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Examining traffic crash injury severity at unsignalized intersections

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ABSTRACT

Introduction: This study presents multiple approaches to the analysis of crash injury severity at three- and four-legged unsignalized intersections in the state of Florida from 2003 until 2006. An extensive data collection process was conducted for this study. *Method:* The dataset used in the analysis included 2,043 unsignalized intersections in six counties in the state of Florida. For the scope of this study, there were three approaches explored. The first approach dealt with the five injury levels, and an ordered probit model was fitted. The second approach was an aggregated one, and dealt with only the severe versus non-severe crash levels, and a binary probit model was used. The third approach dealt with fitting a nested logit model. Results from the three fitted approaches were shown and discussed, and a comparison between the three approaches was shown. *Results:* Several important factors affecting crash severity at unsignalized intersections were identified. These include the traffic volume on the major approach, and the number of through lanes on the minor approach (surrogate measure for traffic volume), and among the geometric factors, the upstream and downstream distance to the nearest signalized intersection, left and right shoulder width, number of left turn movements on the minor approach, and number of right and left turn lanes on the major approach. As for driver factors, young and very young at-fault drivers were associated with the least fatal probability compared to other age groups. *Impact on industry:* The analysis identified some countermeasures to reduce injury severity at unsignalized intersections. The spatial covariates showed the importance of including safety awareness campaigns for speeding enforcement. Also, having a 90-degree intersection design is the most appropriate safety design for reducing severity. Moreover, the assurance of marking stop lines at unsignalized intersections is very essential.

1. Introduction

Intersections, constituting some of the most representative features of any transportation system, are considered to be those entities with a complex nature. For this reason, a thorough understanding of them needs to be achieved in order to design them in the best possible manner. According to the Florida Department of Transportation (2006), almost one in every four fatal crashes occurs at or near an intersection. In 2004, Florida led the nation in intersection fatalities, where 30% of fatalities occurred at intersections. One of the frequent types of intersections is unsignalized intersections, which include intersections with stop control, yield control, and no traffic control. Identifying those geometric and traffic factors leading to severe crashes at unsignalized intersections is an essential task of traffic safety analysts. This helps identify appropriate countermeasures for any observed safety deficiency. Crash injury severity is considered the most serious crash outcome, which is the core of this paper.

This study focuses on analyzing crash injury severity with respect to its inherently ordered nature, not its frequency. The most common statistical frameworks for analyzing crash severity are multinomial logit, ordered probit, and nested logit models (Abdel-Aty, 2003; Chang & Mannering, 1999; Savolainen & Mannering, 2007). The use of the ordered probit model formulation in this study was deemed more beneficial than multinomial logit and probit models because while accounting for the categorical nature of the dependent variable, they do not account for the ordinal nature of the modeled response categories (Duncan, Khattak, & Council, 1998), which can be a serious issue.

In this study, crash injury severity is analyzed at 1,547 three-legged and 496 four-legged unsignalized intersections (i.e., a total of 2,043 intersections, including stop-controlled, yield-controlled and non-controlled intersections) in the state of Florida in 4 years (from 2003 to 2006) using the ordered probit, binary probit, and nested logit methodologies. Six counties (Orange, Hillsborough, Brevard, Seminole, Leon, and Miami-Dade) in Florida were specifically selected so as to geographically represent the state of Florida.

Thus, the main objective of this study is to identify the significant factors that contribute to injury severity at unsignalized intersections. This helps identify those geometric, traffic, and driver-related factors leading to severe crashes at those intersections. A comparison between the three formulations is attempted to select the best modeling scheme for analyzing crash injury severity at unsignalized intersections. Finally, some countermeasures are recommended as a remedy for alleviating safety problems identified in this study.

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2. Prior research

Researchers have employed many statistical techniques to analyze driver injury severity, and those techniques have been used extensively in traffic safety analysis. Examples of those techniques are the multinomial logit, nested logit, and ordered probit models.

Abdel-Aty (2003) used the multinomial logit, nested logit, and ordered probit frameworks to identify those factors that affect injury severity at toll plazas. He concluded that the multinomial logit model produced poor results when compared to the ordered probit model. Moreover, it was found that the ordered probit model is better than the nested logit model due to its simplicity. In addition to toll plazas, the author used the ordered probit model to compare those factors that affect injury severity at other roadway locations, including roadway sections and signalized intersections. The analyses for those roadway elements (segments and intersections) were carried out independent of each other.

For the nested logit model formulation, Savolainen and Mannering (2007) analyzed motorcyclists' injury severities in single and multi-vehicle crashes using nested logit frameworks. The used data were drawn from all police-reported motorcycle crashes in the state of Indiana between 2003 and 2005. They concluded that crashes were less severe under wet pavement conditions, near intersections, and when passengers were on the motorcycle.

Shankar, Mannering, and Barfield (1996) analyzed crash severity of single-vehicle crashes on rural freeways. They found that the nested logit formulation fits the data well. The results demonstrated the significant effect of environmental conditions, highway design, accident type, driver characteristics, and vehicle characteristics on crash severity.

Nassar, Saccomanno, and Shortreed (1994) used three nested logit models to predict crash severity. These models were calibrated for three crash situations: single-vehicle, two-vehicle, and multi-vehicle crashes. It was concluded that road surface condition was not significant in the models. This can be attributed to the fact that bad weather conditions may alert drivers to slow down and keep enough spacing from other vehicles.

For the ordered probit framework, Quddus, Noland, and Chin (2002) analyzed motorcycle's injury severity resulting from crashes using 9-year crash data in Singapore. An interesting result found is that a higher road design standard increases the probability of severe injuries and fatalities. Also, the authors did not find that age increase could increase severity.

Hutchinson (1986) used the ordered probit modeling to study occupants' injury severity involved in traffic crashes. British crash data for 1962–1972 were used in the analysis, and it was concluded that passengers tend to be more seriously injured than drivers in non-overturning crashes, but that there is no difference in overturning crashes.

Kockelman and Kweon (2002) used the ordered probit formulation to investigate the risk of different injury levels for single and two-vehicle crashes. They concluded that pickups and SUVs are less safe than passenger cars for single-vehicle crashes. However, in two-vehicle crashes, they found them to be safer for their drivers and more dangerous for the passengers. Duncan et al. (1998) used the ordered probit framework to examine occupant characteristics as well as roadway and environmental conditions that influence injury severity in rear-end crashes involving truck-passenger car crashes. Two models were developed, one with the basic exogeneous variables, and the other with interactions among those exogeneous variables. They found that there is an increased severity risk for high speed crashes, those occurring at night, for women, when alcohol is involved, and for crashes when a passenger car rear-ends a truck at a large differential speed between the two vehicles.

The following studies address safety analysis at unsignalized intersections. The majority of these studies analyzed crash frequency. For example, Persaud, Lord, and Palmisano (2002) used Toronto data to estimate crash prediction models for three- and four-legged unsignalized intersections, and compared their prediction performance with California and Vancouver models previously calibrated.

Sayed and Rodriguez (1999) used the generalized linear model (GLM) formulation for estimating safety (in terms of accident occurrence) at urban unsignalized junctions. They estimated model parameters using the Poisson error structure, as was shown by Bonneson and McCoy (1997).

