Hindawi
Journal of Advanced Transportation
Volume 2024, Article ID 5568950, 16 pages
https://doi.org/10.1155/2024/5568950

Research Article

An Assessment of the Safety Effects of Roadside Barriers on Reducing Mountainous Crash Injury Severity

Chunhui Zhang,[1] Yanying Wang,[2] Keqi Wu,[3] Le Tian,[2] and Dongdong Song[4]

[1]*North China Municipal Engineering Design and Research Institute Co., Ltd., Tianjin 300110, China*
[2]*China Communications Information Technology Group Co., Ltd., Beijing 100088, China*
[3]*Government Service Center of Beijing Municipal Transport Commission (Beijing Boats Inspection Center), Beijing 100073, China*
[4]*School of Systems Science, Beijing Jiaotong University, Beijing 100044, China*

Correspondence should be addressed to Dongdong Song; 19114009@bjtu.edu.cn

Received 15 August 2023; Revised 10 October 2023; Accepted 28 October 2023; Published 13 January 2024

Academic Editor: Juneyoung Park

Roadside barriers have proven effective in preventing run-off-road accidents that occurred in mountainous areas. Nonetheless, the influence of variables impacting the severity of injuries resulting from collisions involving distinct types of roadside barriers may diverge. This study delves into the factors that influence the severity of driver's injuries in crashes encompassing three specific varieties of roadside barriers in mountainous regions, namely, W-beam barriers, flexible barriers, and roadside trees. The evolution of these factors over time is examined through the application of a random parameters logit modeling approach with heterogeneity in means and variances (RPLHMVs). By employing injury-severity data from 2016 to 2019 for the mountainous regions of a city in Southwest China, various potential influencing factors encompassing driver-, vehicle-, road-, and environment-specific characteristics are subjected to statistical analysis. The extent of the impact of identified statistically significant factors on driver's injury severity is assessed through the computation of pseudoelasticities. The findings reveal distinctions in the outcomes of driver's injury severity contingent upon the type of roadside barrier encountered during vehicle impacts. To illustrate, collisions involving W-beam barriers are more prone to result in severe injuries. Moreover, the influence of variables determining driver's injury severity displays noteworthy temporal shifts. Notably, the pseudoelasticities of numerous explanatory variables remain temporally consistent for incidents involving flexible or roadside barriers. In contrast, crashes involving W-beam barriers highlight that solely the speeding indicator demonstrates temporally stable pseudoelasticities. The insights garnered from this investigation offer the potential to contribute to the formulation of fresh guidelines for the design and selection of roadside barriers aimed at mitigating the severity of injuries incurred in crashes within mountainous regions.

1. Introduction

Over 15% of traffic incidents transpired within mountainous terrains during the period spanning 2012–2016 in China, as delineated by [1]. Of these incidents, approximately 68% led to grave injuries. A parallel scenario is observed in Western nations, exemplified by mountainous highways like the segment of I-70 freeway in Colorado, USA, as highlighted by [2]. This underscores a pervasive safety concern prevalent across mountainous terrains.

In this context, roadside barriers are found to effectively reduce driver's injury severity in mountainous regions [3–8]. In the recent past, numerous investigations have delved into the correlation between median barriers and the magnitude of collisions on highways [3, 4, 9, 10]. The impacts of roadside barriers on highway crash-injury severities have also been investigated [4, 7, 11–13]. The study of [11] showcased a decline in injury severity when comparing road barriers (including guardrails, cable barriers, and concrete barriers) with other objects situated at the roadside along

Indiana highways. Similarly, the study of [12] highlighted the enhanced safety of freeway segments in Florida attributed to W-beam guardrails and concrete barriers. Another study of [7] underscored the significant influence of barrier height and offset distance on crash-injury severity within two-lane roads in Wyoming. The study of [5] employed ordered logit models to explore crash severity, incorporating three distinct roadside barriers (guardrail, rigid, and cable barriers). Their findings unveiled incongruities in the impact of influencing factors across varied types of roadside barriers. Furthermore, the study of [13] developed random parameters logit models to explore the impacts of barrier-specific attributes on crash-injury severity, particularly focusing on high-tension cable barriers and strong-post guardrails within interstate highways in Alabama.

However, a significant number of accidents are still associated with roadside barriers. According to the annual statistical report of traffic accidents in China, a total of 212,846 traffic accidents occurred in 2016, of which approximately 14.15% was associated with roadside trees and 3.69% was associated with W-beam barriers [1]. In addition, the beneficial effect of different types of roadside barriers may vary in magnitude. For example, the W-beam barrier is less sturdy as compared to the concrete barrier, which is more prone to causing a rollover crash when vehicles run off the road on mountainous roads. In addition, roadside trees increase the risk of crash due to blocking the line of sight of drivers, more so in curvy roads. Therefore, it is necessary to investigate the differences in the injury severity of crashes in mountainous regions involving different types of roadside barriers. Furthermore, temporal instability gains intensive attention from researchers [14, 15], As discussed comprehensively by [14], ignoring such instability issues may contribute to ineffective estimation results, wrong findings, or even converse safety countermeasures. Thus, it is worth exploring the temporal instability as sources of unobserved heterogeneities while analyzing the injury severities of mountainous fixed-objects-related crashes.

In this paper, the most commonly utilized roadside barriers (W-beam barriers, flexible barriers, and roadside trees) in the mountainous regions of China are explored. The contribution of this paper is threefold as follows.

First, the random parameters logit model with heterogeneity in means and variances is employed to statistically analyze the injury severity of barrier-related crashes that occurred in mountainous regions. The application of this advanced modeling framework enables accounting for the multilayered unobserved heterogeneity of the crash data.

Second, we investigate the differences among crash-injury severities involving three different roadside barrier types in the mountainous regions in China. We examine whether the crash-injury severities and the corresponding effects of explanatory factors vary across different roadside barrier types. The variation among different barrier types may provide valuable insights for the design consideration and selection of roadside barriers to reduce crash-injury severity, especially on mountainous roads.

Third, we examine how these differences among crash-injury severities involving different barrier types change over time. The average pseudoelasticity of the identified factors affecting the driver's injury severity is computed to quantify their impact. A pseudoelasticity gives the change in the injury-severity outcome probability due to changes in indicator variables from 0 to 1 [16]. Among the identified factors, the ones demonstrating temporally stable pseudoelasticities would be more important for formulating strategies to enhance traffic safety on mountainous roads.

Given this, this study comprehensively estimates the injury severities of drivers using advanced statistical models given the types of fixed objects involved in the crash. The research flowchart is shown in Figure 1. The data used for this study are described, followed by an introduction to the methodological approach. Then, a detailed discussion of the model estimation results is presented. Finally, the last section summarizes the findings of this study and discusses potential future directions.

2. Data Description

In the pursuit of this analysis, a dataset spanning four years (2016–2019) has been employed. This dataset encompasses information concerning collisions involving fixed objects within a city in Southwest China. The severity of injuries has been categorized into three classes as follows: no injury, minor injury, and severe injury. Among the fixed objects, specific attention has been given to W-beam barriers, flexible barriers, and roadside trees. Notably, other categories of barriers (such as concrete and metal barriers) have been omitted from the analysis due to their limited representation in the dataset (constituting less than 3% collectively). Their inclusion could potentially introduce biases that are excessively data specific. The dataset consists of 5,319 fixed-object crashes in mountainous areas, i.e., 1,556 crashes involving W-beam barrier, 1,489 crashes involving cable barrier, and 2,274 crashes involving roadside tree. It is pertinent to underline that this study also incorporates an investigation into the stability of injury severity models pertinent to fixed-object collisions over time. In line with this objective, the dataset has been partitioned into two subsets as follows: one spanning the years 2016-2017 and the other covering the years 2018-2019. A comprehensive breakdown of the frequency and proportionate distribution of crash-related injury severity categories is presented in Table 1. For W-beam barrier collisions, these proportions stand at 66.97% for no injury, 17.67% for minor injury, and 15.36% for severe injury. In the case of cable barrier collisions, the figures are 65.08% for no injury, 26.39% for minor injury, and 8.53% for severe injury. Lastly, for collisions involving roadside trees, the proportions equate to 71.94% for no injury, 21.33% for minor injury, and 6.73% for severe injury. Table 2 presents the descriptive statistics of explanatory variables in injury severity models.

