ME of } X \text{ on } Y_1) * (\mu_{Y_1} + \text{ME of } Y_1 \text{ on } Y_2) - \mu_X * \mu_{Y_1}, \quad (8)$$

where ME represents marginal effects; μ_X is the probability of the outcomes of Y_1 (i.e., precrash actions) when X is at its base; and μ_{Y_1} is the probability of the outcomes of Y_2 (i.e., crash injury severity) when Y_1 is at its base. The calculation example is shown in the results section. Direct marginal effects of contributing factors are calculated based on equation (6) from the injury severity model. The total marginal effects of contributing factors on crash injury severity are then given by

$$\text{total ME on } Y_2 = \text{direct ME of } X \text{ on } Y_2 + \text{indirect ME of } X \text{ on } Y_2. \quad (9)$$

3. Data and Empirical Setting

The study was based on 2014–2018 crash data obtained from the Critical Analysis Reporting Environment (CARE) system developed by the Center for Advanced Public Safety at the University of Alabama. This is the primary database where crash records input directly by all traffic safety law enforcement officers in the state of Alabama are maintained. The CARE database serves as the primary source of historical crash data for research and policy decision-making in the state of Alabama. The database was queried to select crashes that occurred at four-way intersections and T-junctions.

Observations with missing or ambiguous values were omitted from the original dataset before performing the model estimation. This yielded a total of 13,910 observed

crashes at four-way intersections and 10,750 observed crashes at T-junctions. These crashes include both two-vehicle crashes and multivehicle crashes. This study used three main precrash actions (with a fourth category forming the basis for comparison): ran stop sign, failed to yield at stop sign, failed to yield at turn, and “other behaviors.” CARE distinguishes failure to yield right-of-way from ran stop sign based on whether the vehicle came to a stop. If the vehicle did not come to a stop, the “Ran” code is applied. However, if the vehicle came to a stop but then proceeded to pull out into the intersection anyway, this is classified as failed to yield. These three main precrash actions were selected because they contributed to more than 73% of the crashes, and the rest of the precrash actions each contribute to less than 5% of the crashes. Also, five crash outcomes were used: fatal injury, incapacitating injury, nonincapacitating injury, possible injury, and property damage only. The injury severity assigned to a crash corresponds to the highest severity recorded in situations where multiple severities were recorded.

The descriptive statistics of precrash actions (Tables 1 and 2) show that failure to yield right-of-way at a stop sign contributed to the highest number of crashes at both four-way intersections and T-junctions. While failure to yield right-of-way at a turn accounted for 6.9% of the crashes at four-way intersections, it was responsible for 17.8% of the crashes at T-junctions. Also, running a stop sign resulted in only 4.1% of the crashes that occurred at T-junctions but accounted for 12.3% of the crashes at four-way intersections.

In terms of crash outcomes, the side impact crashes that occurred at four-way intersections recorded a higher proportion of some injury in comparison with those that occurred at T-junctions.

Table 3 presents the descriptive statistics of the explanatory variables that were used in model estimation. Notably, a higher proportion of rural side impact crashes occurred at four-way intersections, whereas more of the urban crashes occurred at T-junctions. Similarly, a higher percentage of the crashes that happened in residential areas occurred at four-way intersections, whereas more of those that happened at shopping centers occurred at T-junctions. Overall, the distributions of the crashes by various factors are similar for both four-way intersections and T-junctions, as shown in Table 3.

4. Results and Discussion

4.1. Model Results Overview. Tables 4–7 present the model estimation results for precrash actions and crash factors and crash injury severity and crash factors for four-way intersections and T-junctions. The marginal effects of the explanatory variables are also presented in these tables. The model estimation results reveal that some of the crash factors were more associated with certain precrash factors but not others at either four-way intersections or T-junctions or both. For instance, Table 4 shows that side impact crashes that occurred under daylight conditions at four-way intersections were less likely to involve running a stop sign by 0.61% but more likely to involve failure to yield at a stop sign and failure to yield right-of-way at a turn by 4.89% and 0.07%, respectively. Similarly, under dark but lit lighting conditions, the side impact crashes were less likely to involve running a stop sign but more likely to involve failure to yield right-of-way at a stop sign or at a turn. However, under dark and unlit roadway conditions, the at-fault drivers were more likely to run a stop sign or fail to yield at a stop sign but less likely to be involved in the failure to yield right-of-way at a turn. With respect to the direct associations between various crash factors and crash outcomes, the ran stop sign variable, failed to yield at stop sign, and failed to yield at a turn variable increase the probability of fatal injury by 0.43%, 0.04%, and 0.06%, respectively. The results further show that side impact crashes that occurred at four-way intersections in residential areas and shopping centers were less likely to record injuries, but those that occurred in open country were more likely to result in some form of injury. Similarly, the relationships between crash factors and injury severity outcomes have been found to have some similarities and differences between four-way intersections and T-junctions. For instance, side impact crashes that involved running a stop sign, failure to yield at a stop sign, and failure to yield at a turn were found to be generally associated with lower injury severity outcomes. At four-way intersections, side impact crashes that occurred in open country were more likely to result in some form of injury, whereas those that occurred in residential areas and at shopping centers were less likely to result in injury outcomes. However, crashes that occurred at T-junctions were more likely to

record some form of injury at open country and shopping centers but less likely to result in injury in residential areas. The results further show some similarities and differences in how various factors are associated with precrash actions and injury severities between four-way intersections and T-junctions. For instance, side impact crashes that occurred at T-junctions in the open country, residential areas, and shopping centers were more likely to involve failure to yield at a turn, whereas the crashes that occurred at four-way intersections were less likely to involve failure to yield at a turn in the open country and shopping centers but not residential areas. To have a better understanding of how various crash factors are associated with side impact crash outcomes when drivers engage in certain precrash actions at four-way intersections and T-junctions, the total marginal effects are computed through the behavioral pathways.