Sayed and Zein (1999) used the application of the traffic conflict technique for analyzing safety at unsignalized intersections.

Lau and May (1989) used classification and regression trees (CART) analysis for predicting crashes at unsignalized intersections.

Van Maren (1980) analyzed the number of crashes per million conflicts at signalized and unsignalized intersections, and found that multi-lane unsignalized intersections have a lower number of crashes per million conflicts than signalized intersections.

Poch and Mannering (1996) fitted a rear-end crash frequency model at the approach level using 63 four-legged signalized and unsignalized intersections over 7 years using the negative binomial model. They demonstrated that negative binomial regression was an appropriate model for isolating traffic and geometric factors that influence crash frequencies.

Retting, Weinstein, and Solomon (2003) investigated motor-vehicle crashes at stop-controlled intersections in four U.S. cities: Germantown, Tennessee; Oxnard, California; Springfield, Missouri; and Westfield, New Jersey.

Most of the studies (e.g., Bauer & Harwood, 1996; Del Mistro, 1981; Huang & May, 1991; Kulmala, 1997; Vogt & Bared, 1998) for relating unsignalized intersections' geometry to safety have found traffic volume to be by far the most important variable.

From the aforementioned studies, and to the authors' knowledge, almost no study addressed injury severity at unsignalized intersections. Therefore, one of the objectives of this study is to investigate injury severity at unsignalized intersections for exploring the effect of traffic and roadway covariates on crash injury severity. Also, some of the used covariates were not considered in past studies, as will be shown in the "Variables' Description" section.

3. Methodological approach: probit model specification

Probit models were introduced by Bliss (1935). A widely used approach to estimate models of the probit type is an ordered response model, which allows the application of the probit link function. Ordered probit models assume standard normal distribution for the parameters. Similar to many models for qualitative dependent variables, the ordered probit model has its origins in bio-statistics (Aitchison & Silvey, 1957), but was brought into the social sciences by two political scientists, McKelvey and Zavoina (1975).

The modeled response variable in this study (crash injury severity) is inherently ordered with five main categories: no injury or property damage only (PDO), possible injury, non-incapacitating injury, incapacitating injury, and fatal (within 30 days). Thus, the response variable y takes the following ordered values:

$$y = \begin{cases} 1; \textit{if the accident injury severity level is a PDO} \\ 2; \textit{if the accident injury severity level is a possible injury} \\ 3; \textit{if the accident injury severity level is a non-incapacitating injury} \\ 4; \textit{if the accident injury severity level is an incapacitating injury} \\ 5; \textit{if the accident injury severity level is a fatal injury} \\ \quad (\textit{within 30 days after the accident}) \end{cases}$$

For the aggregated binary probit model, incapacitating injury and fatal injury were combined to represent severe injuries, whereas non-severe crash level included PDO, possible injury, and non-incapacitating injury. The reason for this aggregation is to increase the number of observations to reduce the variability caused by random effects when statistical methods are implemented (Chang & Mannering, 1999). This is essential since the data used in this study had too few observations on incapacitating and fatal injuries to set apart their individual effects. Thus, the response variable y takes the following binary values:

$$y = \begin{cases} 0; \mathit{if\ \ the\ \ accident\ \ is\ \ non-severe} \\ 1; \mathit{if\ \ the\ \ accident\ \ is\ \ severe} \end{cases}$$

The ordered probit models have come into fairly wide use as a framework for analyzing such response variables. The ordered choice model assumes the relationship to be as shown in Eqs. (1) and (2).

$$\sum_{j=1}^{j} P_n(j) = F(\alpha_j - \beta X_n, \theta), \quad j = 1, 2, \ldots\ldots\ldots, J-1 \tag{1}$$

$$P_n(J) = 1 - \sum_{j=1}^{J-1} P_n(j) \tag{2}$$

where:

- $P_n(j)$ is the probability that subject (intersection) n (n = 1, 2, –, N) belongs to category j (with N = total number of intersections);
- J is the total number of categories;
- α_j is a specific parameter (to be estimated with β);
- Xn is a vector of measurable characteristics specific to subjects (intersections);
- β is a vector of estimated coefficients; and
- θ is a shape parameter that controls the cumulative probability distribution F. (For an ordered probit model, the assumed cumulative probability distribution F is the cumulative standard normal distribution Φ).

The marginal effects (also called elasticities, as shown by Chang & Mannering, 1999) are equivalent to the partial derivative of the expectation of the targeted response variable with respect to the vector of covariates (X). Assuming that the used model is:

$$Y = X^T\beta + \varepsilon \tag{3}$$

Thus, the expectation of the target response variable Y is F($X^T\beta$), i.e. E(Y) = F($X^T\beta$). For ordered probit models, E(Y) = Φ($X^T\beta$), and the marginal effects can be estimated as shown in Eq. (4).

$$\frac{\partial E(Y)}{\partial X} = \left\{\frac{dF(X^T\beta)}{d(X^T\beta)}\right\}\beta = \mathrm{f}(X^T\beta) * \beta = \phi(X^T\beta) * \beta \tag{4}$$

It is worth mentioning that the nested logit framework was also examined in this study, and the nested logit model formulation can be found in previous literature (e.g., Abdel-Aty & Abdelwahab, 2004; Ben-Akiva & Lerman, 1985; Chang & Mannering, 1999; McFadden, 1978, 1981).

4. Data collection and preparation

Careful and detailed data collection are essential for obtaining reliable conclusions. Despite the fact that unsignalized intersections have less number of crashes compared to signalized intersections, unsignalized intersections are more frequent than the signalized ones. This makes the process of data collection much more difficult in the essence that the required sample size should be much more than that of the signalized intersections to accurately represent the population.

The analysis done in this study was performed on 2,043 unsignalized intersections collected from six counties in the state of Florida. The county selection was based on its geographic location in Florida, so as to represent the Northern, Southern, Central, Eastern, and Western parts.

The CAR (Crash Analysis Reporting System) database maintained by the Florida Department of Transportation (FDOT) was used to identify all the state roads (SRs) in those six counties. Then, a random selection method was used for choosing some state roads. Unsignalized intersections were then identified along these randomly selected SRs using "Google Earth" and "Video Log Viewer Application." In order to use the "Video Log Viewer Application," the roadway ID for the used SR, the mile point, and the direction of travel should be specified. This application is an advanced tool developed by FDOT, and has the advantage of capturing the driving environment through the roadway. Moreover, this advanced application has two important features allowing different video perspectives, the "right view" and the "front view." The "right view" feature provides the opportunity of identifying whether a stop sign and a stop line exist or not. The "front view" feature provides the opportunity of identifying the median type as well as the number of lanes per direction more clearly.

Afterwards, all the geometric and control fields of the collected intersections were identified and added to the database. These collected fields were then merged with the RCI (Roadway Characteristic Inventory) database to capture those important traffic (such as annual average daily traffic and percentage of trucks) and roadway (such as right shoulder width, left shoulder width, and median width) features. The RCI database – which is developed by the FDOT - includes physical and administrative data, such as functional classification, pavement, shoulder, and median data related to the roadway. Each of these facilities is indexed by a roadway ID number with beginning and ending mile points. The criteria used for merging the two databases (intersections and RCI) were the roadway ID and the mile point. The merging procedure was done using SAS (2002).

