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Median barrier crash severity: Some new insights

Wen Hu, Eric T. Donnell*

The Pennsylvania State University, Department of Civil and Environmental Engineering, 212 Sackett Building, University Park, PA 16802, United States

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ABSTRACT

Median barrier is used to prevent cross-median crashes on divided highways. Although it is well documented that crash frequencies increase after installing median barrier, little is known about median barrier crash severity outcomes. The present study estimated a nested logit model of median barrier crash severity using 5 years of data from rural divided highways in North Carolina. Vehicle, driver, roadway, and median cross-section design data were factors considered in the model. A unique aspect of the data used to estimate the model was the availability of median barrier placement and median cross-slope data, two elements not commonly included in roadway inventory data files. The estimation results indicate that collisions with a cable median barrier increase the probability of less-severe crash outcomes relative to collisions with a concrete or guardrail median barrier. Increasing the median barrier offset was associated with a lower probability of severe crash outcomes. The presence of a cable median barrier installed on foreslopes that were between 6H:1V and 10H:1V were associated with an increase in severe crash probabilities when compared to cable median barrier installations on foreslopes that were 10H:1V or flatter.

1. Introduction

Each year more than 40,000 motorists are killed and another 3 million are injured in crashes on the highway and street network in the United States (NHTSA, 2001). Although freeways are designed using the highest-level of geometric design criteria, Neuman et al. (2008) cites a Federal Highway Administration statistic (Powers, 2003) that indicates that there is one cross-median crash (CMC) fatality annually for every 200 freeway miles; approximately 250 fatalities occur annually on freeways as a result of CMC events; and, that median-related crashes are more than three times severe as other crash types on freeways. The authors also indicate that approximately 44% of CMC events occur on rural freeways, and that nearly two-thirds of fatal CMC crashes involve males. Additionally, more than 50% of fatal CMC events occur at night.

To mitigate CMC events on divided highways, the installation of longitudinal median barrier is one treatment that has generally proven cost-effective (Nystrom et al., 1997; HNTB, 1999; Macedo, 1999; Glad et al., 2002; Bane, 2003; Miaou et al., 2005; Bligh et al., 2006; Donnell and Mason, 2006; Sicking et al., 2009). The American Association of State Highway and Transportation Officials (AASHTO)' *Roadside Design Guide* (2006) contains median barrier warrant criteria, as well as median barrier type and placement guidelines. In the policy, median barrier is recommended when the width is equal to or less than 30 ft (10 m) and the average daily traffic volume (ADT) exceeds 20,000 vehicles per day. Median barrier is recommended for consideration when the median width is between 30 and 50 ft (10 and 15 m) if the ADT exceeds 20,000 vehicles per day. For all other median width-ADT combinations, median barrier is considered optional.

A variety of median barriers can be used to prevent CMC events. These are commonly grouped into flexible, semi-rigid, and rigid systems. AASHTO policy (2006) indicates that flexible or semi-rigid median barriers can be used in wide medians with relatively flat cross-slopes as long as the dynamic deflection of the barrier is less than one-half the median width. Narrow medians, particularly along roadways with high traffic volumes, normally require a rigid median barrier system with a nominal or no dynamic deflection. Median barrier placement is generally recommended near the edge of the inside shoulder on divided highways when the median cross-slope is steeper than 10H:1V. When the cross-slope is 10H:1V or flatter, longitudinal barrier systems may be placed either on the slope or at the center of the median. The only exception to this is for cable median barrier which, during crash tests, has exhibited effective performance on slopes as steep as 6H:1V (AASHTO, 2006).

A variety of research studies have shown that the frequency of median-related crashes increases, while the severity of these events is reduced, after installation of median barrier (McNally and Yaksich, 1992; Elvik, 1995; Nystrom et al., 1997; Sposito and Johnston, 1998; HNTB, 1999; Hunter et al., 2001; Bane, 2003; Monsere et al., 2003; Miaou et al., 2005; Bligh et al., 2006; Donnell

* Corresponding author. Tel.: +1 814 863 7053; fax: +1 814 863 7304.
E-mail addresses: wzh106@psu.edu (W. Hu), edonnell@engr.psu.edu (E.T. Donnell).

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and Mason, 2006; Tarko et al., 2008; Sicking et al., 2009). Most statistical models related to the severity of median-related crashes include only geometric design and traffic variables in the model specification (Miaou et al., 2005; Bligh et al., 2006; Donnell and Mason, 2006; Tarko et al., 2008).

In the present study, a novel data collection system was developed to collect median cross-section design data using a laser-scanning device – these data were appended to electronic roadway inventory and crash data to form a database that could be used to provide additional insights concerning the severity of median barrier collisions on limited-access, rural divided highways. As such, the main objective of this paper is to perform an exploratory analysis of the roadway, environmental, and driver-related factors that are associated with median barrier crash severity. The effects of median barrier offset from the edge of the traveled way, median barrier type, and the cross-slope of the median are factors included in the models that have not traditionally been available for consideration in past median-related crash severity models.