4.2. Four-Way Intersection Behavioral Pathway. The marginal effect of a variable (e.g., crash in the urban area) measures the change in the percentage point of the probability of one response outcome (e.g., a particular precrash behavior—ran stop sign or *K*-fatal injury) compared to the probability of this outcome when this variable is set at its base (e.g., curved roadway or vertical roadway alignment). The four-way intersection injury severity model provides direct marginal effects (ME) of contributing factors (e.g., precrash behaviors) on crash injury severity, while the random-parameter multinomial precrash action model estimates the marginal effects of contributing factors on precrash behaviors. If some of the precrash behaviors are significantly correlated with crash injury severity, then some of the contributing factors (e.g., speeding and DUI) might introduce indirect marginal effects through these precrash behaviors that are statistically significant in the injury severity model.

Table 8 presents the total ME results of four-way intersection behavioral pathway analysis by synthesizing and quantifying the direct and indirect MEs of contributing factors on crash injury severity. MEs based on insignificant model estimations (p value > 0.1) are omitted, and their MEs are assumed to be 0. In the injury severity model, the estimates of “ran stop sign” and “failed to yield at stop sign” are statistically significant (p value ≤ 0.1), but not “failed to yield at turn.” Thus, the total MEs are quantified through both precrash behaviors “ran stop sign” and “failed to yield at stop sign.” Therefore, in Table 8, Y_1 refers to the precrash behaviors of at-fault driver “ran stop sign” and “failed to yield at stop sign,” indicating two significant behavioral pathways. The contributing factors in the injury severity model have their associated MEs on each level of crash injury severity, and Table 4 clearly indicates that MEs on “O: property damage only” have opposite signs compared to MEs on other four higher levels of injury severity (i.e., “C: possible injury,” “B: nonincapacitating injury,” “A: incapacitating injury,” and “K: fatal injury”). This study combines the MEs of four injury severity levels, which are considered as the direct MEs of contributing factors on the probability of *KABC* injury. The notes in Table 8 present more details regarding other notations and abbreviations.

TABLE 1: Descriptive statistics of precrash action and injury severity of four-way intersection crashes.

Variable		Frequency	Percent
Precrash action	Ran stop sign	1704	12.3
	Failed to yield at stop sign	8407	60.4
	Failed to yield at turn	964	6.9
	Others	2835	20.4
Crash injury severity	O: property damage only	8907	64.0
	C: possible injury	1894	13.6
	B: nonincapacitating injury	1858	13.4
	A: incapacitating injury	1137	8.2
	K: fatal injury	114	0.8

TABLE 2: Descriptive statistics of precrash action and injury severity of T-junction crashes.

Variable		Frequency	Percent
Precrash action	Ran stop sign	442	4.1
	Failed to yield at stop sign	5584	51.9
	Failed to yield at turn	1918	17.8
	Others	2806	26.1
Crash injury severity	O: property damage only	7447	69.3
	C: possible injury	1362	12.7
	B: nonincapacitating injury	1175	10.9
	A: incapacitating injury	697	6.5
	K: fatal injury	69	0.6

TABLE 3: Descriptive statistics of variables used in model estimation.

Variable	Four-way intersection		T-junction	
	Frequency	Percent (%)	Frequency	Percent (%)
<i>Crash location</i>				
Rural	3756	27.0	2593	24.1
Urban	10,154	73.0	8157	75.9
<i>Crash location</i>				
Other crash locations	409	2.9	437	4.1
Open country	4004	28.8	2765	25.7
Residential area	4378	31.5	3055	28.4
Shopping center	5119	36.8	4493	41.8
<i>Roadway condition</i>				
Other roadway conditions	70	0.5	57	0.5
Dry roadway condition	12,046	86.6	9127	84.9
Wet roadway condition	1794	12.9	1566	14.6
<i>Lighting condition</i>				
Other lighting conditions	536	3.9	443	4.1
Daylight	11,292	81.2	8694	80.9
Dark without lighting	1359	9.8	1046	9.7
Dark with lighting	723	5.2	567	5.3
<i>Roadway curvature and grade</i>				
Straight level road	11,898	85.5	8352	77.7
Straight road with grade	1781	12.8	1891	17.6
Curved roadway	231	1.7	507	4.7
<i>Turn lane</i>				
No turn lane	11,062	79.5	7497	69.7
Turn lane present	2848	20.5	3253	30.3
<i>Traffic control device</i>				

TABLE 3: Continued.