Crash data for the 4 years used in the analysis were collected from the CAR database. In order to capture the most important crash variables (e.g., crash injury severity), the 2,043 intersections from the six counties were merged with crash data from 2003 until 2006. The criteria used for merging purposes were the roadway ID, mile point, and intersection node number. The final merged dataset has 10,722 observations, with 6,808 observations (63.5%) representing three-legged unsignalized intersections, and 3,914 observations (36.5%) representing four-legged unsignalized intersections.

For the three-legged dataset, the percentages of the five injury levels were as follows, 42.14% PDO, 27.7% possible injury, 21.71% non-incapacitating injury, 7.48% incapacitating injury, and 0.97% fatal. This means that there are 91.55% non-severe injuries, and 8.45% severe injuries.

For the four-legged dataset, the percentages of the five injury levels were as follows, 47.34% PDO, 25.52% possible injury, 19.09% non-incapacitating injury, 7.15% incapacitating injury, and 0.89% fatal. In other words, there are 91.96% non-severe injuries, and 8.04% severe injuries.

5. Variables' description

It was decided to use two separate models for three- and four-legged intersections as both intersection types have different operating characteristics. A full description of the important variables used in the ordered and binary probit, and nested logit modeling procedure for three- and four-legged unsignalized intersections is shown in Table 1.

The investigated continuous covariates in this study were the natural logarithm of the annual average daily traffic (AADT) on the major road, the natural logarithm of the upstream and downstream distances to the nearest signalized intersection, the left shoulder width near the median on the major road, the right shoulder width on the major road, percentage of trucks on the major road, and the natural logarithm of the distance between two successive unsignalized intersections.

Table 1
Variables description for 3 and 4-legged unsignalized intersections.

Variable Description	Variable Levels for 3 Legs	Variable Levels for 4 Legs
Crash location in any of the 6 counties	Orange, Brevard, Hillsborough, Miami-Dade, Leon and Seminole	Orange, Brevard, Hillsborough, Miami-Dade, Leon and Seminole
Existence of stop sign on the minor approach	= 0; if no stop sign exists; = 1; if stop sign exists	= 0; if no stop sign exists; = 1; if only one stop sign exists on one of the minor approaches; = 2; if one stop sign exists on each minor approach
Existence of stop line on the minor approach	= 0; if no stop line exists; = 1; if stop line exists	= 0; if no stop line exists; = 1; if only one stop line exists on one of the minor approaches; = 2; if one stop line exists on each minor approach
Existence of crosswalk on the minor approach	= 0; if no crosswalk exists; = 1; if crosswalk exists	= 0; if no crosswalk exists; = 1; if only one crosswalk exists on one of the minor approaches; = 2; if one crosswalk exists on each minor approach
Existence of crosswalk on the major approach	= 0; if no crosswalk exists; = 1; if one crosswalk exists on one of the major approaches; = 2; if one crosswalk exists on each major approach	= 0; if no crosswalk exists; = 1; if one crosswalk exists on one of the major approaches; = 2; if one crosswalk exists on each major approach
Control type on the minor approach	= 1; if stop sign exists (1-way stop); = 3; if no control exists; = 5; if yield sign exists	= 2; if stop sign exists on each minor approach (2-way stop); = 3; if no control exists on both minor approaches; = 4; if stop sign exists on the first minor approach, and no control on the other
Size of the intersection [a]	= 1; for "1 × 2", "1 × 3" and "1 × 4" intersections; = 2; for "2 × 2" and "2 × 3" intersections; = 3; for "2 × 4", "2 × 5" and "2 × 6" intersections; = 4; for "2 × 7" and "2 × 8" intersections; = 5; for "3 × 2", "3 × 3", "3 × 4", "3 × 5", "3 × 6" and "3 × 8" intersections; = 6; for "4 × 2", "4 × 4", "4 × 6" and "4 × 8" intersections	= 2; for "2 × 2" and "2 × 3" intersections; = 3; for "2 × 4", "2 × 5" and "2 × 6" intersections; = 4; for "2 × 7" and "2 × 8" intersections; = 5; for "3 × 2", "3 × 3", "3 × 4", "3 × 5", "3 × 6" and "3 × 8" intersections; = 6; for "4 × 2", "4 × 4", "4 × 6" and "4 × 8" intersections
Type of unsignalized intersection [b]	= 1; for access point (driveway) intersections; = 2; for ramp junctions; = 3; for regular intersections; = 4; for intersections close to railroad crossings	= 1; for access point (driveway) intersections; = 3; for regular intersections; = 4; for intersections close to railroad crossings
Number of right turn lanes on the major approach	= 0; if no right turn lane exists; = 1; if one right turn lane exists on only one direction; = 2; if one right turn lane exists on each direction [c]	= 0; if no right turn lane exists; = 1; if one right turn lane exists on only one direction; = 2; if one right turn lane exists on each direction
Number of left turn lanes on the major approach	= 0; if no left turn lane exists; = 1; if one left turn lane exists on only one direction; = 2; if one left turn lane exists on each direction [d]	= 0; if no left turn lane exists; = 1; if one left turn lane exists on only one direction; = 2; if one left turn lane exists on each direction
Number of left turn movements on the minor approach	= 0; if no left turn movement exists; = 1; if one left turn movement exists	= 0; if no left turn movement exists; = 1; if one left turn movement exists on one minor approach only; = 2; if one left turn movement exists on each minor approach
Land use at the intersection area	= 1; for rural area; = 2; for urban/suburban areas	= 1; for rural area; = 2; for urban/suburban areas
Median type on the major approach	= 1; for open median; = 2; for directional median; = 3; for closed median; = 4; for two-way left turn lane; = 5; for markings; = 6; for undivided median; = 7; for mixed median [e]	= 1; for open median; = 4; for two-way left turn lane; = 5; for markings; = 6; for undivided median
Median type on the minor approach	= 1; for undivided median, two-way left turn lane and markings; = 2; for any type of divided median	= 1; for undivided median, two-way left turn lane and markings; = 2; for any type of divided median
Skewness level	= 1; if skewness angle <= 75 degrees; = 2; if skewness angle > 75 degrees	= 1; if skewness angle <= 75 degrees; = 2; if skewness angle > 75 degrees
Lighting condition	= 1; for daylight; = 2; for dusk; = 3; for dawn; = 4; for dark (street light); = 5; for dark (no street light)	= 1; for daylight; = 2; for dusk; = 3; for dawn; = 4; for dark (street light); = 5; for dark (no street light)
Road surface type	= 1; if gravel or brick/block; = 2; if concrete; = 3; if blacktop	= 1; if gravel or brick/block; = 2; if concrete; = 3; if blacktop
Road surface condition	= 1; if dry; = 2; if wet; = 3; if slippery	= 1; if dry; = 2; if wet; = 3; if slippery
Posted speed limit on the major road	= 1; if posted speed limit < 45 mph; = 2; if posted speed limit >= 45 mph	= 1; if posted speed limit < 45 mph; = 2; if posted speed limit >= 45 mph
Number of through lanes on the minor approach [f]	= 1; if one through lane exists; = 2; if two through lanes exist; = 3; if three through lanes exist; = 4; if four through lanes exist	= 2; if two through lanes exist; = 3; if more than two through lanes exist
At-fault driver's age category	= 1; if 15 <= age <= 19 (very young) = 2; if 20 <= age <= 24 (young) = 3; if 25 <= age <= 64 (middle) = 4; if 65 <= age <= 79 (old) = 5; if age >= 80 (very old)	= 1; if 15 <= age <= 19 (very young) = 2; if 20 <= age <= 24 (young) = 3; if 25 <= age <= 64 (middle) = 4; if 65 <= age <= 79 (old) = 5; if age >= 80 (very old)