2. Previous research

Published research related to median barrier and other median-related crash severities is limited. Donnell and Mason (2005, 2006) estimated the severity of CMC and median barrier crashes. Both an ordinal and nominal response was considered. An ordinal response is considered when there is a clear ordering of the discrete outcomes and the absolute distances between categories are unknown. In ordered logistic regression, a linear function of the independent variables is specified for each observation, serving as a basis for modeling the ordinal ranking of data. The probability of falling into outcome category *i* is the probability that the estimated linear function plus a logistically distributed random error is within the range of the estimated thresholds (Washington et al., 2003). The ordered logit model assumes that the ratio of the odds of being in the chosen category (or a higher category) to the odds of being in a lower category is the same no matter which category is chosen. If the proportional odds assumption for the ordered logit model is violated, the severity outcomes can be treated as nominal responses and a multinomial logit model can be estimated.

Donnell and Mason (2005) showed that CMC events resulted in a higher proportion of fatal outcomes than median barrier crashes. The crash severity outcomes considered were fatal, injury and property-damage only (PDO). A score test was used to test the proportional odds assumption. The results indicated that the assumption was not violated in the case of CMC events; however, the proportional odds assumption was violated in the median barrier crash severity model. As such, an ordered logit model was used to estimate CMC severity probabilities and a multinomial logit model was used to estimate median barrier crash severity probabilities. In the median barrier crash severity model, a driver under the influence of drugs or alcohol resulted in an increase in the odds of being in a severe median crash. Similarly, the odds of a severe crash outcome were higher when the pavement surface was dry compared to a wet/snow/icy pavement surface. There was also preliminary evidence to suggest that the presence of an interchange entrance ramp increased the probability of severe crash outcomes when compared to roadway segments without an interchange entrance ramp.

Miaou et al. (2005) and Bligh et al. (2006) estimated crash severities for all median-related crashes on divided highways with a median barrier, and hit-median-barrier-only crashes on divided highways with a barrier. Crashes that occurred on Interstate highways, urban freeways, and rural arterial roads in Texas over a 2-year period (1998–1999) were included in the analysis. Fatal (K), incapacitating injury (A), non-incapacitating injury (B), possible injury (C), and PDO severities were considered in an ordered logit modeling framework. The probability of KAB severity outcomes increased as the ADT increased and the median width decreased.

Tarko et al. (2008) estimated median barrier crash severity models for single-vehicle (SV) and multiple-vehicle same direction (SD) occurring on divided highways in eight states. A binary logistic regression model was used to estimate the probability of a severe crash (fatal and injury). Various median types and geometric design features were included in the model specification. The baseline median type in the model was a depressed median, at least 50 ft (15 m) wide, without longitudinal median barrier. From the estimated SV model, the presence of high- or low-tension cable barrier in medians at least 30 ft (10 m) wide resulted in a lower severe crash probability when compared to the baseline median type. The presence of a concrete median barrier on medians less than 30 ft (10 m) wide resulted in an increase in the severe SV crash probability when compared to the baseline. In the SD model, a low-tension cable or concrete barrier installed in medians 30–50 ft (10–15 m) wide increased the severe crash probability when compared to the baseline median type (depressed median, at least 50 ft (15 m) wide with no median barrier). A low-tension cable barrier installed in medians at least 50 ft (15 m) wide reduced the severe SD crash probability when compared to the baseline median type.

In addition to the median barrier crash severity models described above, the published literature is vast with respect to statistical and econometric models of crash severity outcomes. For example, several researchers have used multinomial logit models to estimate crash severity (e.g., Shankar and Mannering, 1996; Carson and Mannering, 2001). There have also been several published studies that estimated crash severity outcomes using nested logit models (e.g., Shankar et al., 1996; Lee and Mannering, 2002; Holdridge et al., 2005; Savolainen and Mannering, 2007). A nested logit model divides crash severities into a hierarchy of levels and takes into account the shared unobserved effects among severity levels. By assuming that the error terms are generalized extreme value (GEV) distributed, the crash severity levels form a nested structure, where the severity levels sharing unobserved effects form the same level.

The mixed multinomial logit model has recently been used to predict crash severity outcomes. A mixed logit model allows for the possibility that the estimated model parameters vary randomly across the study units to account for unobserved effects. For example, Milton et al. (2008) used the mixed logit formulation to model aggregate injury severity proportions at the segment-level. Such an approach differs from other severity modeling approaches, where specific characteristics of a crash are considered individually in the model formulation.

Ordinal logistic regression, the multinomial logit, and the nested logit are three commonly used statistical models to estimate crash severities. The ordered nature of crash severity levels suggests that the ordinal logistic regression model is a logical choice; however, the proportional odds assumption of the model places restrictions on the effects of the explanatory variables. Under this assumption, the explanatory variables either increase the probability of a higher crash severity level and decrease the probability of a lower crash severity level, or increase the probability of a lower crash severity level and decrease the probability of a higher severity level. It is possible, however, that an explanatory variable could increase (decrease) the probability of both the highest and lowest severity levels, and decrease (increase) the probability of middle severity levels (Washington et al., 2003; Holdridge et al., 2005). A limitation of the multinomial logit model is that the disturbance terms among the severity outcomes are assumed to be independent. Previous research (Shankar et al., 1996; Lee and Mannering, 2002; Holdridge et al., 2005; Savolainen and Mannering, 2007) has shown that there are shared unobserved effects at lower crash severity levels. As such, the analysis used in the present study involves estimating a nested logit model of median barrier crash severity based on individual crash characteristics.