Variable	Four-way intersection		T-junction	
	Frequency	Percent (%)	Frequency	Percent (%)
Functional	10,935	78.6	7067	65.7
Not functional	2975	21.4	3683	34.3
<i>Contributing factor</i>				
Speeding	264	1.9	248	2.3
DUI	214	1.5	193	1.8
<i>At-fault driver gender</i>				
Female	7163	51.5	5327	49.6
Male	6747	48.5	5423	50.4
<i>At-fault driver age</i>				
Other age groups	1551	11.2	1128	10.5
Less than 22	3004	21.6	2584	24.0
Between 22 and 31	2917	21.0	2215	20.6
Between 32 and 41	1868	13.4	1374	12.8
Between 42 and 51	1515	10.9	1205	11.2
Between 52 and 61	1593	11.5	1205	11.2
Between 62 and 71	1462	10.5	1039	9.7
<i>Point of initial contact of the causal vehicle</i>				
Others	2576	18.5	2103	19.6
Front passenger side	1174	8.4	1035	9.6
Back passenger side	1035	7.4	798	7.4
Bumper	6496	46.7	4926	45.8
Driver door	1395	10.0	936	8.7
Passenger side behind the driver	1234	8.9	952	8.9
<i>Causal vehicle type</i>				
Other vehicles	921	6.6	774	7.2
Passenger car	7358	52.9	5812	54.1
Pickup	2498	18.0	1853	17.2
SUV	3133	22.5	2311	21.5
<i>Second vehicle type</i>				
Other vehicles	1256	9.0	1091	10.1
Passenger car	7036	50.6	5481	51.0
Pickup	2658	19.1	1997	18.6
SUV	2960	21.3	2181	20.3

TABLE 4: Random-parameter multinomial logit model of precrash actions for side impact crashes at four-way intersections.

Y ₁ = precrash action (base: other behaviors)		Ran stop sign		Failed to yield at stop sign		Failed to yield at turn	
Variables and description		β	ME	β	ME	β	ME
Constant		-1.648	***	-0.134		-4.028	***
Urban	Yes			0.067		-2.06%	
Crash location	Open country	0.013		0.03%		0.096	-0.07%
	Residential area	0.734	***	2.61		-0.523	**
	Shopping center	-0.217	-0.47			0.145	-0.15%
Roadway condition	Dry					1.860	**
	Wet					1.874	**
Lighting condition	Daylight	-0.096		-0.61%	0.423	***	4.89%
	Dark without lighting	0.598	***	0.37%	0.175		0.16%
	Dark with lighting	-0.178	-0.15%	0.037		0.05%	-0.12%
Roadway geometry	Straight level road	1.141	***	12.26%	1.472	***	17.96%
	Straight road with grade	1.345	***	1.65%	1.172	***	2.28%

TABLE 4: Continued.

Y_1 = precrash action (base: other behaviors)		Ran stop sign		Failed to yield at stop sign		Failed to yield at turn			
Variables and description		β	ME	β	ME	β	ME		
Turn lane present	Yes	-1.495	***	-1.38%	-1.199	***	-3.54%		
No functioning traffic control	Yes	-1.559	***	-1.89%	-2.258	***	-6.66%	1.085	*** -1.08%
At-fault driver_speeding	Yes				-4.024	***	-0.37%	-4.219	*** 0.00%
At-fault driver_DUI	Yes	-1.899	***	-0.23%	-3.734	***	-0.46%	-2.793	*** 0.01%
Gender	Male				-0.230	***	-1.64%		
21 years old or younger		0.197		0.37%	0.029		0.09%		
Causal driver age	22~31 years old	0.269	**	0.53%	-0.234	**	-0.72%		
	32~41 years old	0.161		0.19%	-0.127		-0.25%		
	42~51 years old	-0.209		-0.17%	-0.393		-0.63%		
	52~61 years old	-0.105		-0.09%	-0.080		-0.13%		
62~71 years old		-0.051	-0.04%	0.052		0.08%			
Point of impact	Front passenger side	0.601	***	0.55%	0.266	**	0.33%	-0.724	*** 0.04%
	Back passenger side	0.362	**	0.27%	0.095		0.11%	-0.444	* 0.03%
	Bumper	0.160		0.51%	0.708	***	4.57%	1.003	*** -1.46%
	Driver door	0.275	**	0.25%	0.209	*	0.31%	0.435	*** -0.09%
Passenger side behind the driver		0.095		0.07%		0.15%	0.117		-0.02%
Causal vehicle type	Passenger car				0.372	***	2.81%	0.342	** -0.42%
	Pickup				0.314	***	0.85%	0.124	-0.05%
SUV				0.489	***	1.26%	0.291	*	-0.14%
Noncausal vehicle type	Passenger car							-0.089	0.10%
	Pickup							-0.138	0.06%
SUV							-0.296	**	0.12%
Scale parameters for random parameters in precrash actions	Straight level road	1.137	***						
	Urban				1.793	***			
Causal vehicle: SUV				0.721	*				
Summary statistics	Number of observations					13,910			
	Log likelihood at zero L (0)					-19,283.355			
	Log likelihood at convergence L (β)					-12,703.043			
	Pseudo-R2					0.341			
	Likelihood-ratio test (vs. regular multinomial logit)					Prob. = 0.000			
	AIC					25,556.1			

Significance at ***1%; **5%; *10% levels.