[a] The first number represents total number of approach lanes for the minor approach, and the second number represents total number of through lanes for the major approach.
[b] Regular unsignalized intersections are those intersections having distant stretches on the minor approaches; whereas access points include parking lots at plazas and malls as well as driveways that are feeding to the major approach; and railroad crossing can exist upstream or downstream the intersection of interest.
[c] One right turn lane on each major road direction for 3-legged unsignalized intersections: Two close unsignalized intersections, one on each side of the roadway, and each has one right turn lane. The extended right turn lane of the first is in the influence area of the second.
[d] One left turn lane on each major road direction for 3-legged unsignalized intersections: One of these left turn lanes is only used as U-turn.
[e] Mixed median is directional from one side, and closed from the other side (i.e., allows access from one side only).
[f] Surrogate measure for AADT on the minor approach.

This study is comprehensive since it explores new important roadway and traffic covariates that were not extensively examined before. Examples of those new roadway covariates are the existence of crosswalks on the minor and major approaches, effect of various minor approach control types (e.g., stop sign, no control and yield sign), various sizes of intersections, intersection type (whether it is a regular unsignalized intersection, access point or ramp junction), various median types on the major approach (open, closed, two-way left turn lane, etc.), distance between unsignalized intersections and signalized ones (from both the upstream and downstream aspects), distance between successive unsignalized intersections, and left (or median) shoulder width. An important traffic covariate explored in this study is the surrogate measure for AADT on the minor approach, which is represented by the number of through lanes on this approach. The AADT on the minor approaches was not available for most of the cases, since they are mostly non-state roads.

6. Analysis of the ordered probit framework

The fitted ordered probit model for both three- and four-legged unsignalized intersections using the five crash injury levels of the response variable is shown in Table 2, which includes some goodness-of-fit statistics as well, such as log-likelihood at convergence, log-likelihood at zero, and Akaike information criterion “AIC.” The marginal effects for the estimated models for both three- and four-legged intersections are shown in Table 3.

The marginal effects shown in Table 3 depict the effect of change in a certain explanatory variable on the probability of an injury severity level. Since the main concern is on fatal injuries (as they are the most serious) the interpretation will be focused on them. Also, the interpretations for both the three- and four-legged models are shown separately.

6.1. Three-legged model interpretation

From Table 3, increasing the natural logarithm of AADT on the major road by unity (which inherently means increasing AADT) significantly reduces fatal injury probability by 0.2%. As the AADT increases, speed decreases, and hence fatal crashes decrease as well, whereas crashes occurring at higher AADT (like rear-end and sideswipe crashes) are not generally fatal. This result is consistent with that done by Klop and Khattak (1999), who found a significant decrease in bicycle injury severity with the increase in AADT.

The spatial effect for the upstream distance to the nearest signalized intersection from the unsignalized intersection of interest showed that there is a 0.1% increase in the fatal injury probability for a unit increase in the natural logarithm of the distance. This could be attributed to the fact that as the distance between intersections increases, drivers tend to drive at (or above) the speed limit on that stretch (which is mostly high), and thus accident severity increases at

Table 2
Ordered probit estimates for 3 and 4-legged unsignalized intersections.

Variable Description	Three-Legged Model		Four-Legged Model	
	Estimate [a]	P-value	Estimate [a]	P-value
Intercept	1.3855 (0.5170)	0.0074	2.2809 (0.6888)	0.0009
Natural logarithm of AADT on the major road	−0.0807 (0.0332)	0.0151	−0.2447 (0.0518)	<0.0001
Natural logarithm of the upstream distance to the nearest signalized intersection	0.0442 (0.0153)	0.0039	0.0457 (0.0255)	0.0731
Natural logarithm of the downstream distance to the nearest signalized intersection	N/S [b]		0.0383 (0.0250)	0.1262
Posted speed limit on major road < 45 mph	−0.1096 (0.0337)	0.0011	−0.0818 (0.0496)	0.0994
Posted speed limit on major road >=45 mph	– [c]		– [c]	
Skewness angle <= 75 degrees	N/S		0.1563 (0.0826)	0.0586
Skewness angle > 75 degrees	N/S		– [c]	
No right turn lane exists on the major approach	−0.1725 (0.0935)	0.0654	N/S	
One right turn lane exists on only 1 major road direction	−0.1710 (0.0968)	0.0776	N/S	
One right turn lane exists on each major road direction	– [c]		N/S	
No left turn movement exists on the minor approach	−0.0536 (0.0350)	0.1258	N/S	
One left turn movement exists on the minor approach	– [c]		N/S	
One through lane exists on the minor approach	0.7919 (0.3917)	0.0432	N/A [d]	
Two through lanes exist on the minor approach	0.5098 (0.2827)	0.0713	N/S	
Three through lanes exist on the minor approach	0.5658 (0.3264)	0.0831	N/S	
Four through lanes exist on the minor approach	– [c]		N/A	
15 <= At-fault driver's age <= 19 (very young)	−0.1391 (0.0954)	0.1448	N/S	
20 <= At-fault driver's age <= 24 (young)	−0.1705 (0.0946)	0.0716	N/S	
25 <= At-fault driver's age <= 64 (middle)	−0.1646 (0.0900)	0.0674	N/S	
65 <= At-fault driver's age <= 79 (old)	−0.0473 (0.1016)	0.6414	N/S	
At-fault driver's age >= 80 (very old)	– [c]		N/S	
Left shoulder width near the median on the major road	0.0323 (0.0126)	0.0105	0.080737 (0.0194)	<0.0001
Right shoulder width on the major road	N/S		−0.0189 (0.0076)	0.0130
Daylight lighting condition	−0.2718 (0.0615)	<0.0001	N/S	
Dusk lighting condition	−0.3030 (0.0999)	0.0024	N/S	
Dawn lighting condition	−0.3372 (0.1477)	0.0225	N/S	
Dark (street light) lighting condition	−0.1428 (0.0678)	0.0353	N/S	
Dark (no street light) lighting condition	– [c]		N/S	
“1 × 2”, “1 × 3” and “1 × 4” intersections	−0.4077 (0.3135)	0.1935	N/A	
“2 × 2” and “2 × 3” intersections	−0.2897 (0.1329)	0.0293	N/S	
“2 × 4”, “2 × 5” and “2 × 6” intersections	−0.1482 (0.1281)	0.2474	N/S	
“2 × 7” and “2 × 8” intersections	−0.0383 (0.1532)	0.8024	N/S	
“3 × 2”, “3 × 3”, “3 × 4”, “3 × 5”, “3 × 6” and “3 × 8” intersections	−0.1384 (0.1367)	0.3113	N/S	
“4 × 2”, “4 × 4”, “4 × 6” and “4 × 8” intersections	– [c]		N/S	
Dummy variable for Brevard County	−0.0378 (0.0796)	0.6346	0.2636 (0.0983)	0.0074
Dummy variable for Hillsborough County	−0.4935 (0.0664)	<0.0001	−0.2668 (0.0757)	0.0004
Dummy variable for Leon County	−0.5359 (0.0678)	<0.0001	−0.1392 (0.0884)	0.1153
Dummy variable for Miami-Dade County	−0.6560 (0.0659)	<0.0001	−0.4452 (0.0805)	<0.0001
Dummy variable for Orange County	−0.0060 (0.0663)	0.9277	0.3314 (0.0852)	0.0001
Dummy variable for Seminole County	– [c]		– [c]	
Log-likelihood at convergence	−8514		−4696	
Log-likelihood at zero [e]	−8783.5		−4890.6	
AIC	17091		9423	