3. Methodology

The objective of the present study is to predict the severity of median barrier crashes using a nested logit model. Four severity categories are defined, including no injury; class C or minor injury; class B or moderate injury; and the sum of class A (major injury) and fatality. Given these four categories, a statistical model can be derived to predict the severity of a crash given that it has occurred. Below is a brief overview of the nested logit model (Washington et al., 2003).

Consider the following linear function to determine the severity outcome i for crash n (S_{in}):

$$S_{in} = \beta_i X_{in} + \varepsilon_{in} \tag{1}$$

where X_{in} is a vector of explanatory variables used to determine the severity outcome for a crash, β_i is a vector of estimable coefficients for severity outcome i, and ε_{in} is a GEV-distributed error term to account for the unobserved factors associated with severity outcome i and crash n. The probability that crash n falls in severity level i, $P_n(i)$ is expressed as follows:

$$P_n(i) = P(S_{in} \geq S_{jn}) \quad \text{for any } i \neq j \tag{2}$$

where j includes all possible severity outcomes. Substituting Eq. (1) into Eq. (2) yields the following:

$$P_n(i) = P(\beta_i X_{in} + \varepsilon_{in} \geq \beta_j X_{jn} + \varepsilon_{jn}) \quad \text{or}$$
$$P(\beta_i X_{in} - \beta_j X_{jn} \geq \varepsilon_{jn} - \varepsilon_{in}) \quad \text{for any } i \neq j \tag{3}$$

The multinomial logit model assumes that the unobserved error terms (ε_{in}) of severity category i are independent of any other severity category j. As discussed in the previous section, it is possible that there are shared unobserved effects across lower crash severity levels and thus this assumption may not be satisfied. Violating this assumption could lead to inconsistent coefficient estimates and severity probabilities. The nested logit model accounts for the shared unobserved effects across severity levels.

The nested logit model has the following structure (McFadden, 1981; Washington et al., 2003):

$$P_n(i) = \frac{\exp(\beta_i X_{in} + \theta_i L_{in})}{\sum_{i \in I} \exp(\beta_i X_{in} + \theta_i L_{in})} \tag{4}$$

$$P_n(j|i) = \frac{\exp(\beta_{j|i} X_{jn})}{\sum_{j \in J} \exp(\beta_{j|i} X_{jn})} \tag{5}$$

$$L_{in} = \ln\left[\sum_{j \in J} \exp(\beta_{j|i} X_{jn})\right] \tag{6}$$

where $P_n(i)$ is the unconditional probability of crash n falling in severity outcome i, $P_n(j|i)$ is the conditional probability of crash n falling in severity outcome j (lower level) given that the crash falls in severity category i (higher level). I is the unconditional severity set (higher level), and J is the conditional severity set (lower level) on I. L_{in} is the inclusive value representing the maximum value of the attributes that determine the probability of crash n falling in severity i. θ_i is the coefficient of inclusive value L_{in} and its value has to be greater than 0 and less than 1 to be consistent with the nested logit derivation (McFadden, 1981). If the estimated value of θ_i is not significantly different from 1 and the nested structure has only 2 levels, the nested logit model is reduced to a simple multinomial logit model.

Full information maximum likelihood (FIML) is used to estimate the nested logit model. FIML estimates the parameters in all levels simultaneously and leads to consistent and efficient parameter estimates (Holdridge et al., 2005).

4. Description of data

Electronic roadway and crash data were acquired from the North Carolina Highway Safety Information System (HSIS) dataset (Council et al., 2006). Median barrier crashes occurring between

Table 1
Crash severity distribution by categorical variable.