3. Methodology

Separate random-parameter logit models with heterogeneity in means and variances (RPLHMVs) were estimated to identify the factors influencing the driver's injury and

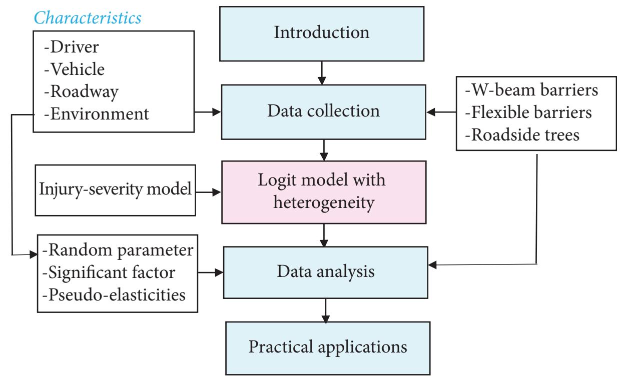

FIGURE 1: Flowchart of the study.

TABLE 1: Fixed-object crashes observations on mountainous roads.

Years	Severe injury			Minor injury			No injury			Total		
	W-beam barriers	Flexible barriers	Trees	W-beam barriers	Flexible barriers	Trees	W-beam barriers	Flexible barriers	Trees	W-beam barriers	Flexible barriers	Trees
2016-2017	155	69	80	122	189	187	561	452	830	838	710	1097
2018-2019	84	58	73	153	204	298	481	517	806	718	779	1177

severity involved in different fixed-object crashes. The application of this modeling framework enables accounting for the multilayered unobserved heterogeneity of the crash data in terms of (a) factors varying across the observations, (b) factors affecting the mean of the parameter density function of the random parameters (and thus shifts in the peak of the distribution of the betas), and (c) factors affecting the variance of the parameter density function of the random parameters (and thus changes in the tails of the distribution of the betas). To begin with, an injury-severity function, Y_{in}, that determines the driver's injury-severity level i in crash n, is specified as follows [16–21]:

$$Y_{\text{in}} = \boldsymbol{\beta}_{\mathbf{i}}\mathbf{X}_{\mathbf{in}} + \varepsilon_{\text{in}}, \tag{1}$$

where vectors $\mathbf{X}_{\mathbf{in}}$ represent the explanatory variables influencing the level of driver injury severity i (no injury: NI, minor injury: MI, or severe injury: SI) in crash n, $\boldsymbol{\beta}_{\mathbf{i}}$ comprises estimable parameters associated with the respective variables, and ε_{in} denotes the error term assumed to conform to an independent and identically distributed pattern with a mean of zero and a variance of σ^2. To account for unobserved heterogeneity, random parameters with heterogeneity in means and variances (RPLHMVs) are introduced as follows [16, 22–25]:

$$\beta_{\text{in}} = \beta_i + \boldsymbol{\Theta}_{\text{in}}\mathbf{Z}_{\mathbf{in}} + \sigma_{\text{in}}\text{EXP}\left(\boldsymbol{\psi}_{\text{in}}\mathbf{W}_{\mathbf{in}}\right) + \upsilon_{\text{in}}, \tag{2}$$

where β_{i} represents the average parameter estimate encompassing all collisions, $\mathbf{Z}_{\mathbf{in}}$ signifies arrays of explanatory variables exerting influence on this average, $\boldsymbol{\Theta}_{\text{in}}$ represents corresponding estimable parameters, $\mathbf{W}_{\mathbf{in}}$ symbolizes arrays of explanatory variables capturing variability in variances, σ_{in}, $\boldsymbol{\psi}_{\text{in}}$ denotes estimable parameters linked to this variability, and υ_{in} stands for the perturbation term. Consequently, the likelihood of the outcome within the framework of the RPLHMV model formulation can be articulated as illustrated by [16] as follows:

$$P_n(i\,|\,\varphi) = \int \frac{\exp\left(\boldsymbol{\beta}_{\mathbf{i}}\mathbf{X}_{\mathbf{in}}\right)}{\sum_{i\in I}\exp\left(\boldsymbol{\beta}_{\mathbf{i}}\mathbf{X}_{\mathbf{in}}\right)} f\left(\boldsymbol{\beta}_{\mathbf{i}}\,|\,\boldsymbol{\varphi}\right) d\boldsymbol{\beta}_{\mathbf{i}}, \tag{3}$$

where the likelihood of the injury severity level is i, $p_n(i\,|\,\varphi)$ is contingent upon the function $f(\boldsymbol{\beta}_{\mathbf{i}}\,|\,\boldsymbol{\varphi})$, wherein $f(\boldsymbol{\beta}_{\mathbf{i}}\,|\,\boldsymbol{\varphi})$ signifies the probability density function associated with β_{i}, and in this context, φ encompasses a parameter vector encompassing means and variances.

The RPLHMV model is computed using a simulated maximum likelihood approach, employing 200 Halton draws to attain reliable parameter estimations, as proposed by [26]. The selection of the normal distribution for the random parameters' distribution is made to optimize the model's goodness of fit [27–33].

Pseudoelasticities are computed to quantitatively describe the impact of explanatory variables on the driver's injury severity. In this paper, all variables used in the estimated models are binary indicator variables. Therefore, the pseudoelasticities quantify the change in outcome probability when an explanatory variable changes from "0" to "1" [16].

4. Model Estimation Results

The RPLHMV model estimation results and corresponding pseudoelasticities for the W-beam barrier crashes are shown in Tables 3 and 4 for 2016-2017 and 2018-2019, respectively. In the context of the 2016-2017 model, the dark-lighted indicator exhibited notable significance as a normally distributed random parameter, affecting the minor injury severity outcome. Within the dataset, this indicator led to a heightened likelihood of minor injury in 97.14% of instances, while conversely contributing to a decrease in only

Table 2: Descriptive statistics of explanatory variables.