[a] Standard error in parentheses [b] N/S means not significant [c] Base case [d] N/A means not applicable [e] Likelihood while fitting the intercept only.

Table 3
Marginal effects for fatal injury probability for the fitted covariates in the 3 and 4-legged models.

Variable Description	Three-Legged Model	Four-Legged Model
	Probability of fatal injury	Probability of fatal injury
Natural logarithm of AADT on the major road	−0.002	−0.006
Natural logarithm of the upstream distance to the nearest signalized intersection from the unsignalized intersection of interest	0.001	0.001
Natural logarithm of the downstream distance to the nearest signalized intersection from the unsignalized intersection of interest	N/S [a]	0.001
Posted speed limit on major road <45 mph	−0.003	−0.002
Skewness angle <= 75 degrees	N/S	0.004
No right turn lane exists on the major approach	−0.004	N/S
One right turn lane exists on only 1 major road direction	−0.004	N/S
No left turn movement exists on the minor approach	−0.001	N/S
One through lane exists on the minor approach	0.021	N/A [b]
Two through lanes exist on the minor approach	0.013	N/S
Three through lanes exist on the minor approach	0.015	N/S
15 <= At-fault driver's age <= 19 (very young)	−0.004	N/S
20 <= At-fault driver's age <= 24 (young)	−0.004	N/S
25 <= At-fault driver's age <= 64 (middle)	−0.004	N/S
65 <= At-fault driver's age <= 79 (old)	−0.001	N/S
Left shoulder width near the median on the major road	0.001	0.002
Right shoulder width on the major road	N/S	0.000
Daylight lighting condition	−0.007	N/S
Dusk lighting condition	−0.008	N/S
Dawn lighting condition	−0.009	N/S
Dark (street light) lighting condition	−0.004	N/S
"1×2", "1×3" and "1×4" intersections	−0.011	N/A
"2×2" and "2×3" intersections	−0.008	N/S
"2×4", "2×5" and "2×6" intersections	−0.004	N/S
"2×7" and "2×8" intersections	−0.001	N/S
"3×2", "3×3", "3×4", "3×5", "3×6" and "3×8" intersections	−0.004	N/S
Dummy variable for Brevard County	−0.001	0.006
Dummy variable for Hillsborough County	−0.013	−0.006
Dummy variable for Leon County	−0.014	−0.003
Dummy variable for Miami-Dade County	−0.017	−0.011
Dummy variable for Orange County	0.000	0.008

[a] N/S means not significant [b] N/A means not applicable.

high speeds, which is an expected outcome. This was also examined by Malyshkina and Mannering (2008), and Klop and Khattak (1999), as previously illustrated. Moreover, its probit coefficient is statistically significant at the 95% confidence.

Lower speed limits (less than 45 mph "72.4 km/hr or 20.13 m/s") significantly reduce fatal injury probability by 0.3%, when compared to speed limits greater than 45 mph "72.4 km/hr or 20.13 m/s." This result is consistent with the previous finding, and is very reasonable, as fatal crashes always occur at higher speeds. This conforms to the study done by Malyshkina and Mannering (2008) and Renski, Khattak, and Council (1998), who examined the safety effect of speed limits on severe accidents, and found that high speed limits are associated with high accident severities. Also, the study by Klop and Khattak (1999) found a significant increase in bicycle and passenger car injury severity with increase in speed limits.

An interesting finding is that having no right turn lanes or one right turn lane on the major road decreases fatal injury probability by 0.4% when compared to having two right turn lanes. Their probit estimates are statistically significant at the 90% confidence.

Having no left turn movement on the minor approach decreases the probability of fatal injury by 0.1%, when compared to having one left turn movement. This is mainly due to the reduction of conflict points while prohibiting the left turn maneuver. This result is consistent with the studies done by Liu, Lu, and Chen (2007), Lu, Dissanayake, and Xu (2001), Lu, Dissanayake, and Castillo (2001), and Lu, Pirinccioglu, and Pernia (2004, 2005), who found that there is a reduction in total crashes and fatality for right turns followed by U-turns, as an alternative to direct left turn maneuvers from driveways. However, the probit estimate is not statistically significant at the 90% confidence.

Having one, two, and three through lanes on the minor approach always increases the fatal injury probability when compared to having four though lanes. The highest increase is 2.1% where one through lane existed. One through lane could exist at ramp junctions with yield signs, where merging and diverging maneuvers always occur, thus these traffic conflicts result in traffic problems and serious injuries. Its estimate is statistically significant at the 95% confidence.

The highest significant reduction in the probability of having a fatal injury occurs in middle, young, and very young at-fault drivers, which is 0.4% less than that at very old drivers. This result is consistent with the study by Abdel-Aty, Chen, and Schott (1998), who concluded that young and very young drivers are associated with fatal injury reduction as well. Although very old drivers tend to drive slowly and carefully, their weak physical condition, as well as their higher reaction time could explain the higher fatality risk.

Increasing the inside (left or median) shoulder width by 1 foot "0.3 m" significantly increases fatal injury by 0.1%. This finding contradicts with the finding of Noland and Oh (2004), who found that there is no statistical association with changes in safety for inside shoulder widths. The use of the inside shoulder width was not explored extensively in traffic safety analysis in terms of severe crashes. For example, Klop and Khattak (1999) did not use the inside shoulder width in their analysis due to the unrealistic values documented in their dataset.

The highest significant reduction in the probability of having a fatal injury occurs at dawn, which is 0.9% less than that at dark with no street lights. This might be attributed to the fact that drivers are attentive and more aware in the early morning, hence the fatal injury probability is reduced. This is also consistent with previous studies, for example, Li and Bai (2008) concluded that crashes at dawn are less fatal than at dark. Likewise, Abdel-Aty (2003), Wang and Kockelman (2005), and Khattak, Kantor, and Council (1998) have shown that dark lighting conditions result in higher injury fatality.