Crash or segment characteristic	Severity frequency (%)					Total
	No injury	Class C	Class B	Class A	Fatal	
Total median barrier crashes	2709 (73.4)	635 (17.2)	272 (7.4)	50 (1.4)	25 (0.7)	3691
Daytime crashes	1719 (73.8)	392 (16.8)	168 (7.2)	37 (1.6)	13 (0.6)	2329
Nighttime crashes	867 (72.2)	218 (18.2)	91 (7.6)	13 (1.1)	12 (1.0)	1201
Collisions with cable barrier	1660 (79.1)	290 (13.8)	114 (5.4)	20 (1.0)	15 (0.7)	2099
Collisions with guardrail barrier	945 (66.7)	299 (21.1)	139 (9.8)	24 (1.7)	10 (0.7)	1417
Collisions with concrete barrier	104 (59.4)	46 (26.3)	19 (10.9)	6 (3.4)	0 (0.0)	175
Crashes with shoulder rumble strips present	1782 (72.2)	440 (17.8)	195 (8.9)	32 (1.3)	20 (0.8)	2469
Crashes without a shoulder rumble strip present	632 (76.1)	134 (16.1)	50 (6.0)	11 (1.3)	3 (0.4)	830
Crashes on a tangent roadway segment	2448 (74.1)	568 (17.2)	230 (7.0)	36 (1.1)	23 (0.7)	3305
Crashes on a curved roadway segment	250 (67.2)	64 (17.2)	42 (11.3)	14 (3.8)	2 (0.5)	372
Crashes on a road with a concrete pavement surface	621 (79.0)	120 (15.3)	30 (3.8)	9 (1.1)	6 (0.8)	786
Crashes on a road with an asphalt pavement surface	2074 (71.8)	512 (17.7)	241 (8.3)	41 (1.4)	19 (0.7)	2887
Crashes on road segments with an interchange on-ramp	592 (75.0)	126 (16.0)	58 (7.4)	11 (1.4)	2 (0.3)	789
Crashes on road segments with an interchange off-ramp	599 (75.3)	131 (16.5)	50 (6.3)	12 (1.5)	3 (0.4)	795
Crashes on road segments without interchange ramps	1116 (73.2)	266 (17.5)	107 (7.0)	22 (1.4)	13 (0.9)	1524
Crashes involving a belted driver	2660 (74.7)	612 (17.2)	238 (6.7)	36 (1.0)	13 (0.4)	3559
Crashes involving an unbelted driver	25 (34.2)	10 (13.7)	22 (30.1)	9 (12.3)	7 (9.6)	73
Male driver	1784 (75.7)	350 (14.8)	174 (7.4)	31 (1.3)	18 (0.8)	2357
Female driver	915 (69.3)	285 (21.6)	96 (7.3)	18 (1.4)	7 (0.5)	1321
Crashes involving an impaired driver	418 (68.5)	114 (18.7)	63 (10.3)	9 (1.5)	6 (1.0)	610
Crashes where the vehicle overturned	63 (24.9)	61 (24.1)	84 (33.2)	28 (11.1)	17 (6.7)	253
Single-vehicle crashes	2440 (77.7)	459 (14.6)	200 (6.4)	27 (0.9)	16 (0.5)	3142
Multi-vehicle crashes	269 (49.0)	176 (32.1)	72 (13.1)	23 (4.2)	9 (1.6)	549
Crashes involving a heavy vehicle	190 (58.5)	74 (22.8)	46 (14.2)	6 (1.8)	9 (2.8)	325
Crashes when the roadway surface was covered with water/snow/ice/slush	1216 (80.7)	215 (14.3)	58 (3.9)	11 (0.7)	6 (0.4)	1506
Crashes when the roadway surface was dry	1490 (68.3)	419 (19.2)	214 (9.8)	39 (1.8)	19 (0.9)	2181

Table 2
Descriptive statistics of continuous variables used in severity model estimation.

Variable	Mean	Standard deviation	Minimum	Maximum
Median foreslope (H:V)	11.0:1	5.06	13.9:1	4.7:1
Median backslope (H:V)	7.7:1	3.84	13.2:1	3.7:1
Median barrier offset (ft)	5	1.40	2	11
Left shoulder width (ft)	0.05	0.77	0	16
Median width (ft)	41	16.69	4	99
Average daily traffic (veh/day)	35,797	13,806	8700	89,000
Driver age (years)	35	15.62	13	91

2000 and 2004 on divided, rural Interstate highways and expressways with longitudinal median barrier were used for the analysis. Information on crash severity, median barrier type, median barrier offset from the edge of the traveled way, median cross-slope, roadway and weather characteristics, vehicle type, driver characteristics, and crash contributory factors were included in the electronic data. A total of 3691 median barrier crashes were identified over the 5-year analysis period on 453 miles of roadway. More than 95% of the divided highway crash locations contained two travel lanes per direction, while the remaining crash locations had three travel lanes per direction. Of the divided highways included in the analysis, 257 miles of highways contained cable median barrier; 172 miles contained guardrail; and, 24 miles contained concrete median barrier. Of the 453 roadway miles included in the analysis database, 452 miles had median foreslopes flatter than or equal to 6H:1V. A 1 mile segment had a 4.7:1 foreslope and a 3.7:1 backslope. This segment was included in the 6:1 category for the purposes of this analysis. The severity distribution included 25 fatal crashes, 50 class A injury crashes, 272 class B injury crashes, 635 class C injury crashes, and 2709 PDO crashes. Table 1 shows the distribution of median barrier crash severities based on the categorical variables included in the analysis dataset.

The severity distributions shown in Table 1 provide some preliminary insights regarding the association between median barrier crash severities and a variety of explanatory variables. Among the three median barrier types, collisions with concrete barriers appear associated with higher crash severities when compared to crashes with a guardrail or cable barrier. Collisions with guardrail appear associated with higher crash severities when compared to collisions with a cable barrier. Crash severities appear to be higher in the presence of a curved roadway segment and on asphalt pavement surfaces, when compared to tangent roadway segments and concrete pavement surfaces, respectively. Female and physically impaired drivers appear to suffer from higher severities when compared to male and unimpaired drivers. Unbelted drivers, overturning vehicles, multi-vehicle crashes, and median barrier crashes involving heavy vehicles appear to increase crash severity outcomes. Crash severities appear to be lower in the presence of water/snow/ice/slush. No apparent trends exist between crash severity and the day/night period, the presence of shoulder rumble strips, or the presence of interchange entrance ramps.