Variables	2016-2017						2018-2019					
	W-beam		Flexible		Trees		W-beam		Flexible		Trees	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Driver characteristics												
Male indicator (1 if yes; otherwise, 0)	0.916	0.277	0.907	0.291	0.905	0.293	0.919	0.273	0.909	0.288	0.885	0.319
Middle age driver indicator (1 if 25–60 years old; otherwise, 0)	0.891	0.311	0.889	0.315	0.871	0.336	0.866	0.341	0.865	0.342	0.870	0.336
Young driver indicator (1 if below 25 years old; otherwise, 0)	0.109	0.311	0.111	0.315	0.129	0.336	0.134	0.341	0.135	0.342	0.130	0.336
Intermediate driving experience indicator (1 if 10–15 years; otherwise, 0)	0.202	0.401	0.199	0.399	0.195	0.396	0.166	0.372	0.146	0.354	0.150	0.357
Novice driving experience indicator (1 if 3–10 years; otherwise, 0)	0.495	0.500	0.531	0.499	0.514	0.500	0.545	0.498	0.579	0.494	0.566	0.496
Rookie driving experience indicator (1 if below 3 years; otherwise, 0)	0.128	0.334	0.132	0.339	0.108	0.311	0.111	0.315	0.107	0.309	0.110	0.314
Expert driving experience indicator (1 if above 15 years; otherwise, 0)	0.175	0.381	0.138	0.345	0.182	0.386	0.178	0.383	0.168	0.374	0.174	0.379
Driver seatbelt use indicator (1 if yes; otherwise, 0)	0.850	0.358	0.892	0.311	0.928	0.259	0.873	0.333	0.893	0.309	0.944	0.230
Driver under alcohol influence indicator (1 if yes; otherwise, 0)	0.154	0.361	0.162	0.369	0.178	0.382	0.188	0.391	0.173	0.379	0.204	0.403
Vehicle characteristics												
Car indicator (1 if yes; otherwise, 0)	0.741	0.438	0.858	0.350	0.845	0.362	0.783	0.413	0.849	0.359	0.874	0.332
Truck indicator (1 if yes, 0 otherwise)	0.259	0.438	0.142	0.350	0.155	0.362	0.217	0.413	0.151	0.359	0.126	0.332
Improper braking and steering indicator (1 if yes; otherwise, 0)	0.442	0.497	0.462	0.499	0.423	0.494	0.408	0.492	0.334	0.472	0.137	0.344
Speeding indicator (1 if yes; otherwise, 0)	0.301	0.459	0.242	0.429	0.269	0.444	0.217	0.413	0.272	0.445	0.506	0.500
Improper lane changing indicator (1 if yes; otherwise, 0)	0.104	0.305	0.134	0.341	0.130	0.337	0.187	0.390	0.221	0.415	0.153	0.360
Local vehicle indicator (1 if yes; otherwise, 0)	0.865	0.342	0.921	0.270	0.915	0.279	0.872	0.334	0.908	0.290	0.924	0.264
Roadway characteristics												
Road without isolation indicator (1 if yes; otherwise, 0)	0.316	0.465	0.669	0.471	0.206	0.405	0.352	0.478	0.669	0.471	0.210	0.407
Road in good condition indicator (1 if yes; otherwise, 0)	0.969	0.173	0.966	0.181	0.993	0.085	0.965	0.183	0.981	0.138	0.986	0.119
Dry surface indicator (1 if yes; otherwise, 0)	0.723	0.448	0.779	0.415	0.784	0.412	0.724	0.447	0.718	0.450	0.716	0.451
Intersection indicator (1 if yes; otherwise, 0)	0.155	0.362	0.200	0.400	0.175	0.380	0.171	0.377	0.167	0.373	0.133	0.340
Ramp indicator (1 if yes; otherwise, 0)	0.041	0.197	0.008	0.092	0.026	0.158	0.091	0.287	0.035	0.183	0.019	0.135
Homogeneous section indicator (1 if yes; otherwise, 0)	0.678	0.468	0.751	0.433	0.779	0.415	0.063	0.243	0.013	0.113	0.834	0.372
Tunnel indicator (1 if yes; otherwise, 0)	0.126	0.333	0.041	0.198	0.020	0.140	0.675	0.469	0.786	0.411	0.014	0.116
Small uphill grade indicator (1 if 0–2% vertical grade; otherwise, 0)	0.758	0.429	0.748	0.435	0.895	0.306	0.758	0.429	0.783	0.412	0.933	0.250
Small downhill grade indicator (1 if −2–0% vertical grade; otherwise, 0)	0.082	0.275	0.169	0.375	0.064	0.245	0.092	0.289	0.123	0.329	0.047	0.211
Large uphill grade indicator (1 if 2% or greater vertical grade; otherwise, 0)	0.062	0.241	0.042	0.201	0.037	0.190	0.049	0.215	0.056	0.231	0.020	0.138
Large downhill grade indicator (1 if −2% or less vertical grade; otherwise, 0)	0.098	0.297	0.041	0.198	0.004	0.060	0.102	0.302	0.037	0.189	0.001	0.029
Crash characteristics												
Sideswipe indicator (1 if yes; otherwise, 0)	0.447	0.498	0.604	0.489	0.681	0.466	0.497	0.500	0.562	0.496	0.730	0.444
Head-on collision indicator (1 if yes; otherwise, 0)	0.089	0.286	0.092	0.289	0.036	0.188	0.111	0.315	0.121	0.326	0.195	0.397
Rear-end indicator (1 if yes; otherwise, 0)	0.362	0.481	0.185	0.388	0.196	0.397	0.318	0.466	0.191	0.394	0.020	0.141
Winter indicator (1 if yes; otherwise, 0)	0.254	0.436	0.193	0.395	0.127	0.333	0.223	0.416	0.232	0.423	0.221	0.415
Summer indicator (1 if yes; otherwise, 0)	0.267	0.443	0.270	0.444	0.344	0.475	0.256	0.437	0.266	0.442	0.250	0.433
Spring indicator (1 if yes; otherwise, 0)	0.199	0.400	0.220	0.414	0.266	0.442	0.291	0.455	0.268	0.443	0.302	0.460
Autumn indicator (1 if yes; otherwise, 0)	0.279	0.449	0.317	0.466	0.263	0.441	0.230	0.421	0.234	0.423	0.227	0.419
Sunny indicator (1 if yes; otherwise, 0)	0.278	0.448	0.308	0.462	0.254	0.436	0.292	0.455	0.279	0.449	0.249	0.433
Cloudy indicator (1 if yes; otherwise, 0)	0.527	0.500	0.546	0.498	0.608	0.488	0.542	0.499	0.542	0.499	0.579	0.494
Rainy/snowy/foggy indicator (1 if yes; otherwise, 0)	0.195	0.396	0.145	0.352	0.138	0.345	0.166	0.372	0.180	0.384	0.172	0.378
Low visibility indicator (1 if below 50 meters; otherwise, 0)	0.107	0.310	0.118	0.323	0.048	0.215	0.110	0.313	0.090	0.286	0.023	0.150

Table 2: Continued.

Variables	2016-2017						2018-2019					
	W-beam		Flexible		Trees		W-beam		Flexible		Trees	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Medium-low visibility indicator (1 if 50–100 meters; otherwise, 0)	0.321	0.467	0.386	0.487	0.316	0.465	0.306	0.461	0.336	0.473	0.339	0.474
Medium visibility indicator (1 if 100–200; otherwise, 0)	0.331	0.471	0.321	0.467	0.405	0.491	0.247	0.431	0.294	0.456	0.393	0.489
High visibility indicator (1 if above 200 meters; otherwise, 0)	0.241	0.428	0.175	0.380	0.231	0.421	0.337	0.473	0.280	0.449	0.245	0.430
Daylight indicator (1 if yes; otherwise, 0)	0.443	0.497	0.468	0.499	0.448	0.498	0.486	0.500	0.498	0.500	0.442	0.497
Dark-lighted indicator (1 if yes; otherwise, 0)	0.352	0.478	0.380	0.486	0.490	0.500	0.312	0.464	0.358	0.480	0.512	0.500
Dark-no light indicator (1 if yes; otherwise, 0)	0.205	0.404	0.152	0.359	0.062	0.241	0.202	0.402	0.144	0.351	0.046	0.209
Temporal characteristics												
Weekends indicator (1 if yes; otherwise, 0)	0.716	0.451	0.749	0.434	0.731	0.444	0.701	0.458	0.678	0.468	0.744	0.436
Weekdays indicator (1 if yes; otherwise, 0)	0.284	0.451	0.251	0.434	0.269	0.444	0.299	0.458	0.322	0.468	0.256	0.436
Morning peak indicator (1 if 7:00–8:59; otherwise, 0)	0.240	0.427	0.206	0.404	0.238	0.426	0.255	0.436	0.208	0.406	0.212	0.409
Night time off-peak indicator (1 if 19:30–23:59; otherwise, 0)	0.169	0.375	0.128	0.335	0.127	0.333	0.138	0.345	0.130	0.336	0.110	0.314
Early morning indicator (1 if 00:00–7:00; otherwise, 0)	0.086	0.280	0.120	0.325	0.118	0.322	0.127	0.333	0.168	0.374	0.103	0.304
Afternoon peak indicator (1 if 17:00–19:29; otherwise, 0)	0.344	0.475	0.341	0.474	0.337	0.473	0.276	0.447	0.295	0.456	0.344	0.475
Daytime off-peak indicator (1 if 9:00–16:59; otherwise, 0)	0.161	0.368	0.206	0.404	0.180	0.385	0.205	0.404	0.199	0.399	0.230	0.421

Table 3: Model results for W-beam barriers crashes in 2016-2017.