TABLE 5: Random-parameter ordered logit model of injury severity for side impact crashes at four-way intersections.

Y_2 = four-way intersection crash injury severity		Model estimates			Marginal effects			
Variables and description		β	O	C	B	A	K	
Constant		0.042						
Precrash actions (base: other behaviors)	Ran stop sign	0.718	***	-17.00%	4.48%	7.37%	4.73%	0.43%
	Failed to yield at stop sign	0.092	*	-2.03%	0.67%	0.85%	0.47%	0.04%
	Failed to yield at turn	0.123		-2.77%	0.88%	1.16%	0.66%	0.06%
Urban	Yes	-0.524	***	12.01%	-3.62%	-5.10%	-3.02%	-0.27%

TABLE 5: Continued.

Y_2 = four-way intersection crash injury severity		Model estimates		Marginal effects				
Variables and description		β	O	C	B	A	K	
Crash location (base: other crash locations)	Open country	0.286	* *	−6.45%	2.05%	2.72%	1.56%	0.14%
	Residential area	−0.240	* *	−1.78%	−2.17%	−1.20%	−0.10%	
	Shopping center	−0.213	*	−1.57%	−1.94%	−1.07%	−0.09%	
Roadway geometry (base: curved roadway)	Straight level road	0.143	* * *	−3.24%	1.03%	1.36%	0.78%	0.07%
	Straight road with grade	−0.086		1.89%	−0.64%	−0.78%	−0.43%	−0.04%
Turn lane present	Yes	0.103	* *	−2.31%	0.75%	0.97%	0.55%	0.05%
At-fault driver_speeding	Yes	0.775	* * *	−18.66%	4.42%	8.18%	5.55%	0.51%
At-fault driver_DUI	Yes	1.048	* * *	−25.39%	4.95%	11.21%	8.43%	0.80%
Gender	Male	−0.167	* * *	3.71%	−1.23%	−1.55%	−0.86%	−0.07%
	21 years old or younger	−0.263	* * *	5.68%	−1.96%	−2.34%	−1.27%	−0.11%
Causal driver age	22~31 years old	−0.218	* * *	4.73%	−1.62%	−1.95%	−1.07%	−0.09%
	32~41 years old	−0.259	* * *	5.56%	−1.93%	−2.29%	−1.23%	−0.11%
	42~51 years old	−0.242	* * *	5.19%	−1.81%	−2.13%	−1.15%	−0.10%
	52~61 years old	−0.167	* *	3.62%	−1.24%	−1.49%	−0.82%	−0.07%
	62~71 years old	−0.176	* *	3.82%	−1.31%	−1.58%	−0.86%	−0.07%
	Front passenger side	−0.356	* * *	7.47%	−2.67%	−3.05%	−1.62%	−0.14%
Point of impact	Back passenger side	−0.965	* * *	17.93%	−7.00%	−7.08%	−3.55%	−0.30%
	Bumper	0.755	* * *	−16.76%	5.33%	7.03%	4.04%	0.35%
	Driver door	0.412	* * *	−9.57%	2.80%	4.09%	2.46%	0.22%
Passenger side behind the driver	−0.633	* * *	12.64%	−4.72%	−5.08%	−2.63%	−0.22%	
	Passenger car	−0.138	*	3.06%	−1.01%	−1.28%	−0.71%	−0.06%
Causal vehicle type	Pickup	−0.209	* *	4.53%	−1.55%	−1.87%	−1.02%	−0.09%
	SUV	−0.112		2.47%	−0.83%	−1.02%	−0.57%	−0.05%
	Passenger car	−0.330	* * *	7.32%	−2.40%	−3.05%	−1.71%	−0.15%
Noncausal vehicle type	Pickup	−0.497	* * *	10.40%	−3.71%	−4.24%	−2.26%	−0.19%
	SUV	−0.289		0.819	6.21%	−2.15%	−2.56%	−1.39%
Scale parameters for random parameters	Failed to yield at stop sign	0.523	* * *					
	Male	0.950	* * *					
Mu(01)		0.819	* * *					
Mu(02)		2.003	* * *					
Mu(03)		4.588	* * *					
Summary statistics	Number of observations				13,910			
	Log likelihood at zero $L(0)$				−14,882.277			
	Log likelihood at convergence $L(\beta)$				−14,116.792			
	Pseudo- R^2				0.051			
	Likelihood-ratio test (vs. regular ordered logit)				Prob. = 0.000			
	AIC				28,305.6			

Together, equations (8) and (9) formulate the process to quantitatively combine direct and indirect MEs of contributing factors. Figure 2 illustrates how the total ME of the straight level roadway section at four-way intersections is calculated to be 18.61%, relative to intersections located at curved roadway sections. Other variables can be calculated based on the same logical procedure.

The behavioral pathway analysis indeed reveals extra implications besides the one generated from the traditional injury severity model. For example, crashes that occurred at a four-way intersection with the straight and flat roadway (vs. curved roadway) are 3.24% more likely to result in some form of injury regardless of the at-fault driver's precrash behavior. However, by adding the indirect effects through the precrash behaviors (e.g., ran stop sign and failed to yield

TABLE 6: Random-parameter multinomial logit model of precrash actions for side impact crashes at T-junctions.