A unique aspect of the present study is the availability of median cross-section data not normally available in electronic roadway inventory databases. Researchers at the Thomas D. Larson Pennsylvania Transportation Institute developed a laser-scanning system that could be used to collect median barrier offset and median cross-slope data while traveling at highway speeds. A full description of the system is contained in Vemulapalli and Brennan (2009). Descriptive statistics of the data used in the crash severity modeling are shown in Table 2 (continuous variables) and Table 3 (categorical variables). It should be noted that the continuous variable for vehicle travel speed shown in Table 2 is an estimate from the investigating police officer of the vehicle travel speed prior to the crash event sequence. This variable was closely correlated to the posted speed limit on the roadway segment where the median barrier crash occurred and was considered a more accurate descriptor of the vehicle speed in the crash event than the posted speed limit.

5. Model estimation

A nested logit model was estimated to analyze the effects of median, roadway, driver, environmental, and vehicle factors on median barrier crash severities in North Carolina. Four crash severity outcomes were modeled: no injury, class C injury, class B injury, class A injury/fatality. The class A injury and fatality categories were combined due to the small number of cases in these two categories. Numerous nesting structures were tested – the one used in the

Table 3
Descriptive statistics of categorical variables used in severity model estimation.

Variable	Proportion
Severity	
Fatal	0.01
Class A injury	0.01
Class B injury	0.07
Class C injury	0.17
No injury	0.74
Time of day indicator	
Night/day	0.33/0.63
Road surface condition indicator	
Dry/covered with water or ice or snow or slush	0.41/0.59
Road alignment indicator	
Curved segment/tangent segment	0.10/0.90
Pavement surface indicator	
Concrete/asphalt	0.19/0.81
Shoulder rumble strips indicator	
Inside Shoulder rumble strips present/shoulder rumble strips not present	0.75/0.25
Median barrier type indicator	
Cable/guardrail/concrete	0.56/0.40/0.05
Median foreslope indicator	
Steeper than 10H:1V (including 10H:1V)/flatter than 10H:1V	0.30/0.70
Ramp indicators	
On-ramp present/Off-ramp present/no ramp present	0.22/0.23/0.58
Estimated travel speed prior to crash event sequence (mph)	
<60/60–70/>70	0.30/0.36/0.34
Number of vehicles involved in crash indicator	
One vehicle/more than one vehicle	0.85/0.15
Driver physically impaired indicator	
Driver not physically impaired/driver physically impaired	0.83/0.17
Driver gender indicator	
Female/male	0.36/0.64
Driver seatbelt usage indicator	
Unbelted/belted	0.02/0.98
Vehicle overturned indicator	
No vehicle overturned/vehicle overturned	0.94/0.06
Heavy vehicle indicator	
No heavy vehicle involved/Heavy vehicle involved	0.91/0.09

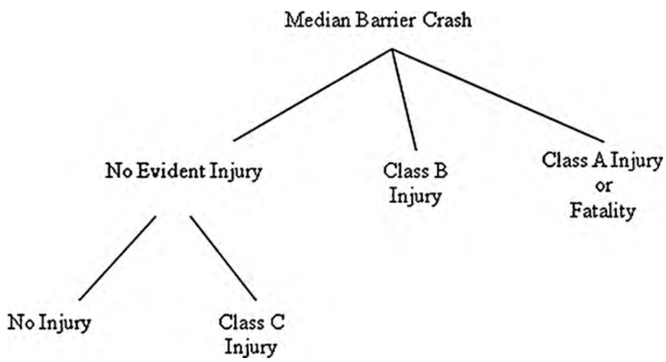

Fig. 1. Nesting structure of median barrier crashes.

present analysis is shown in Fig. 1. This structure accounts for the correlation of unobserved effects across the no-injury and class C severity levels, is consistent with nesting structures used in previous studies (e.g., Shankar et al., 1996; Lee and Mannering, 2002; Holdridge et al., 2005; Savolainen and Mannering, 2007), and was the most appropriate for the present study based on tests of other possible nesting structures.

The lower level of the nest (no injury and class C injury) estimation results for median barrier crashes is presented in Table 4, while the upper level estimation results are presented in Table 5. The signs of the coefficients presented in Tables 4 and 5 are of plausible sign and the estimated model has a good overall fit ($\rho^2 = 0.609$). The estimated inclusive value for the *no evident injury* category (lower nest) is 0.468, and is statistically different from both zero and one at the 90th-percentile confidence level. This indicates that the nesting structure could not be rejected and therefore unobserved effects exist between the no injury and class C injury levels. A discussion of the modeling results are provided below.

5.1. No injury and class C injury results

Based on the results shown in Table 4 (model for no injury and class C injury, conditioned on the occurrence of no evident injury), colliding with a concrete or guardrail median barrier decreases the probability of no injury relative to a class C injury, when compared to the baseline of colliding with a cable barrier. This result was expected because a cable median barrier has a greater dynamic deflection than either concrete or semi-rigid guardrail median barriers, resulting in reduced vehicle occupant decelerations in a collision. The relative effect of the guardrail median barrier indicator is smaller than that for the concrete median barrier indicator. This indicates that colliding with a concrete median barrier decreases the probability of no injury more so than colliding with a guardrail median barrier. Again, this finding was expected based on the rigidity of a concrete barrier relative to a guardrail median barrier that does deflect when impacted.

Table 4
Estimation results for the *no evident injury* conditional model (lower nest).