Variables	Coefficient	t-stat	Pseudoelasticities (%)		
			Severe injury (SI)	Minor injury (MI)	No injury (NI)
Constant (SI)	−1.618***	−5.22	—	—	—
Constant (MI)	−1.466***	−3.61	—	—	—
Random parameter (normally distributed)					
Dark-lighted indicator (1 if yes; otherwise, 0) (MI)	0.693**	2.09	−9.77	35.78	−9.77
Standard deviation of the parameter density function	1.506**	2.06	—	—	—
Heterogeneity in the mean of random parameter					
Dark-lighted indicator (1 if yes; otherwise, 0) (MI): improper braking and steering indicator (1 if yes; otherwise, 0)	0.998*	1.74	—	—	—
Vehicle characteristics					
Truck indicator (1 if yes; otherwise, 0) (SI)	0.713***	3.46	12.06	−6.25	−6.40
Truck indicator (1 if yes; otherwise, 0) (MI)	−1.607***	−3.06	1.02	−39.21	1.02
Improper braking and steering indicator (1 if yes; otherwise, 0) (SI)	2.671***	6.45	90.31	−26.38	−27.64
Improper braking and steering indicator (1 if yes; otherwise, 0) (NI)	2.518***	6.37	−76.08	−69.30	35.09
Improper lane changing indicator (1 if yes; otherwise, 0) (MI)	−1.773***	−3.76	2.12	−14.69	2.12
Speeding indicator (1 if yes; otherwise, 0) (NI)	−2.634***	−6.49	3.95	3.95	−70.93
Nonlocal vehicle indicator (1 if yes; otherwise, 0) (SI)	0.544**	2.05	4.86	−2.39	−2.49
Roadway characteristics					
Road in bad condition indicator (1 if yes; otherwise, 0) (SI)	−1.725**	−2.22	−4.94	0.39	0.41
Road in bad condition indicator (1 if yes; otherwise, 0) (MI)	−2.040**	−2.17	0.44	−5.23	0.44
Homogeneous section indicator (1 if yes; otherwise, 0) (SI)	−1.576***	−8.28	−87.88	17.95	18.96
Homogeneous section indicator (1 if yes; otherwise, 0) (MI)	−1.010***	−3.44	8.44	−53.60	8.44
Intersection indicator (1 if yes; otherwise, 0) (NI)	1.033***	3.50	−11.37	−10.45	4.64
Ramp indicator (1 if yes; otherwise, 0) (NI)	2.079***	3.93	−7.08	−6.65	1.36
Large downhill grade indicator (1 if −2% or less vertical grade; otherwise, 0) (SI)	−1.764***	−3.99	−15.37	1.88	1.90
Crash characteristics					
Sideswipe indicator (1 if yes; otherwise, 0) (MI)	1.110***	3.84	−8.31	36.09	−8.31
Head-on collision indicator (1 if yes; otherwise, 0) (NI)	−0.962***	−3.32	4.84	4.62	−3.77
Sunny indicator (1 if yes; otherwise, 0) (SI)	−1.161***	−4.67	−28.81	3.42	3.48
Medium-low visibility indicator (1 if 50–100 meters; otherwise, 0) (SI)	0.691***	3.33	16.31	−5.46	−5.88
Low visibility indicator (1 if below 50 meters; otherwise, 0) (NI)	−0.738***	−2.69	4.57	4.07	−3.36
Dark lighted indicator (1 if yes; otherwise, 0) (SI)	−1.064***	−4.47	−33.18	2.98	4.26
Number of observations above and below zero generated from the random parameter	Above zero			Below zero	
Dark-lighted indicator (1 if yes; otherwise, 0) (MI)	97.14%			2.86%	
Goodness-of-fit measures					
McFadden R-squared	0.374				

***, **, *==> significance at 0.99, 0.95, and 0.90 level of confidence, respectively.

Table 4: Model results for W-beam barriers crashes in 2018-2019.

Variables	Coefficient	t-stat	Pseudoelasticities (%) Severe injury (SI)	Pseudoelasticities (%) Minor injury (MI)	Pseudoelasticities (%) No injury (NI)
Constant (SI)	−1.809***	−6.47	—	—	—
Constant (MI)	−2.094***	−6.84	—	—	—
Random parameter (normally distributed)					
Cloudy indicator (1 if yes; otherwise, 0) (MI)	−2.878**	−2.00	5.65	14.77	1.85
Standard deviation of the parameter density function	2.468**	2.11			
Novice driving experience indicator (1 if 3–10 years; otherwise, 0) (MI)	−3.593**	−2.37	0.13	−3.16	−1.63
Standard deviation of the parameter density function	2.700**	2.05	—	—	—
Heterogeneity in the mean of random parameter					
Cloudy indicator (1 if yes; otherwise, 0) (MI): dark-lighted indicator (1 if yes; otherwise, 0)	2.326*	1.74	—	—	—
Novice driving experience indicator (1 if 3–10 years; otherwise, 0) (MI): weekends indicator (1 if yes; otherwise, 0)	2.376**	2.33	—	—	—
Novice driving experience indicator (1 if 3–10 years; otherwise, 0) (MI): dark-lighted indicator (1 if yes; otherwise, 0)	3.516**	2.32	—	—	—
Heterogeneity in the variance of random parameter					
Cloudy indicator (1 if yes; otherwise, 0) (MI): road without isolation indicator (1 if yes; otherwise, 0)	0.775*	1.70	—	—	—
Cloudy indicator (1 if yes; otherwise, 0) (MI): intersection indicator (1 if yes; otherwise, 0)	1.212**	2.12	—	—	—
Driver characteristics					
Rookie driving experience indicator (1 if below 3 years; otherwise, 0) (MI)	−1.097*	−1.84	2.12	−7.07	1.56
Expert driving experience indicator (1 if above 15 years; otherwise, 0) (SI)	−0.758*	−1.93	−11.54	1.25	1.20
Driver under alcohol influence indicator (1 if yes; otherwise, 0) (MI)	3.997***	4.65	−24.51	17.44	−18.75
Driver under alcohol influence indicator (1 if yes; otherwise, 0) (NI)	1.020**	1.98	−8.94	−3.36	6.74
Vehicle characteristics					
Improper braking and steering indicator (1 if yes; otherwise, 0) (SI)	−1.515***	−5.18	−49.08	5.78	5.28
Speeding indicator (1 if yes otherwise, 0) (MI)	−1.276**	−2.26	2.17	−16.43	1.82
Improper lane changing indicator (1 if yes; otherwise, 0) (NI)	0.865***	2.77	−10.95	−7.52	3.10
Roadway characteristics					
Intersection indicator (1 if yes; otherwise, 0) (MI)	−0.799**	−2.26	1.83	−13.45	1.55
Crash characteristics					
Head-on collision indicator (1 if yes; otherwise, 0) (MI)	−4.872**	−2.54	1.13	−42.25	0.60
Low visibility indicator (1 if below 50 meters; otherwise, 0) (SI)	2.313**	1.99	19.40	−3.85	−4.26
Low visibility indicator (1 if below 50 meters; otherwise, 0) (NI)	2.193**	1.98	−16.47	−12.19	5.60
Medium visibility indicator (1 if 100–200 meters; otherwise, 0) (SI)	−1.113**	−2.47	−22.43	2.20	1.71
Medium visibility indicator (1 if 100–200 meters; otherwise, 0) (MI)	−1.338**	−2.44	4.22	−15.79	3.20
Temporal characteristics					
Weekends indicator (1 if yes; otherwise, 0) (SI)	−0.579*	−1.73	−13.85	1.27	1.41
Number of observations above and below zero generated from the random parameters	Above zero			Below zero	
Cloudy indicator (1 if yes; otherwise, 0) (MI)	15.32%			84.68%	
Novice driving experience indicator (1 if 3–10 years; otherwise, 0) (MI)	19.78%			80.22%	
Goodness-of-fit measures					
McFadden R-squared	0.355				