Y_1 = precrash action (base: other behaviors)		Ran stop sign		Failed to yield at stop sign		Failed to yield at turn	
Variables and description		β	ME	β	ME	β	ME
Constant		-2.349	***		0.386		-2.766 ***
Urban	Yes				0.532 ***		4.06%
Crash location	Open country				0.260		1.10%
	Residential area				-0.045		-0.17%
	Shopping center				0.564 ***		3.00%
Roadway condition	Dry						1.646 ***
	Wet						1.501 **
Lighting condition	Daylight	-0.179		-0.43%			
	Dark without lighting	-1.489		0.42%			
	Dark with lighting	0.175		0.06%			
Roadway geometry	Straight level road	1.578 ***	3.66%	1.107 ***	11.82%		
	Straight road with grade	1.695 ***	1.11%	1.018 ***	2.56%		
Turn lane present	Yes	-2.718	0.819	-0.01%	-0.479	0.819	-1.90%
No functioning traffic control	Yes	-2.027	2.003	-1.04%	-2.959	2.003	-11.45%
At-fault driver_speeding	Yes				-4.840	4.588	-0.31%
At-fault driver_DUI	Yes	-0.894 ***	-0.07%	-3.952 ***	-0.40%	-2.146 ***	-0.20%
Gender	Male	-0.696	1.53%				
At-fault driver age	21 years old or younger			-0.082	-0.27%	-0.097	-0.26%
	22~31 years old			-0.412 ***	-1.17%	-0.203 *	-0.49%
	32~41 years old			-0.558 ***	-1.00%	-0.336 ***	-0.49%
	42~51 years old			-0.372 ***	-0.58%	-0.187	-0.26%
	52~61 years old			-0.444 ***	-0.71%	-0.354 ***	-0.45%
	62~71 years old			-0.245 *	-0.33%	-0.105	-0.12%
Point of impact	Front passenger side	0.665 ***	0.32%			-0.542 ***	-0.33%
	Back passenger side	0.314	0.09%			-0.714 ***	-0.29%
	Bumper	-0.168	-0.18%			0.820 ***	5.55%
	Driver door	0.284	0.09%			0.173	0.18%
	Passenger side behind the driver	0.013	0.00%			0.067	0.06%
Causal vehicle type	Passenger car			0.248 **	1.82%		
	Pickup			0.033	0.08%		
	SUV			0.157	0.47%		
Noncausal vehicle type	Passenger car	-0.454 ***	-0.63%				
	Pickup	-0.127	-0.09%				
	SUV	-0.389 *	-0.23%				
Scale parameters for random parameters in precrash actions	Dark without lighting	3.364	*				
	Turn lane present	2.046	***				
	Male	1.694	***				
Urban				1.876	***		
Summary statistics	Number of observations				10,750		
	Log likelihood at zero L (0)				-12,143.177		
	Log likelihood at convergence L (β)				-10,184.482		
	Pseudo- R^2				0.161		
	Likelihood-ratio test (vs. regular multinomial logit)				Prob. = 0.000		
	AIC				20,485.0		

at stop sign), this type of crash is associated with an even greater likelihood of exacerbated injury severity (an increase by 18.61 percentage points). This increased positive correlation also applies to some other contributing factors such as “turn lane at present,” “at-fault driver speeding,” “at-fault driver-DUI,” and “collision impact point at bumpers or driver door.”

On the contrary, some other factors are negatively associated with injury severity in the injury severity model. However, their indirect MEs are positive, meaning their association magnitudes with injury severity are reduced (e.g., at-fault male driver, causal vehicle driver aged 22 to 31 years old, collision impact point at the front and back

TABLE 7: Random-parameter ordered logit model of injury severity for side impact crashes at T-junctions.