Variable	No injury coefficient	*t*-Statistic
Constant	0.927	2.11
Concrete median barrier indicator (1: if median barrier is concrete; 0: otherwise)	−1.102	−5.11
Guardrail median barrier indicator (1: if median barrier is guardrail; 0: otherwise)	−0.561	−5.30
Median foreslope indicator (1: if median foreslope is flatter than 10H:1V; 0: otherwise)	0.213	1.87
Male indicator (1: if driver is male; 0: otherwise)	0.601	5.75
Driver physically impaired indicator (1: if driver is physically impaired; 0: otherwise)	−0.498	−3.84
Belted (1: if driver is belted; 0: otherwise)	0.669	1.58
Travel speed indicator (1: if travel speed ≤60 mph; 0: otherwise)	0.283	2.47
Overturning vehicle indicator (1: if vehicle overturned in median barrier crash; 0: otherwise)	−1.538	−6.91
Multi-vehicle indicator (1: if more than one vehicle was involved in crash; 0: otherwise)	−1.300	−10.45
Nighttime crash indicator (1: if crash occurred at night; 0: otherwise)	−0.120	−1.14

Note: The estimated coefficients are specific to the *no injury* category, and are relative to the *class C injury* category. A positive coefficient estimate indicates an increased probability of no injury relative to the class C injury category. A negative coefficient indicates a decreased probability of no injury relative to the class C injury category.

The positive coefficient estimate for the median foreslope indicator indicates that median foreslopes flatter than 10H:1V increase the probability of no injury relative to a class C injury, when compared to a steeper foreslope. This result was expected because median foreslopes flatter than 10H:1V provide a more traversable recovery area for errant vehicles that leave the roadway to the left and encroach into the median on a divided highway.

The positive coefficient estimate for the male driver indicator suggests that male drivers have a higher probability of no injury in a median barrier crash with no evident injury when compared to female drivers. The negative coefficient estimate for a physically impaired driver indicates that these drivers have a higher probability of a class C injury when compared to unimpaired drivers. The positive coefficient estimate for the seatbelt usage indicator suggests that the use of a seat belt significantly increases the probability of no injury relative to a class C injury in a median barrier crash with no evident injury.

The positive coefficient estimate for the travel speed indicator suggests that travel speeds less than or equal to 60 mph (100 km/h) increases the probability of no injury relative to a class C injury in a median barrier crash with no evident injury. This finding was expected because lower barrier impact speeds are associated with reduced levels of kinetic energy dissipation relative to higher travel speeds. The negative coefficient for overturning vehicles indicates that an overturned vehicle in a median barrier crash decreases the probability of no injury relative to a class C injury, when compared to median barrier crashes where no vehicle overturns. The negative coefficient for a multi-vehicle crash indicates that if more than one vehicle was involved in a median barrier crash, the probability of no injury resulting from the crash is lower when compared to a single-vehicle crash. This finding was expected because, although it was not possible to determine the contributory factor in multi-vehicle crashes from the data, it is likely that such crashes occurred on the roadway and both vehicles involved in the roadway crash likely collided with the median barrier, or that a single-vehicle that initially collided with the barrier was re-directed onto the through travel lanes. In such instances, high vehicle speeds or high impact angles with the median barrier may contribute to the reduced probability of no injury in a multi-vehicle crash.

The negative coefficient estimate for the nighttime crash occurrence indicator suggests that a median barrier crash occurring at night has lower probability of no injury relative to a class C injury, given no evident injury. This finding is likely the result of limited visibility present when traveling at night, which may decrease a driver's brake reaction time when departing the travel lanes. As a result, the vehicle speed at impact during a nighttime crash may be higher than the speed during the daytime.

Efforts to include main effects for the average daily traffic (ADT), median barrier offset, shoulder rumble strips indicator, road surface condition indicator, road alignment indicator, road pavement indicator, interchange ramp indicator, driver age indicator, and heavy vehicle indicator were made in the lower nest, but none were statistically significant at the 80th-percentile confidence level. Additionally, several interaction terms were included in the lower nest (e.g., median width and median foreslope, median foreslope and barrier offset, barrier type and barrier offset, and barrier type and median foreslope); however, none were statistically significant in the conditional model.

5.2. No evident injury, class B injury, and class A/fatality

Table 5 shows the modeling results for the upper-part of the nesting structure in Fig. 1 for the no evident injury, class B injury, and class A/fatality severity categories. A positive coefficient estimate in an injury category indicates an increased probability of falling into the given category relative to the baseline category, while a negative coefficient estimate in an injury category indicates a decreased probability of falling into the given category relative to the baseline category. In most cases, the no evident injury severity category was used as the baseline.

When controlling for other factors, the positive coefficient estimates for the horizontal curve indicator in both the class B injury and class A injury/fatality categories indicate that the presence of a horizontal curve in a roadway segment increases the probability of a class B injury and class A injury/fatality in a median barrier crash relative to a no evident injury crash. This finding was expected because vehicles leaving the roadway and entering into the median on curved roadway segments will likely impact a longitudinal barrier at higher impact angles than vehicles leaving the roadway on a tangent roadway segment. The relative effect of the horizontal curve indicator is smaller for the class B injury category when compared to the class A injury/fatality category. This indicates that the probability of a class A injury or fatality is higher on curved roadway sections when compared to the class B injury severity.