The only significant reduction in the probability of having a fatal injury occurs at "2×2" and "2×3" intersections, which is 0.8% less than that at "4×2," "4×4," "4×6," and "4×8" intersections. This result is considered reasonable, given the complexity of large intersections for some drivers.

The highest reduction in the probability of having a fatal injury occurs at Miami-Dade County, which is 1.7% (0.017) less than that at Seminole County. Miami-Dade County is the heaviest-populated and most urbanized county used in this study (U.S. Census, 2000), thus, more crash frequency is expected to occur, however, less fatal injuries could happen due to high-dense roadways (relatively high AADT). Moreover, its probit estimate is statistically significant, as shown in Table 2.

6.2. Four-legged model interpretation

From Table 3, as anticipated, increasing the natural logarithm of AADT on the major road by unity significantly reduces fatal injury probability by 0.6%.

As expected, there is a 0.1% increase in the fatal injury probability for a unit increase in the natural logarithm of the upstream and downstream distances to the nearest signalized intersections. This is consistent with that at three-legged unsignalized intersections.

Lower speed limits (less than 45 mph "72.4 km/hr or 20.13 m/s") reduce fatal injury probability by 0.2%, when compared to speed limits greater than 45 mph "72.4 km/hr or 20.13 m/s." This finding is consistent with that at three-legged unsignalized intersections.

Intersection's skewness angle less than or equal to 75 degrees significantly increases fatal injury probability by 0.4%, when compared to skewness angle greater than 75 degrees. This is a very reasonable outcome, as the sight distance is a problem. This illustrates the significant importance of designing intersections with skewness angle around 90 degrees, to reduce severe crashes.

As found in the three-legged model, increasing the inside (left or median) shoulder width by 1 foot "0.3 m" significantly increases fatal injury by 0.2%.

An increase in the right shoulder width by 1 foot "0.3 m" has almost no effect on the probability of fatal injuries. This finding is consistent with that of Klop and Khattak (1999), who examined the effect on the right shoulder width on bicycle crash severity on two-lane, undivided roadways in North Carolina, and found that the right shoulder width has no statistical effect on severity compared to the absence of a shoulder.

The highest significant reduction in the probability of having a fatal injury occurs at Miami-Dade County, which is 1.1% less than that at Seminole County. This finding is consistent with the three-legged model. This might also be related to varying reporting thresholds at different counties.

7. Analysis of the binary probit framework

The fitted binary probit model for both three- and four-legged unsignalized intersections using the two levels (severe vs. non-severe) of the response variable is shown in Table 4. The marginal effects for the estimated models for both three- and four-legged intersections are shown in Table 5.

7.1. Three-legged model interpretation

From Table 5, as expected, increasing the natural logarithm of AADT on the major road by unity reduces severe injury probability by 1.5%.

There is a 0.8% and 0.9% significant increase in severity probability for a unit increase in the natural logarithm of the upstream and downstream distances to the nearest signalized intersection, respectively.

Table 4
Binary probit estimates for 3 and 4-legged unsignalized intersections.

Variable Description	Three-Legged Model		Four-Legged Model	
	Estimate [a]	P-value	Estimate [a]	P-value
Intercept	−0.5872 (0.8890)	0.5089	0.6682 (0.6980)	0.3384
Natural logarithm of AADT on the major road	−0.1015 (0.0592)	0.0866	−0.1643 (0.0651)	0.0117
Natural logarithm of the upstream distance to the nearest signalized intersection	0.0528 (0.0255)	0.0383	N/S [b]	
Natural logarithm of the downstream distance to the nearest signalized intersection	0.0639 (0.0265)	0.0161	N/S	
No stop line exists on the minor approach	0.1133 (0.0629)	0.0718	N/S	
A stop line exists on the minor approach	— [c]		N/S	
Posted speed limit on major road <45 mph	−0.1252 (0.0633)	0.0481	−0.2547 (0.0722)	0.0004
Posted speed limit on major road >= 45 mph	— [c]		— [c]	
Skewness angle <= 75 degrees	N/S		0.3183 (0.1178)	0.0069
Skewness angle >75 degrees	N/S		— [c]	
No right turn lane exists on the major approach	−0.2139 (0.1413)	0.1302	−0.1964 (0.1106)	0.0758
One right turn lane exists on only 1 major road direction	−0.2363 (0.1464)	0.1066	0.0133 (0.1236)	0.9142
One right turn lane exists on each major road direction	— [c]		— [c]	
No left turn lane exists on the major approach	0.0036 (0.0751)	0.9613	N/S	
One left turn lane exists on only 1 major road direction	0.1124 (0.0607)	0.0641	N/S	
One left turn lane exists on each major road direction	— [c]		N/S	
15 <= At-fault driver's age <= 19 (very young)	−0.2720 (0.1496)	0.0692	N/S	
20 <= At-fault driver's age <= 24 (young)	−0.2360 (0.1480)	0.1109	N/S	
25 <= At-fault driver's age <= 64 (middle)	−0.1837 (0.1391)	0.1867	N/S	
65 <= At-fault driver's age <= 79 (old)	−0.1401 (0.1591)	0.3785	N/S	
At-fault driver's age >= 80 (very old)	— [c]		N/S	
Right shoulder width on the major road	0.0209 (0.0113)	0.0651	N/S	
Daylight lighting condition	−0.4425 (0.0864)	<0.0001	N/S	
Dusk lighting condition	−0.6063 (0.1696)	0.0004	N/S	
Dawn lighting condition	−0.3626 (0.2316)	0.1175	N/S	
Dark (street light) lighting condition	−0.2314 (0.0971)	0.0172	N/S	
Dark (no street light) lighting condition	— [c]		N/S	
Access point unsignalized intersections	0.4426 (0.2853)	0.1209	N/S	
Ramp junctions	-4.1439 (0.1987)	<0.0001	N/A [d]	
Regular unsignalized intersections	0.4640 (0.2798)	0.0972	N/S	
Unsignalized intersections close to railroad crossings	— [c]		N/S	
"1×2", "1×3" and "1×4" intersections	4.8632 (0.1987)	<0.0001	N/A	
"2×2" and "2×3" intersections	−0.1546 (0.2140)	0.4701	N/S	
"2×4", "2×5" and "2×6" intersections	0.0419 (0.2064)	0.8391	N/S	
"2×7" and "2×8" intersections	0.1258 (0.2489)	0.6132	N/S	
"3×2", "3×3", "3×4", "3×5", "3×6" and "3×8" intersections	0.0174 (0.2199)	0.9367	N/S	
"4×2", "4×4", "4×6" and "4×8" intersections	— [c]		N/S	
Dummy variable for Brevard County	−0.1314 (0.1216)	0.2798	0.1706 (0.1460)	0.6467
Dummy variable for Hillsborough County	−0.1444 (0.1018)	0.1562	−0.0534 (0.1166)	0.0975
Dummy variable for Leon County	−0.6443 (0.1109)	<0.0001	−0.2390 (0.1442)	0.0109
Dummy variable for Miami-Dade County	−0.4746 (0.1070)	<0.0001	−0.3263 (0.1281)	0.6467
Dummy variable for Orange County	−0.2244 (0.1041)	0.0312	−0.0477 (0.1331)	0.7198
Dummy variable for Seminole County	— [c]		— [c]	
Percentage of trucks on the major road	−0.0096 (0.0085)	0.2612	N/S	
Log-likelihood at convergence	−1869		−1039	
Log-likelihood at zero [e]	−1971.1		−1095.7	
AIC	3804		2100	

[a] Standard error in parentheses [b] N/S means not significant [c] Base case [d] N/A means not applicable [e] Likelihood while fitting the intercept only.