***, **, *==> significance at 0.99, 0.95, and 0.90 level of confidence, respectively.

2.86% of the cases. The improper braking and steering indicator were found to increase the mean of the dark-lighted indicator, further increasing the likelihood of minor injuries. This finding is in line with [6] who found that vehicles' impact with W-beam barriers resulted in severe injuries and that improper braking and steering were related to severe injuries in mountainous regions.

W-beam barriers exhibit a notably lower level of rigidity in comparison to concrete barriers. This heightened flexibility makes them more susceptible to inducing vehicle rollovers and instances of running off the road following a collision. As a result, when considering road safety measures, it may be prudent to opt for sturdier alternatives like concrete barriers, particularly in mountainous terrains. Furthermore, the installation of appropriate cautionary signage before areas with reduced visibility, especially those lacking adequate lighting, can play a crucial role in assisting drivers to avert unnecessary and potentially hazardous reactions such as abrupt braking or erratic steering.

In the scope of the 2018-2019 model, the indicators pertaining to cloudy weather and novice driving experience (spanning 3–10 years) emerged as statistically significant random parameters influencing the minor injury severity outcome. The majority of the instances demonstrated a low probability of minor injury occurrence, with rates of 84.68% for cloudy weather and 80.22% for novice driving experience. Interestingly, the presence of the dark-lighted indicator exhibited an effect on the mean of the cloudy weather indicator, leading to an elevated likelihood of minor injuries. Moreover, the weekend and dark-lighted indicators exerted an influence on the mean of the driving experience indicator, thereby contributing to an increased probability of minor injuries. In a broader context, existing literature indicates a connection between nighttime crashes, even those under sufficient lighting conditions, and the occurrence of injuries—often severe ones—in mountainous regions [34, 35]. With the objective of achieving this goal, it is advisable to contemplate the implementation of highly effective street lighting along extended stretches of mountainous terrain. This strategic measure would serve to enhance visibility levels during nighttime scenarios. The variance of the cloudy weather indicator is affected by the following two variables: the road without isolation and the intersection indicators in the 2018-2019 period (Table 4). Both variables increased the variance of cloudy weather indicator in the minor injury outcome, reflecting higher variability.

The model estimation results and corresponding pseudoelasticities for the flexible barrier crashes are presented in Tables 5 and 6 for 2016-2017 and 2018-2019, respectively.

In the context of the 2016-2017 model, the indicator for roads lacking isolation demonstrated statistical significance as a random parameter within the context of the no injury severity outcome. This indicator resulted in an increased probability of no injury in 89.15% of the recorded crashes, with the remaining cases experiencing a reduction in this probability. Notably, the presence of the homogeneous section indicator led to a reduction in the mean of the road without isolation indicator, thereby decreasing the likelihood of no injuries. It is worth highlighting that, in the same period (as shown in Table 5), the variability of the road without isolation indicator within the no injury severity outcome was influenced by the high visibility indicator (visibility exceeding 200 meters). This influence contributed to an altered variance, leading to a more uniformly distributed parameter density function of the betas, flattening the tail of the distribution. This observation could potentially capture the behavior of drivers who perceive high visibility conditions on homogeneous sections without isolation as safe or low risk. Consequently, such drivers might exhibit decreased vigilance or a reduced level of alertness while driving under these conditions.

Regarding the 2018-2019 models, the random parameters associated with medium-low visibility (ranging from 50 to 100 meters) and the dark-lighted conditions within the no injury severity outcome displayed notable statistical significance. In particular, the medium-low visibility indicator led to a heightened probability of no injury in 72.91% of the recorded instances, while 27.09% experienced a decrease. On the other hand, the dark-lighted indicator contributed to a decrease in the probability of no injury in 86.26% of the observations, with an increase in the remaining 13.74%. The presence of indicators denoting rainy, snowy, or foggy weather, as well as the winter season, was observed to elevate the mean of the medium-low visibility indicator, thereby rendering no injuries more likely. Conversely, the road without the isolation indicator was associated with a lowered mean for the medium-low visibility parameter, resulting in reduced likelihood of no injuries. In the case of the dark with the road streetlights indicator, the head-on collision and summer season indicators led to an increased mean, heightening the likelihood of no injuries. Conversely, the winter season indicator caused a decrease in the mean of the darkness with the road streetlights indicator, diminishing the likelihood of no injuries.

The model estimation results and corresponding pseudoelasticities for the roadside-tree crashes are presented in Tables 7 and 8 for the 2016-2017 and 2018-2019 periods, respectively. In the 2016-2017 model, the absence of an isolation indicator on the road showed a statistically significant impact on the outcome of no injury severity. Specifically, a random parameter analysis revealed that this factor had a notable effect. Out of the total crashes studied, approximately 82.59% experienced an elevation in the probability of no injury, while the remaining cases showed a reduction in this probability. The wet-surface and dark-lighted indicators were found to decrease the mean of the road without the isolation indicator, making no injuries less likely. Drivers may change lanes frequently when driving on a road without isolation. Such maneuvers, when associated with lower visibility during nighttime, can result in higher injury severities. In addition, roadside trees can increase the risk of collision by blocking the driver's line of sight, especially on curvy roads. Consequently, roadside trees need regular inspection (and, possibly, trimming) to prevent them from obstructing the drivers' line of sight.

In the context of the 2018-2019 model, the winter season indicator displayed statistical significance as a random parameter in relation to the no injury outcome. Notably, this

Table 5: Model results for flexible barriers crashes in 2016-2017.