The positive coefficient estimate for the concrete pavement surface indicator in the no evident injury category suggests that concrete roadway surfaces are associated with an increased probability of a no evident injury crash relative to higher crash severity levels in a median barrier crash, when compared to asphalt pavement surfaces. A possible explanation for this finding is that concrete pavement surfaces produce higher levels of in-vehicle noise relative to flexible pavement surfaces. As such, when drivers depart the through travel lanes on a concrete roadway surface, the change in the ambient in-vehicle noise level may produce the necessary alerting properties to warn a driver that correction is needed and, therefore, drivers may attempt to brake the vehicle or steer away from a median barrier, resulting in a decrease in the crash severity.

The positive coefficient estimate for the cable median barrier indicator in the no evident injury category suggests that colliding with a cable barrier increases the probability of a no evident injury crash relative to higher crash severity levels in a median barrier crash, when compared to striking a guardrail or concrete median barrier. The median barrier offset variable had a negative coefficient in the class B injury and class A injury/fatality categories, indicating that a one-unit increase in the median barrier offset is associated with a reduction in the probability of higher severity outcomes relative to the no evident injury outcome. Placing a median barrier further away from the through travel lanes is likely providing drivers with some recovery area where braking can occur, resulting in lower median barrier impact speeds.

The coefficient estimate for the cable barrier-median foreslope interaction effect suggests that placing a cable barrier on a median with a foreslope between 6H:1V and 10H:1V increases the probability of a class B injury and class A injury/fatality in a median barrier crash relative to the no evident injury severity. In the analysis database, it was found that a significant proportion of cable median barriers were installed on a foreslope, consistent with AASHTO policy (2006). The increased probability of a high-severity crash in medians with a cable barrier installed on a foreslope may be indicative of a vehicle under riding or penetrating the barrier.

The coefficient for the shoulder rumble strip indicator was restricted to be equal across the class B injury and class A injury/fatality categories since the coefficients were similar in magnitude. The positive coefficient estimates indicate that the presence of a shoulder rumble strip on the inside shoulder of a divided highway increases the probability of a class B injury and class A injury/fatality relative to no evident injury in a median barrier crash. This finding may be considered counterintuitive; however, as Noyce and Elango (2004) showed in a simulator study, approximately 27% of research participants steer left when encountering centerline rumble strips on undivided highways. If similar reactions occur on divided highways when rumble strips are present on the inside shoulder, the likely result is a vehicle entering the median and subsequently impacting the median barrier at a high angle. Furthermore, drivers may be more inclined to steer away from through vehicle traffic on high-speed roadways when encountering shoulder rumble strips due to concerns over a high-speed rear-end or sideswipe crash.

The coefficient for a road with water/ice/snow/slush indicator were restricted to be equal across the class B injury and class A injury/fatality categories since the coefficients were similar in magnitude. The negative coefficient estimate indicates that the presence of water/ice/snow/slush on the road decreases the probability of a class B injury and class A injury/fatality in a median barrier crash relative to the no evident injury severity level. This may be due to the fact that drivers travel more cautiously in adverse weather conditions, resulting in lower vehicle impact speeds in collisions with a longitudinal median barrier.

The negative coefficient estimates for the seatbelt usage indicator in both the class B injury and class A injury/fatality categories indicates that the use of a seat belt significantly decreases the probability of a class B injury and class A/fatality injury relative to no evident injury in a median barrier crash. The relative effect for the seatbelt usage indicator in the class B injury category is smaller than that in the class A injury/fatality category. This indicates that the probability of a class A injury/fatality is lower than the class B injury probability when the driver is belted in a median barrier crash.

The positive coefficient estimates for the travel speed indicator in both the class B injury and class A injury/fatality categories indicate that travel speeds greater than 70 mph (115 km/h) increase the probability of class B injury and class A injury/fatality relative to no evident injury in a median barrier crash. The relative effect of the class A injury/fatality category is higher than the class B injury category indicating that higher speeds increase the probability of class A injury/fatality severity more so than class B injury severity relative to the baseline of no evident injury.

The positive coefficient estimates for the overturning vehicle indicator in both the class B injury and class A injury/fatality categories indicates that an overturned vehicle in a median barrier crash increases the probability of class B injury and class A injury/fatality relative to no evident injury. As expected, the relative effect for the class A injury/fatality severity level is greater than the class B injury category.

The positive coefficient estimates for the multi-vehicle indicator in both the class B injury and class A injury/fatality categories indicates that if more than one vehicle is involved in a median barrier crash, the probability of a class B injury and class A injury/fatality is increased relative to the no evident injury category. The relative effect of the class B injury category is lower than the relative effect for the class A injury/fatality severity level.

Efforts to include main effects for the ADT, traffic composition, time of day, presence of interchange ramps, driver age and gender, and driver impairment resulted in coefficient estimates that

Table 5
Estimation results for the no evident injury, class B, and class A/fatal model (upper nest).