Y2 = T-junction crash injury severity		Model estimates			Marginal effects			
Variables and description		β	O	C	B	A	K	
Constant		0.128						
Precrash actions (base: other behaviors)	Ran stop sign	0.844	***	-19.07%	5.85%	7.73%	5.02%	0.48%
	Failed to yield at stop sign	0.208	***	-4.09%	1.59%	1.56%	0.86%	0.08%
	Failed to yield at turn	0.262	***	-5.37%	2.00%	2.08%	1.18%	0.11%
Urban	Yes	-0.442	***	9.14%	-3.35%	-3.56%	-2.05%	-0.19%
Crash location (base: other crash locations)	Open country	0.220	*	-4.44%	1.68%	1.71%	0.96%	0.09%
	Residential area	-0.043		0.85%	-0.33%	-0.32%	-0.18%	-0.02%
	Shopping center	0.092		-1.82%	0.70%	0.39%	0.04%	
Lighting condition (base: other lighting conditions)	Daylight	-0.196	*	3.96%	-1.50%	-1.53%	-0.86%	-0.08%
	Dark without lighting	-0.039		0.76%	-0.30%	-0.29%	-0.16%	-0.01%
	Dark with lighting	0.089		-1.79%	0.69%	0.39%	0.04%	
Turn lane present	Yes	0.183	***	-3.67%	1.40%	1.41%	0.79%	0.07%
At-fault driver_speeding	Yes	0.916	***	-20.94%	6.16%	8.54%	5.69%	0.55%
At-fault driver_DUI	Yes	0.919	***	-21.03%	6.16%	8.58%	5.74%	0.55%
Gender	Male	-0.250	***	4.93%	-1.91%	-1.88%	-1.04%	-0.09%
At-fault age	21 years old or younger	-0.186	**	3.59%	-1.42%	-1.36%	-0.74%	-0.07%
	22~31 years old	-0.190	**	3.64%	-1.44%	-1.38%	-0.75%	-0.07%
	32~41 years old	-0.061		1.20%	-0.47%	-0.46%	-0.25%	-0.02%
	42~51 years old	-0.045		0.87%	-0.34%	-0.33%	-0.18%	-0.02%
	52~61 years old	-0.176	*	3.36%	-1.34%	-1.27%	-0.69%	-0.06%
	62~71 years old	-0.151		2.89%	-1.15%	-1.09%	-0.59%	-0.05%
Point of impact	Front passenger side	-0.209	**	3.96%	-1.59%	-1.49%	-0.81%	-0.07%
	Back passenger side	-0.613	***	10.59%	-4.46%	-3.91%	-2.04%	-0.18%
	Bumper	1.013	***	-20.19%	7.45%	7.82%	4.51%	0.41%
	Driver door	0.003		-0.07%	0.03%	0.03%	0.02%	0.00%
Passenger side behind the driver	-1.012	***	16.01%	-6.94%	-5.83%	-2.98%	-0.26%	
Causal vehicle type	Passenger car	-0.435	***	8.64%	-3.31%	-3.31%	-1.85%	-0.17%
	Pickup	-0.590	***	10.57%	-4.36%	-3.94%	-2.09%	-0.19%
	SUV	-0.528	***	9.67%	-3.94%	-3.62%	-1.94%	-0.17%
Noncausal vehicle type	Passenger car	-0.599	***	11.83%	-4.53%	-4.53%	-2.54%	-0.23%
	Pickup	-0.871	***	14.93%	-6.25%	-5.52%	-2.90%	-0.26%
	SUV	-0.629	***	11.30%	-4.65%	-4.22%	-2.24%	-0.20%
Scale parameters for random parameters	Failed to yield at stop sign	0.097	***					
	Male	0.869	***					
Mu(01)		0.819	***					
Mu(02)		2.003	***					
Mu(03)		4.588	***					
Summary statistics	Number of observations				10,750			
	Log likelihood at zero $L(0)$				-10,403.858			
	Log likelihood at convergence $L(\beta)$				-9,747.577			
	Pseudo- R^2				0.063			
	Likelihood-ratio test (vs. regular ordered logit)				Prob. = 0.000			
	AIC				19,569.2			

TABLE 8: Behavioral pathway analysis of four-way intersections with direct and indirect marginal effects.

Variable (X)		Direct ME on Y_2	μ_X for Y_1 RSS	μ_X for Y_1 FYSS	ME on Y_1 RSS	ME on Y_1 FYSS	μ_{Y_1} for Y_2	ME of Y_1 RSS on Y_2	ME of Y_1 FYSS on Y_2	Indirect ME on Y_2 through RSS	Indirect ME on Y_2 through FYSS	Total ME on Y_2
Urban	Yes	-12.01%					31.75	17.00	2.03	0.00	0.00%	-12.01%
Crash location (base: other crash locations)	Open country	6.45%					31.75	17.00	2.03	0.00	0.00%	6.45%
	Residential area	-5.25%	10.51		2.61%		31.75	17.00	2.03	3.06	0.00%	-2.19%
Shopping center	-4.67%					31.75	17.00	2.03	0.00	0.00%	-4.67%	
Roadway condition	Dry						31.75	17.00	2.03	0.00	0.00%	0.00%
	Wet					31.75	17.00	2.03	0.00	0.00%	0.00%	
Lighting condition	Daylight			51.68		4.89%	31.75	17.00	2.03	0.00	2.70%	2.70%
	Dark without lighting		14.37		0.37%		31.75	17.00	2.03	2.62	0.00%	2.62%
	Dark with lighting					31.75	17.00	2.03	0.00	0.00%	0.00%	
Roadway geometry (base: curved roadway)	Straight level road	3.24%	12.26	61.44	12.26%	17.96%	31.75	17.00	2.03	8.06	7.31%	18.61%
	Straight road with grade	12.26	61.44	1.65%	2.28%	31.75	17.00	2.03	2.89	2.02%	4.91%	
Turn lane present	Yes	2.31%	13.98	64.63	-1.38%	-3.54%	31.75	17.00	2.03	1.70	0.12%	4.13%
No functioning traffic control	Yes		13.62	68.17	-1.89%	-6.66%	31.75	17.00	2.03	1.39	-0.87%	0.53%
At-fault driver_speeding	Yes	18.66%		61.48		-0.37%	31.75	17.00	2.03	0.00	1.12%	19.79%
At-fault driver_DUI	Yes	25.39%	12.27	61.19	-0.23%	-0.46%	31.75	17.00	2.03	1.97	1.09%	28.45%
Gender	Male	-3.71%		62.61		-1.64%	31.75	17.00	2.03	0.00	0.72%	-2.99%
At-fault driver age	21 years old or younger	-5.68%					31.75	17.00	2.03	0.00	0.00%	-5.68%
	22~31 years old	-4.73%	10.90	64.54	0.53%	-0.72%	31.75	17.00	2.03	2.11	1.07%	-1.55%
	32~41 years old	-5.56%					31.75	17.00	2.03	0.00	0.00%	-5.56%
	42~51 years old	-5.19%					31.75	17.00	2.03	0.00	0.00%	-5.19%
	52~61 years old	-3.62%					31.75	17.00	2.03	0.00	0.00%	-3.62%
62~71 years old	-3.82%					31.75	17.00	2.03	0.00	0.00%	-3.82%	
Point of impact	Front passenger side	-7.47%	13.20	55.94	0.55%	0.33%	31.75	17.00	2.03	2.51	1.25%	-3.71%
	Back passenger side	-17.93%	13.20		0.27%		31.75	17.00	2.03	2.38	0.00%	-15.55%
	Bumper	16.76%		55.94		4.57%	31.75	17.00	2.03	0.00	2.68%	19.43%
	Driver door	9.57%	13.20	55.94	0.25%	0.31%	31.75	17.00	2.03	2.37	1.24%	13.18%
Passenger side behind the driver	-12.64%					31.75	17.00	2.03	0.00	0.00%	-12.64%	