Table 5
Marginal effects for severe injury probability for the fitted covariates in the 3 and 4-legged models.

Variable Description	Three-Legged Model	Four-Legged Model
	Probability of severe injury	Probability of severe injury
Natural logarithm of AADT on the major road	−0.015	−0.023
Natural logarithm of the upstream distance to the nearest signalized intersection from the unsignalized intersection of interest	0.008	N/S [a]
Natural logarithm of the downstream distance to the nearest signalized intersection from the unsignalized intersection of interest	0.009	N/S
No stop line exists on the minor approach	0.017	N/S
Posted speed limit on major road<45 mph	−0.018	−0.036
Skewness angle <= 75 degrees	N/S	0.045
No right turn lane exists on the major approach	−0.031	−0.028
One right turn lane exists on only 1 major road direction	−0.035	0.002
No left turn lane exists on the major approach	0.001	N/S
One left turn lane exists on only 1 major road direction	0.017	N/S
15 <= At-fault driver's age <= 19 (very young)	−0.040	N/S
20 <= At-fault driver's age <= 24 (young)	−0.035	N/S
25 <= At-fault driver's age <= 64 (middle)	−0.027	N/S
65 <= At-fault driver's age <= 79 (old)	−0.021	N/S
Right shoulder width on the major road	0.003	N/S
Daylight lighting condition	−0.065	N/S
Dusk lighting condition	−0.089	N/S
Dawn lighting condition	−0.053	N/S
Dark (street light) lighting condition	−0.034	N/S
Access point unsignalized intersections	0.065	N/S
Ramp junctions	−0.650	N/A [b]
Regular unsignalized intersections	0.068	N/S
“1×2”, “1×3” and “1×4” intersections	0.716	N/A
“2×2” and “2×3” intersections	−0.023	N/S
“2×4”, “2×5” and “2×6” intersections	0.006	N/S
“2×7” and “2×8” intersections	0.019	N/S
“3×2”, “3×3”, “3×4”, “3×5”, “3×6” and “3×8” intersections	0.003	N/S
Dummy variable for Brevard County	−0.019	0.024
Dummy variable for Hillsborough County	−0.021	−0.008
Dummy variable for Leon County	−0.095	−0.034
Dummy variable for Miami-Dade County	−0.070	−0.046
Dummy variable for Orange County	−0.033	−0.007
Percentage of trucks on the major road	−0.001	N/S

[a] N/S means not significant [b] N/A means not applicable.

Having no stop lines on the minor approach increases severity probability by 1.7%, when compared to having stop lines. This is a reasonable outcome, emphasizing the importance of marking stop lines at unsignalized intersections for reducing severity. Moreover, their probit estimates are statistically significant at the 90% confidence.

Lower speed limits (less than 45 mph “72.4 km/hr or 20.13 m/s”) significantly reduce severe injury probability by 1.8%, when compared to speed limits greater than 45 mph “72.4 km/hr or 20.13 m/s.”

As concluded from the ordered probit model, having no right turn lanes or one right turn lane on the major road decreases severe injury probability when compared to having two right turn lanes. However, their probit estimates are not statistically significant at the 90% confidence.

An interesting finding is that having one left turn lane on one of the major approaches increases severe injury probability by 1.7%, when compared to having two left turn lanes. The estimate is statistically significant at the 90% confidence.

As previously found, the highest reduction in the severity probability occurs in young and very young at-fault drivers.

An increase in the right shoulder width by 1 foot “0.3 m” increases the severity probability by 0.3%. This can be attributed to the fact that wide shoulders encourage inappropriately using this shoulder, hence, there is a high sideswipe and rear-end crash risk, which might be severe at relatively high speeds. This finding indeed conforms to that of Noland and Oh (2004), who found that increasing the right shoulder width increases severity.

The highest significant reduction in the probability of having a severe injury occurs at dusk, which is 8.9% less than that at dark with no street lights. This might be attributed to the relatively lower conflict risk.

Although ramp junctions are usually controlled by a yield sign, and merging maneuvers are more dominant, those intersection types significantly reduce severe injury probability by 65% than intersections near railroad crossings.

The highest significant increase in the probability of severe injury occurs at “1×2,” “1×3,” and “1×4” intersections, which is 71.6% higher than that at “4×2,” “4×4,” “4×6,” and “4×8” intersections. Intersection's configurations (“1×2,” “1×3,” and “1×4”) could exist at ramp junctions with yield signs, where merging and diverging maneuvers occur, hence traffic conflicts and serious injuries are more likely, especially at higher speeds.

The second highest significant reduction in the probability of severe injury occurs at Miami-Dade County, which is 7% less than that at Seminole County. This assesses the previous finding that highly-urbanized areas experience less severity.

7.2. Four-legged model interpretation

From Table 5, as expected, increasing the natural logarithm of AADT on the major road by unity significantly reduces severe injury probability by 2.3%.

Lower speed limits (less than 45 mph “72.4 km/hr or 20.13 m/s”) significantly reduce severe injury probability by 3.6%, when compared to speed limits greater than 45 mph “72.4 km/hr or 20.13 m/s.” This finding is consistent with that at 3-legged unsignalized intersections.

As previously found, having skewness angle less than or equal to 75 degrees significantly increases severity probability, when compared to skewness angle greater than 75 degrees.

As concluded from the three-legged model, having no right turn lanes on the major road decreases severe injury probability when compared to having two right turn lanes. However, the probit estimate is not statistically significant at the 90% confidence.

As previously found, the highest significant reduction in the probability of severe injury occurs at Miami-Dade County, which is 4.6% less than that at Seminole County. This finding is consistent with that from the three-legged model.

8. Comparing the two probit frameworks

By comparing the AIC and the log-likelihood values in the four fitted three- and four-legged probit models, it is obvious that the aggregated binary probit models fit the data better than the disaggregated ordered probit models (lower AIC and higher log-likelihood at convergence). This demonstrates that the aggregate model works better in analyzing crash severity at unsignalized intersections.