Variables	Coefficient	t-stat	Pseudoelasticities (%) Severe injury (SI)	Minor injury (MI)	No injury (NI)
Constant (NI)	1.198**	1.98	—	—	—
Constant (MI)	1.194**	2.10	—	—	—
Random parameter (normally distributed)					
Road without isolation indicator (1 yes; otherwise, 0) (NI)	1.689***	2.98	−4.22	−4.22	12.14
Standard deviation of the parameter density function	1.490***	2.85	—	—	—
Heterogeneity in the mean of random parameter					
Road without isolation indicator (1 if yes; otherwise, 0) (NI): homogeneous section indicator (1 if yes; otherwise, 0)	−0.916**	−2.01	—	—	—
Heterogeneity in the variance of random parameter					
Road without isolation indicator (1 if yes; otherwise, 0) (NI): high visibility indicator (1 if above 200 meters; otherwise, 0)	1.149**	2.35	—	—	—
Driver characteristics					
No seatbelt use indicator (1 if yes; otherwise, 0) (SI)	1.624***	3.01	11.84	−5.77	−3.28
Driver under alcohol influence indicator (1 if yes; otherwise, 0) (NI)	−2.280***	−6.26	6.12	6.12	−25.95
Vehicle characteristics					
Truck indicator (1 if yes; otherwise, 0) (MI)	−2.443***	−4.33	4.08	−30.67	2.36
Truck indicator (1 if yes; otherwise, 0) (NI)	−0.847*	−1.81	5.90	5.90	−2.97
Speeding indicator (1 if yes; otherwise, 0) (SI)	1.903***	3.47	35.25	−10.85	−4.03
Speeding indicator (1 if yes; otherwise, 0) (NI)	1.489***	3.66	−21.89	−21.89	5.52
Roadway characteristics					
Homogeneous section indicator (1 if yes; otherwise, 0) (SI)	−1.600***	−3.57	−103.25	16.86	7.40
Small uphill grade indicator (1 if 0–2% vertical grade; otherwise, 0) (SI)	−1.026***	−2.74	−66.45	10.25	4.41
Crash characteristics					
Sideswipe indicator (1 if yes; otherwise, 0) (SI)	−1.316***	−3.53	−71.14	8.40	3.54
Summer indicator (1 if yes; otherwise, 0) (SI)	−1.117**	−2.16	−27.74	2.47	0.95
Medium visibility indicator (1 if 100–200 meters; otherwise, 0) (SI)	−1.005**	−1.96	−30.22	2.06	1.12
High visibility indicator (1 if above 200 meters; otherwise, 0) (MI)	−1.526***	−2.73	6.82	−19.83	2.18
Daylight indicator (1 if yes; otherwise, 0) (SI)	2.310***	4.60	83.99	−24.02	−8.83
Daylight indicator (1 if yes; otherwise, 0) (NI)	1.988***	6.24	−55.75	−55.75	14.62
Temporal characteristics					
Morning peak indicator (1 if time 7:00–8:59; otherwise, 0) (SI)	1.368***	2.59	23.06	−5.06	−3.46
Morning peak indicator (1 if time 7:00–8:59; otherwise, 0) (MI)	0.950***	2.94	−10.09	9.44	−7.64
Afternoon peak indicator (1 if time 17:00–19:29; otherwise, 0) (NI)	0.709***	2.98	−12.04	−12.04	7.39
Number of observations above and below zero generated from the random parameter	Above zero			Below zero	
Road without isolation indicator (1 if yes; otherwise, 0) (NI)	89.15%			10.85%	
Goodness-of-fit measures					
McFadden R-squared	0.435				

***, **, *==> significance at 0.99, 0.95, and 0.90 level of confidence, respectively.

Table 6: Model results for flexible barriers crashes in 2018-2019.

Variables	Coefficient	t-stat	Pseudoelasticities (%)		
			Severe injury (SI)	Minor injury (MI)	No injury (NI)
Constant (SI)	−1.663***	−4.15	—	—	—
Constant (MI)	−1.414***	−3.21	—	—	—
Random parameter (normally distributed)					
Medium-low visibility indicator (1 if 50–100 meters; otherwise, 0) (NI)	2.068***	2.95	−22.07	−22.07	8.63
Standard deviation of parameter density function	1.570*	1.74			
Dark-lighted indicator (1 if yes; otherwise, 0) (NI)	−2.660***	−4.08	20.97	20.97	−22.66
Standard deviation of the parameter density function	1.822**	2.04	—	—	—
Heterogeneity in the mean of random parameters					
Medium-low visibility indicator (1 if 50–100 meters; otherwise, 0) (NI): road without isolation indicator (1 if yes; otherwise, 0)	−2.157***	−3.13	—	—	—
Medium-low visibility indicator (1 if 50–100 meters; otherwise, 0) (NI): rainy/snowy/foggy indicator (1 if yes; otherwise, 0)	1.635**	2.03	—	—	—
Medium-low visibility indicator (1 if 50–100 meters; otherwise, 0) (NI): winter indicator (1 if yes; otherwise, 0)	1.755**	2.18	—	—	—
Dark-lighted indicator (1 if yes; otherwise, 0) (NI): head-on collision indicator (1 if yes; otherwise, 0)	2.748**	2.04	—	—	—
Dark-lighted indicator (1 if yes; otherwise, 0) (NI): winter indicator (1 if yes; otherwise, 0)	−2.137***	−2.68	—	—	—
Dark-lighted indicator (1 if yes; otherwise, 0) (NI): summer indicator (1 if yes; otherwise, 0)	1.925**	2.52	—	—	—
Driver characteristics					
Young driver indicator (1 if below 25-years-old; otherwise, 0) (SI)	−1.641**	−2.09	−21.66	0.46	0.41
Driver under alcohol influence indicator (1 if yes; otherwise, 0) (SI)	−2.178***	−3.90	−35.52	2.22	1.71
Driver under alcohol influence indicator (1 if yes; otherwise, 0) (NI)	−2.340***	−5.63	9.44	9.44	−20.86
No seatbelt use indicator (1 if yes; otherwise, 0) (SI)	1.119**	2.41	9.03	−2.89	−1.83
Vehicle characteristics					
Truck indicator (1 if yes; otherwise, 0) (SI)	1.882***	5.56	20.28	−8.22	−6.86
Improper braking and steering indicator (1 if yes; otherwise, 0) (SI)	−0.777**	−2.15	−23.78	2.15	1.72
Speeding indicator (1 if yes; otherwise, 0) (NI)	0.945***	3.41	−18.47	−18.47	4.23
Roadway characteristics					
Road without isolation indicator (1 if yes; otherwise, 0) (NI)	1.025***	4.04	−39.77	−39.77	18.27
Wet surface indicator (1 if yes; otherwise, 0) (MI)	1.087***	2.86	−14.38	16.32	−8.67
Tunnel indicator (1 if yes; otherwise, 0) (MI)	−1.191***	−4.41	31.69	−61.86	18.83
Intersection indicator (1 if yes; otherwise, 0) (NI)	0.966**	2.51	−10.26	−10.26	2.91
Large downhill grade indicator (1 if −2% or less vertical grade; otherwise, 0) (SI)	2.327***	4.44	5.14	−3.52	−3.08
Crash characteristics					
Head-on collision indicator (1 if yes; otherwise, 0) (MI)	−1.514***	−2.72	3.15	−15.12	1.45
Summer indicator (1 if yes; otherwise, 0) (SI)	−1.207***	−2.97	−29.84	2.24	1.66
Sunny indicator (1 if yes; otherwise, 0) (SI)	−0.681*	−1.94	−17.14	1.84	1.39
Low visibility indicator (1 if below 50 meters; otherwise, 0) (MI)	1.106***	2.58	−4.38	5.55	−3.71
Medium visibility indicator (1 if 100–200 meters; otherwise, 0) (NI)	1.181***	4.05	−12.62	−12.62	9.18
Dark-lighted indicator (1 if yes; otherwise, 0) (SI)	−3.828***	−5.92	−134.05	3.04	1.15

Table 6: Continued.

Variables	Coefficient	t-stat	Pseudoelasticities (%)		
			Severe injury (SI)	Minor injury (MI)	No injury (NI)
Dark-no light indicator (1 if yes; otherwise, 0) (MI)	0.848**	2.32	−4.00	8.20	−3.32
Number of observations above and below zero generated from the random parameters	Above zero			Below zero	
Medium-low visibility indicator (1 if 50–100 meters; otherwise, 0) (NI)	72.91%			27.09%	
Dark lighted indicator (1 if yes; otherwise, 0) (NI)	13.74%			86.26%	
Goodness-of-fit measures					
McFadden R-squared	0.484				

***, **, *==> significance at 0.99, 0.95, and 0.90 level of confidence, respectively.

Table 7: Model results for roadside trees barriers crashes in 2016-2017.