Variable	No evident injury		Class B injury		Class A injury or fatality	
	Coefficient	*t*-Statistic	Coefficient	*t*-Statistic	Coefficient	*t*-Statistic
Constant	1.134	1.32	1.142	1.46		
Curved roadway segment indicator (1: if curve is present in crash segment; 0: otherwise)			0.243	1.10	1.161	3.05
Concrete pavement surface indicator (1: if the pavement surface is concrete; 0: otherwise)	0.593	2.72				
Cable barrier indicator (1: if median barrier is cable; 0: otherwise)	0.471	2.05				
Median barrier offset (feet)			−0.076	−1.29	−0.227	−1.82
Cable barrier and median foreslope indicator (1: if barrier is cable and median foreslope is between 6H:1V and 10H:1V; 0: otherwise)			0.199	0.82	0.541	1.29
Shoulder rumble strip indicator (1: if inside shoulder rumble strip is present; 0: otherwise)			0.346	1.84	0.346	1.84
Road with water/ice/snow/slush (1: if there is water/ice/snow/slush present on roadway; 0: otherwise)			−0.603	−3.59	−0.603	−3.59
Belted (1: if driver is belted; 0: otherwise)			−1.886	−5.13	−3.227	−6.66
Travel speed indicator (1: if travel speed $\geq$ 70 mph; 0: otherwise)			0.643	3.84	1.012	3.05
Overturning vehicle indicator (1: if vehicle overturned in median barrier crash; 0: otherwise)			1.904	5.71	3.364	7.93
Multi-vehicle indicator (1: if more than one vehicle involved; 0: otherwise)			0.481	1.73	1.713	4.30
Inclusive value of *no evident injury* (lower nest)	0.468	1.71				

Note: (1) Blank cells in Table 5 are the baseline severity category for the upper nest. (2) Number of observations is 3691; likelihood ratio at zero is −5497.07; likelihood ratio at convergence is −2141.85; $\rho^2 = 0.609$. (3) A positive coefficient estimate in an injury category indicates increased probability of falling into the given category relative to the baseline category. (4) A negative coefficient estimate in an injury category indicates decreased probability of falling into the given category relative to the baseline category. (5) The coefficients for the road with water/ice/snow/slush indicator and shoulder rumble strips indicator were restricted to be equal across class B and class A/fatality levels.

were not significantly associated with severity outcomes. Similarly, interactions between the median width and median foreslope, barrier type, and barrier offset were not statistically significant in the model.

6. Conclusions

This study estimated a nested logit model of median barrier crash severity using data from North Carolina. From a methodological perspective, the model estimation showed that PDO and class C injury severities shared unobservable characteristics, which is consistent with past nested logit severity outcome models.

Factors considered in the nested logit model included median barrier type and offset from the edge of the traveled way, roadway segment characteristics, roadway surface conditions, and driver and vehicle characteristics. A unique aspect of the model specification was the inclusion of median barrier type and placement data, as well as median cross-slope data. Data related to the median cross-section design on divided highways are not commonly found in electronic roadway inventory databases maintained by state transportation agencies; therefore, the exploratory analysis presented in this paper confirms the importance of median design characteristics on median barrier crash severity.

Based on the modeling results, all coefficients appeared to have plausible signs that are consistent with published median barrier crash severity outcome models. Several findings worth highlighting include the association between severity outcomes and the median barrier type and placement. Median barrier offsets further from the edge of the traveled way were shown to reduce the probability of high-severity outcomes. The interaction between a cable median barrier and the median foreslope indicator deserves further exploration. In the present study, the probability of high-severity outcomes increases when cable barriers are placed on a foreslope that is between 6H:1V and 10H:1V when compared to placing cable barrier on flatter foreslopes (10H:1V or flatter). From the crash database used in the present study, it is not clear why this occurred, but may be indicative of vehicles under riding or penetrating the barrier on a slope that is steeper than 10H:1V. As noted by Sheikh et al. (2008), cable median barrier has proven very effective in reducing cross-median crash events. However, the authors' noted that in some evaluations injury rates increased after installation of cable median barrier, and that vehicle under-ride is likely reduced when a cable barrier is placed one foot (0.3 m) from the ditch line in a median, rather than four feet (1.2 m) from the ditch as is common practice. Future research is recommended to explore the relationship between cable barrier placement on slopes and crash severity outcomes.

When a vehicle overturns in a median barrier crash, the probability of a higher injury severity increases when compared to crashes where vehicles do not overturn. While it was not possible to determine the cause of vehicles overturning in median barrier crashes, this may be the result of improper median barrier mounting heights or the result of the median side-slope being designed such that vehicles are not impacting the barrier as intended. This issue requires further exploration.

Increases in the higher severity outcome probabilities when rumble strips are present on the inside shoulder of a rural divided highway also deserves further exploration. While simulator research has shown that some drivers steer left when encountering centerline rumble strips on undivided highways, it is not clear how this finding relates to driver reactions to rumble strips placed on the inside shoulder of divided highways, other than to possibly avoid possible multi-vehicle rear-end or sideswipe crashes.

Because the primary purpose of this study was to perform an exploratory analysis of median barrier crash severity using median cross-section data not commonly available for such analyses, models of crash frequency and other median-related crash types were not considered. Although a crash severity analysis of cross-median and rollover crashes in medians without a longitudinal median barrier would be desirable using data from North Carolina for comparative purposes, few of these events are observed on rural divided highways in the state. This is primarily due to a program undertaken in North Carolina to install protective barrier on medians less than 70 ft (23 m) wide in the late 1990s (Lynch, 1998).

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