9. Nested logit model estimates

The last approach performed in this study is fitting a nested logit model for both three- and four-legged intersections. Figs. 1 and 2 show the two attempted nesting structures. For example, Fig. 2 describes the analysis of crash injury level (PDO, possible injury, and non-incapacitating injury) conditioned on non-severe injury, as well as the analysis of crash injury level (incapacitating injury and fatal) conditioned on severe injury. The shown nesting structure has two levels. The first level (at the bottom of the nest) contains the five crash

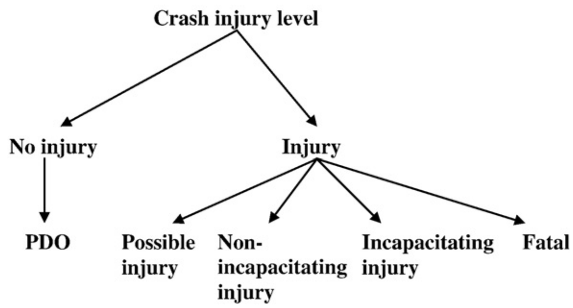

Fig. 1. First attempted two-level nesting structure for the nested logit framework.

injury levels, whereas the second level (at the top of the nest) contains the two crash injury levels, severe and non-severe injuries.

The nesting structure shown in Fig. 2 showed better results than Fig. 1. This was concluded from the resulted AIC and log-likelihood values. The fitted nested logit model for three-legged intersections using the nesting structure sketched in Fig. 2 is shown in Table 6.

From Table 6, the inclusive parameter is significantly different from zero and one, thus providing a statistical validation of using the nesting structure in Fig. 2. It is obvious that fewer variables are significant in the model and the goodness-of-fit criterion (e.g., AIC) is not as favorable as the ordered or binary probit models. Variables like the natural logarithm of the upstream distance and the speed limit have unexpected negative coefficients, as opposed to the corresponding probit estimates, hence, they are difficult to interpret.

10. Summary of results

The important geometric, traffic, driver and demographic factors from this study affecting fatal (severe) injury at unsignalized intersections are summarized in Table 7. The effect of the shown continuous variables is estimated based on an increase of unity in each of them, while the effect of those categorical variables is estimated with respect to the base case for each.

11. Conclusions and recommendations

This study attempted to put insight into factors affecting crash injury severity at three- and four-legged unsignalized intersections using the most comprehensive data collected at those locations by using the ordered probit, binary probit and nested logit frameworks. The common factors found in the fitted probit models are the logarithm of AADT on the major road, and the speed limit on the major road. It was found that higher severity (and fatality) probability is always associated with a reduction in AADT, as well as an increase in speed limit. The fitted probit models also showed several important traffic, geometric, and driver-related factors affecting safety at

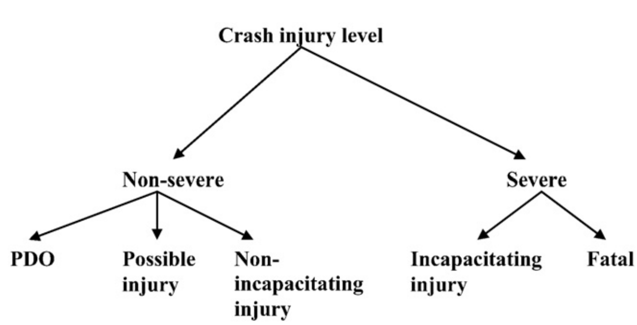

Fig. 2. Second attempted two-level nesting structures for the nested logit framework.

Table 6
Nested logit estimates for 3-legged unsignalized intersections (for the nesting structure shown in Fig. 2).

Variable Description	Estimate	Standard Error	P-value
Posted speed limit on the major road	−0.0100	0.0015	<0.0001
At-fault driver's age	−0.0011	0.0004	0.0173
Left shoulder width near the median on the major road	0.0173	0.0084	0.0396
Natural logarithm of the upstream distance to the nearest signalized intersection from the unsignalized intersection of interest	−0.0110	0.0096	0.2532
Size of the intersection	−0.0136	0.0097	0.1657
Inclusive parameter of the "severity" nest	4.8495	0.3695	<0.0001
Log-likelihood at convergence	−9182		
AIC	18375		
Number of observations	34040		

unsignalized intersections. Traffic factors include AADT on the major approach and the number of through lanes on the minor approach (surrogate measure for AADT on the minor approach). Geometric factors include the upstream and downstream distance to the nearest signalized intersection, existence of stop lines, left and right shoulder width, number of left turn movements on the minor approach, and number of right and left turn lanes on the major approach. As for driver factors, young and very young at-fault drivers were always associated with the least fatal/severe probability compared to other

Table 7
Important factors affecting fatal (severe) injury at unsignalized intersections.

Factors	Effect on fatal (severe) injury (Statistical significance)
Geometric and roadway factors	
Right shoulder width on the major approach (in feet)	Increase*
Left shoulder width near the median on the major approach (in feet)	Increase**
Natural logarithm of the upstream distance to the nearest signalized intersection from the unsignalized intersection of interest	Increase*
Natural logarithm of the downstream distance to the nearest signalized intersection from the unsignalized intersection of interest	Increase*
Posted speed limit on major road <45 mph (Base is speed limit >= 45 mph)	Decrease*
No stop line exists on the minor approach (Base is 1 stop line)	Increase*
Skewness angle <= 75 degrees (Base is skewness angle >75 degrees)	Increase**
Ramp junctions (Base are intersections close to railroad crossings)	Decrease**
One left turn lane on the major approach (Base is 2 left turn lanes)	Increase*
Traffic factors	
Natural logarithm of AADT on the major approach	Decrease*
One, two and three through lanes on the minor approach (Surrogate measure for AADT on the minor approach) (Base is 4 through lanes)	Increase***
Driver-related factors	
Young at-fault drivers (Base is very old at-fault drivers)	Decrease*
Demographic factors	
Heavily-populated and highly-urbanized area (Base is less-populated area)	Decrease**

*Statistical significance at the 90% confidence **Statistical significance at the 95% confidence.
***Existence of one through lane is the only statistically significant at the 90% confidence.

age groups. Also, heavily-populated and highly-urbanized areas experience lower fatal/severe injury.

Comparing the aggregated binary probit model and the disaggregated ordered probit model showed that the aggregate probit model produces comparable if not better results, thus for its simplicity the binary probit models could be used to model crash injury severity at unsignalized intersections if the objective is to identify the factors contributing to severe injuries in general rather than the specific injury category. The nested logit models did not show any improvement over the probit models.

This analysis identifies different issues that can be dealt with to reduce injury severity at unsignalized intersections. The spatial covariates showed the importance of including safety awareness campaigns encouraging speed control, and enforcement on speeding. Also, having a 90-degree intersection design is the most appropriate safety design for reducing severity. Moreover, the assurance of marking stop lines at unsignalized intersections is essential.

Although the work conducted in this study has shown that the binary and ordered probit models are more appropriate than the nested logit model for analyzing crash injury severity at unsignalized intersections, it is worth noting that this is mainly concerned with unsignalized intersections, as well as the specific data structure used. Hence, the same frameworks need to be attempted and validated for other data collected at different locations, such as signalized intersections and toll plazas.

Although the work carried out in this research provided useful information about various geometric, traffic, and driver factors affecting crash injuries at three- and four-legged unsignalized intersections, further research could be conducted to extend this work. Since the probit models illustrated the significance of the spatial effect of the spacing between signalized and unsignalized intersections, analyzing unsignalized intersections along with the stretches linking them as one entity can be an encouraging prospect. This result suggests that spatial correlation between intersections exists, and unsignalized intersections should not be treated as isolated locations.

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