Variables	Coefficient	t-stat	Pseudoelasticities (%) Severe injury (SI)	Minor injury (MI)	No injury (NI)
Constant (SI)	−2.238***	−6.76	—	—	—
Constant (MI)	−1.303***	−2.79	—	—	—
Random parameter (normally distributed)					
Road without isolation indicator (1 if yes; otherwise, 0) (NI)	5.974*	1.78	3.84	3.84	−0.73
Standard deviation of the parameter density function	5.494**	1.97	—	—	—
Heterogeneity in the mean of random parameter					
Road without isolation indicator (1 if yes; otherwise, 0) (NI): wet surface indicator (1 if yes; otherwise, 0)	−2.913*	−1.70	—	—	—
Road without isolation indicator (1 if yes; otherwise, 0) (NI): dark-lighted indicator (1 if yes; otherwise, 0)	−5.237*	−1.79	—	—	—
Driver characteristics					
Expert driving experience indicator (1 if above 15 years; otherwise, 0) (SI)	−0.718**	−2.09	−11.72	1.37	0.70
Driver under alcohol influence indicator (1 if yes; otherwise, 0) (MI)	2.057***	9.10	−19.69	16.88	−14.37
Vehicle characteristics					
Truck indicator (1 if yes; otherwise, 0) (SI)	1.119***	4.09	12.35	−4.98	−3.03
Truck indicator (1 if yes; otherwise, 0) (MI)	−2.335***	−4.86	1.73	−34.45	1.01
Improper braking and steering indicator (1 if yes; otherwise, 0) (SI)	−1.722***	−6.83	−65.71	7.12	3.34
Improper lane changing indicator (1 if yes; otherwise, 0) (SI)	−1.468***	−3.75	−17.21	1.93	1.10
Roadway characteristics					
Wet surface indicator (1 if yes; otherwise, 0) (SI)	−0.709**	−2.23	−13.71	1.60	0.89
Intersection indicator (1 if yes; otherwise, 0) (MI)	−0.622**	−2.09	2.00	−8.88	1.11
Small downhill grade indicator (1 if −2–0% vertical grade; otherwise, 0) (SI)	−2.548**	−2.20	−15.69	0.57	0.16
Small uphill grade indicator (1 if 0–2% vertical grade; otherwise, 0) (MI)	−1.424***	−8.49	26.80	−100.63	18.01
Crash characteristics					
Head-on collision indicator (1 if yes; otherwise, 0) (NI)	1.136*	1.88	−2.42	−2.42	0.54
Autumn indicator (1 if yes; otherwise, 0) (SI)	−0.501*	−1.81	−11.56	1.63	0.92
Winter indicator (1 if yes; otherwise, 0) (MI)	0.766***	2.92	−3.48	6.22	−2.83
Summer indicator (1 if yes; otherwise, 0) (NI)	0.435**	2.22	−10.69	−10.69	2.40
Sunny indicator (1 if yes; otherwise, 0) (MI)	−0.891**	−2.20	1.75	−20.91	0.85
Sunny indicator (1 if yes; otherwise, 0) (NI)	0.444*	1.69	−8.46	−8.46	1.47
Dark lighted indicator (1 if yes; otherwise, 0) (SI)	−1.282***	−4.71	−57.56	5.20	3.32
Temporal characteristics					
Nighttime off-peak indicator (1 if time 19:30–23:59; otherwise, 0) (SI)	−1.285***	−3.07	−14.25	2.03	0.87
Nighttime off-peak indicator (1 if time 19:30–23:59; otherwise, 0) (MI)	−1.522***	−2.81	1.60	−17.69	0.54
Early morning indicator (1 if time 00:00–7:00; otherwise, 0) (MI)	−1.759***	−2.87	1.04	−19.64	0.48
Number of observations above and below zero generated from the random parameter	Above zero			Below zero	
Road without isolation indicator (1 if yes; otherwise, 0) (NI)	82.59%			17.41%	
Goodness-of-fit measures					
McFadden R-squared	0.478				

***, **, *==> significance at 0.99, 0.95, and 0.90 level of confidence, respectively.

Table 8: Model results for roadside trees barriers crashes in 2018-2019.

Variables	Coefficient	t-stat	Pseudoelasticities (%)		
			Severe injury (SI)	Minor injury (MI)	No injury (NI)
Constant (SI)	−2.895***	−9.51	—	—	—
Constant (MI)	−1.454***	−9.56	—	—	—
Random parameter (normally distributed)					
Winter indicator (1 if yes; otherwise, 0) (NI)	1.356***	2.89	−0.03	−0.03	0.39
Standard deviation of the parameter density function	1.737*	1.85	—	—	—
Heterogeneity in the mean of random parameter					
Winter indicator (1 if yes; otherwise, 0) (NI): rainy/snowy/foggy indicator (1 if yes; otherwise, 0)	−1.246**	−2.48	—	—	—
Winter indicator (1 if yes; otherwise, 0) (NI): head-on collision indicator (1 if yes; otherwise, 0)	−1.396**	−2.41	—	—	—
Driver characteristics					
Female indicator (1 if yes; otherwise, 0) (SI)	−1.750***	−2.91	−19.58	0.49	0.40
Young driver indicator (1 if below 25-years-old; otherwise, 0) (SI)	−0.952**	−2.27	−11.63	0.74	0.61
Rookie driving experience indicator (1 if below 3 years; otherwise, 0) (NI)	0.580**	2.44	−4.18	−4.18	1.84
Intermediate driving experience indicator (1 if 10–15 years; otherwise, 0) (SI)	−1.460***	−3.71	−20.69	1.14	0.95
Intermediate driving experience indicator (1 if 10–15 years; otherwise, 0) (MI)	−0.351*	−1.68	1.63	−3.62	1.32
Expert driving experience indicator (1 if above 15 years; otherwise, 0) (SI)	−0.973***	−3.09	−15.59	1.35	1.11
Driver under alcohol influence indicator (1 if yes; otherwise, 0) (MI)	1.542***	8.84	−17.39	14.05	−14.96
No seatbelt use indicator (1 if yes; otherwise, 0) (MI)	1.040***	3.51	1.00	−4.79	0.81
Vehicle characteristics					
Truck indicator (1 if yes; otherwise, 0) (SI)	2.014***	5.66	19.51	−5.82	−5.00
Truck indicator (1 if yes; otherwise, 0) (NI)	−2.332***	−4.86	−8.44	−8.44	4.03
Roadway characteristics					
Road without isolation indicator (1 if yes; otherwise, 0) (NI)	0.768***	4.19	−10.67	−10.67	4.38
Large uphill grade indicator (1 if 2% or greater vertical grade; otherwise, 0) (NI)	1.144*	1.98	−1.80	−1.80	0.39
Crash characteristics					
Head-on collision indicator (1 if yes; otherwise, 0) (SI)	−1.452***	−4.11	−26.63	1.75	1.28
Head-on collision indicator (1 if yes; otherwise, 0) (MI)	−0.618***	−2.99	4.00	−8.07	3.18
Summer indicator (1 if yes; otherwise, 0) (SI)	−0.728***	−2.71	−16.95	1.24	1.24
Autumn indicator (1 if yes; otherwise, 0) (MI)	−0.304*	−1.82	2.01	−4.88	2.01
Rainy/snowy/foggy indicator (1 if yes; otherwise, 0) (NI)	1.020***	4.28	−10.40	−10.40	4.77
Low visibility indicator (1 if below 50 meters; otherwise, 0) (MI)	1.764***	3.59	−2.12	1.93	−1.95
Medium visibility indicator (1 if 100–200 meters; otherwise, 0) (MI)	−0.348**	−2.54	4.13	−9.57	3.27
Dark-no light indicator (1 if yes; otherwise, 0) (NI)	1.314***	3.46	−4.31	−4.31	1.32
Temporal characteristics					
Nighttime off-peak indicator (1 if time 19:30–23:59; otherwise, 0) (SI)	−1.691***	−3.91	−17.28	1.40	0.96
Nighttime off-peak indicator (1 if time 19:30–23:59; otherwise, 0) (MI)	−0.713***	−2.63	1.70	−6.18	1.24
Early morning indicator (1 if time 00:00–7:00; otherwise, 0) (SI)	−1.768***	−3.31	−17.46	0.72	0.60
Daytime off-peak indicator (1 if time 9:00–16:59; otherwise, 0) (SI)	−0.581**	−2.34	−11.98	1.39	1.19
Number of observations above and below zero generated from the random parameter	Above zero			Below zero	
Winter indicator (1 if yes; otherwise, 0) (NI)	78.08%			21.92%	
Goodness-of-fit measures					
McFadden R-squared	0.307				