TABLE 8: Continued.

Variable (X)		Direct ME on Y_2	μ_X for Y_1 RSS	μ_X for Y_1 FYSS	ME on Y_1 RSS	ME on Y_1 FYSS	μ_{Y_1} for Y_2	ME of Y_1 RSS on Y_2	ME of Y_1 FYSS on Y_2	Indirect ME on Y_2 through RSS	Indirect ME on Y_2 through FYSS	Total ME on Y_2
Causal vehicle type	Passenger car	-3.06%		55.27		2.81%	31.75	17.00	2.03	0.00	2.07%	-0.99%
	Pickup	-4.53%		55.27	0.85%	31.75	17.00	2.03	0.00	1.41%	-3.12%	
	SUV			55.27	1.26%	31.75	17.00	2.03	0.00	1.55%	1.55%	
Noncausal vehicle type	Passenger car	-7.31%					31.75	17.00	2.03	0.00	0.00%	-7.31%
	Pickup	-10.40%					31.75	17.00	2.03	0.00	0.00%	-10.40%
	SUV	-6.21%					31.75	17.00	2.03	0.00	0.00%	-6.21%

Notes: Y_2 is the KABC injury; Y_1 is one of "ran stop sign (RSS)" or "failed to yield at stop sign (FYSS)"; μ_X is the probability of Y_1 when contributing factor X is at the base; μ_{Y_1} is the probability of KABC injury when precrash behavior Y_1 is at the base (i.e., "other behaviors"); indirect ME of X on $Y_2 = (\mu_X + \text{ME of } X \text{ on } Y_1) * (\mu_{Y_1} + \text{ME of } Y_1 \text{ on } Y_2) - \mu_X * \mu_{Y_1}$; total ME on $Y_2 = \text{direct ME of } X \text{ on } Y_2 + \text{indirect ME of } X \text{ on } Y_2$; some cells are empty due to the insignificant estimates (p value > 0.1) from the models.

FIGURE 2: The logical procedure to calculate the total marginal effects based on the direct marginal effects through the injury severity model and the indirect marginal effects through the precrash behavior model.

TABLE 9: Continued.

Variable (X)	Direct ME on Y_2	μ_X for Y_1 RSS (%)	μ_X for Y_1 FYSS (%)	μ_X for Y_1 FYT (%)	ME on Y_1 RSS	ME on Y_1 FYSS	ME on Y_1 FYT	μ_{Y_1} for Y_2 (%)	ME of Y_1 RSS on Y_2 (%)	ME of Y_1 FYSS on Y_2 (%)	ME of Y_1 FYT on Y_2 (%)	Indirect ME on Y_2 through RSS (%)	Indirect ME on Y_2 through FYSS	Indirect ME on Y_2 through FYT (%)	Total ME on Y_2	
Point of impact	Front passenger side	-3.96%	4.28		14.17	0.32%		-0.33%	25.52	19.07	4.09	5.37	0.96	0.00%	0.66	-2.34%
	Back passenger side	-10.59%			14.17			-0.29%	25.52	19.07	4.09	5.37	0.00	0.00%	0.67	-9.92%
	Bumper	20.19%			14.17			5.55%	25.52	19.07	4.09	5.37	0.00	0.00%	2.47	22.66%
	Driver door								25.52	19.07	4.09	5.37	0.00	0.00%	0.00	0.00%
	Passenger side behind the driver	-16.01%							25.52	19.07	4.09	5.37	0.00	0.00%	0.00	-16.01%
Causal vehicle type	Passenger car	-8.64%	48.32			1.82%			25.52	19.07	4.09	5.37	0.00	2.52%	0.00	-6.12%
	Pickup	-10.57%							25.52	19.07	4.09	5.37	0.00	0.00%	0.00	-10.57%
	SUV	-9.67%							25.52	19.07	4.09	5.37	0.00	0.00%	0.00	-9.67%
Noncausal vehicle type	Passenger car	-11.83%	5.59			-0.63%			25.52	19.07	4.09	5.37	0.79	0.00%	0.00	-11.04%
	Pickup	-14.93%							25.52	19.07	4.09	5.37	0.00	0.00%	0.00	-14.93%
	SUV	-11.30%	5.59			-0.23%			25.52	19.07	4.09	5.37	0.96	0.00%	0.00	-10.34%

Notes: Y_2 is the KABC injury; Y_1 is one of "ran stop sign (RSS)," "failed to yield at stop sign (FYSS)," or "failed to yield at turn (FYT)"; μ_X is the probability of Y_1 when contributing factor X is at the base; μ_{Y_1} is the probability of KABC injury when precrash behavior Y_1 is at the base (i.e., "other behaviors"); indirect ME of X on $Y_2 = (\mu_X + \text{ME of } X \text{ on } Y_1) * (\mu_{Y_1} + \text{ME of } Y_1 \text{ on } Y_2) - \mu_X * \mu_{Y_1}$; total ME on $Y_2 = \text{direct ME of } X \text{ on } Y_2 + \text{indirect ME of } X \text{ on } Y_2$; some cells are empty due to the insignificant estimates (p value > 0.1) from the models.

passenger side, and causal vehicle type—passenger car or pickup). Noticeably, some variables, such as lighting condition—dark and unlit, are not statistically significantly correlated with injury severity, but they are significantly associated with dangerous precrash behaviors (e.g., ran stop sign). Thus, the behavioral pathway is important in the sense to highlight these contributing factors that are indirectly correlated to crash injury severity at four-way intersections.

4.3. T-Junction Behavioral Pathway. The behavioral pathway analysis is applied to the T-junction side impact crashes based on the same quantifying process as the four-way intersection (see Table 9). Three significant behavioral pathways have been identified through “ran stop sign,” “failed to yield at the turn,” and “failed to yield at stop sign.” In addition to the findings from the traditional injury severity model, the behavioral pathway analysis provides extra implications in terms of the indirect and total marginal effects. For example, if the crash occurred at a T-Junction with a turn lane, then the likelihood of the crash to be an injury crash is increased by 6.36% if the indirect effect is considered through the precrash behaviors (e.g., failed to yield at the turn, ran stop sign, and failed to yield at the stop sign), which is much greater than the 3.68% points’ increase of the marginal effects without considering behavioral pathways. This kind of stronger positive correlation with injury severity at T-junctions also applies to some other contributing factors including open country crash location, at-fault driver speeding, at-fault driver driving under the influence, and collision impact point at bumpers.

Some other factors were found to be negatively associated with injury severity, but their indirect MEs are positive, indicating that their correlation magnitudes with injury severity are lessened (e.g., urban area, at-fault male driver, at-fault drivers aged 22 to 31 and 52 to 61 years old, collision impact point—front and back passenger sides, causal vehicle type—passenger car, and noncausal vehicle type—passenger car or SUV). It should be noted that some variables, such as straight level road and dry or wet roadway condition, are not statistically significantly correlated with injury severity, but they are significantly associated with dangerous precrash behaviors (e.g., ran stop sign or failed to yield at turn), which again confirmed the usefulness and benefit of applying the pathway analysis to investigate the crash injury outcomes.

5. Conclusions

This study performs a behavioral path analysis to understand the factors that influence driver behaviors at unsignalized intersections and how these factors influence the severity of side impact crashes. Models are built to segment the correlates of precrash actions and side impact crash severity by quantifying the indirect marginal effects of various crash contributing factors through specific traffic violation behaviors at unsignalized four-way intersections and T-junctions. The results are useful in understanding how precrash actions and other crash factors influence the severity of side impact crash outcomes. The study was based on

2009–2016 crash data obtained from the Critical Analysis Reporting Environment (CARE) system developed by the Center for Advanced Public Safety at the University of Alabama.

By developing a random-parameter logit model, this paper unravels significant associations between precrash actions and a number of crash contributing factors (e.g., lighting conditions and land use). Additionally, random-parameter ordered logit models were developed to investigate the contributing factors that are directly associated with side impact crash outcomes. Through behavioral pathway analysis, the marginal effects of the contributing factors on precrash actions and crash injury severity were combined to show how the behavioral pathways influence injury severities. For example, the total marginal effect of straight and flat roadways (compared with curved roadway) on four-way intersection crash injury severity increases from 3.24% to 18.61% by adding the indirect marginal effect through the precrash behaviors (e.g., ran stop sign and failed to yield at stop sign). The findings from this study contribute to the larger body of safety literature on understanding the associations between crash contributing factors and crash outcomes by unraveling complex relationships in the role of precrash actions.

This study attempted to investigate the behavioral pathways through which side impact crashes occur at unsignalized intersections and focused on four-way intersections and T-junctions in Alabama. For the purpose of this study, only three precrash actions were considered. However, it is possible that these precrash actions may not be the only ones that significantly influence crash outcomes at these intersections. Besides, the assignment of fault for these crashes solely depends on the reporting police officer, and limited information is presented regarding the drivers not at fault. Also, lower injury crashes do not go through rigorous investigation to identify which driver is truly at fault. As such, this could bias the research findings considering that lower injury crashes made up the highest proportion of the data used. In spite of these limitations, the findings of this study are consistent with previous findings and provide adequate information for informed decision-making to reduce the incidence and severity of side impact crashes at unsignalized intersections.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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