***, **, *==> significance at 0.99, 0.95, and 0.90 level of confidence, respectively.

indicator had a significant impact. Among the analyzed crashes, approximately 78.08% demonstrated an upsurge in the probability of no injury, while the remaining instances exhibited a reduction in this probability. The rainy/snowy/foggy weather indicator and the head-on collision indicator were found to decrease the mean of the road without the isolation indicator, thus making no injuries less likely. During the winter months, low temperatures on mountainous regions, alongside with snow and ice on the road, will likely result in poor pavement friction, which in turn will result in higher injury severities.

In addition, a number of explanatory variables were found to be statistically significant for each specific barrier type. For example, the indicators for novice (3–10 years) driving experience, road in bad condition, ramp, cloudy, weekend, and nonlocal vehicles were only significant for the W-beam barriers models. The indicators for tunnel, morning peak, afternoon peak, daylight, and high visibility (200 meters or greater) were only significant for the flexible barriers models. The indicators for female driver, intermediate (10–15 years) driving experience, low (0–2%) vertical grade, high (2% or greater) vertical grade, rainy/snow/foggy, autumn, winter, early morning, daytime off-peak, and nighttime off-peak were only significant for the roadside trees barriers models.

The temporal stability of each roadside barrier type, in terms of their pseudoelasticities, also deserves some attention. For W-beam barrier crashes, the improper braking and steering indicator, the speeding indicator, and the low (less than 50 meters) visibility indicator significantly affected the driver injury severity outcomes across both time periods. The improper braking and steering indicator increased the probability of severe injury by 90.31% for 2016-2017, while it decreased the likelihood of severe injury by 49.08% for 2018-2019. The low visibility (less than 50 meters) indicator was also found to produce opposite effects. The effect of low visibility on no injury probabilities varied from −3.36% in 2016-2017 to 5.60% in 2018-2019. Only the speeding indicator demonstrates relative sings of stable pseudoelasticities, decreasing the likelihood of no injury by 70.93% and 16.43% for 2016-2017 and 2018-2019, respectively.

For flexible barrier crashes, four variables (driver without seatbelt indicator, driver under alcohol influence indicator, speeding indicator, and summer season indicator) significantly affected driver injury severity across both time periods. The driver without the seatbelt indicator increased the likelihood of severe injury by 11.84% and 9.03% for 2016-2017 and 2018-2019, respectively. The driver under the alcohol influence indicator decreased the likelihood of no injury by 25.95% and 20.86% for 2016-2017 and 2018-2019, respectively. The speeding indicator decreased the likelihood of no injury by 5.52% and 4.23% for 2016-2017 and 2018-2019, respectively. And, the summer season indicator decreased the probability of severe injury by 27.74% and 29.84% for 2016-2017 and 2018-2019, respectively.

For roadside tree crashes, five variables (the expert, i.e., 15 years or greater driving experience indicator, the driver under the alcohol influence indicator, the truck indicator, the road without the isolation indicator, and the nighttime off-peak hour indicator) significantly affected driver's injury severity across both time periods. The expert (15 years or greater) driving experience indicator decreased the likelihood of severe injury by 11.72% and 15.59% for 2016-2017 and 2018-2019, respectively. The driver under the alcohol influence indicator increased the likelihood of minor injury by 16.88% and 14.05% for 2016-2017 and 2018-2019, respectively. The truck indicator increased the likelihood of severe injury by 12.35% and 19.51% for 2016-2017 and 2018-2019, respectively. The nighttime off-peak hour indicator decreased the likelihood of minor injury by 17.69% and 6.18% for 2016-2017 and 2018-2019, respectively. Lastly, it is noteworthy that the effect of the road without the isolation indicator on the no injury outcome probabilities changed from −0.73 in 2016-2017 to 4.38 in 2018-2019.

5. Discussion and Conclusion

Leveraging crash data extracted from mountainous regions within a city in Southwest China, spanning the period from 2016 to 2019, this research utilized the random parameters logit model with heterogeneity in means and variances (RPLHMVs). The aim was to discern the determinants influencing crash-injury severity, focusing on three prevalent types of roadside barriers, namely, W-beam, flexible, and roadside trees. Going beyond conventional cause-and-effect exploration, this study delved into the dynamic shifts of these effects over time and across distinct barrier categories. The investigation encompassed the following three tiers of driver injury severity: no injury, minor injury, and severe injury. The outcomes extracted from the estimated models unveiled a diverse array of factors tied to driver, vehicle, road, environment, and temporal aspects that influence the severity of driver injuries. The principal findings are succinctly outlined as follows:

(1) The utilization of the random parameters logit model with heterogeneity in means and variances (RPLHMVs) presents an enhanced statistical fitting and imparts further insights when contrasted with its conventional lower-order logit model counterparts. By accommodating variations in the explanatory variables across observations and accounting for factors influencing the means and variances of the parameter density functions of the random parameters, this approach facilitates the identification of supplementary factors that might contribute to revealing the genuine impact of a parameter on injury severity.

(2) The effects of the explanatory factors are found to vary across different roadside barriers. Specifically, the indicators representing novice (3–10 years) driving experience, road in bad condition, ramp, cloudy weather, weekend, and nonlocal vehicles were only significant for the W-beam barriers models. The indicators representing presence of a tunnel, morning peak, afternoon peak, daylight, and high (200 meters or greater) visibility were only significant for the flexible barriers models. The indicators for

female drivers, intermediate (10–15 years) driving experience, low (0–2%) vertical grade, high (2% or greater) vertical grade, rainy/snow/foggy, autumn, winter, early morning, daytime off-peak, and nighttime off-peak were only significant for the roadside trees barriers models. In contrast, the head-on collision indicator was found to produce consistent effects on accident injury severities across all barriers.

(3) Overall, the effect of factors that determine injury severities in each barrier-specific model changed significantly over time. Some of the influencing factors involving flexible barriers or roadside trees had relatively stable pseudoelasticities over time, whereas only the speeding indicator showed temporally stable pseudoelasticities in crashes involving W-beam barriers.

The conclusions drawn from this analysis carry several practical implications as well. (1) This study revealed the variation in the crash-injury severity across different barriers. The outcomes hold the potential to contribute to the formulation of novel guidelines for the design and choice of roadside barriers in mountainous terrains. For instance, in light of the findings indicating a higher frequency of severe-injury crashes linked to W-beam barriers, it may be advisable to consider rigid options like concrete barriers as more appropriate for mountainous road conditions. Roadside trees need regular checking and trimming to prevent them from obstructing the drivers' line of sight. (2) This study confirmed the temporal instability of the effect of explanatory variables in barrier-related models. In pursuit of this objective, variables demonstrating consistent and stable elasticities over time are presumed to hold greater significance in devising enduring strategies aimed at augmenting traffic safety on mountainous roadways. However, extreme caution should be exercised when taking temporally instable variables into account to form the basis of long-term strategies and policy interventions for effective improvement in traffic safety. The temporal instability detected through our analysis naturally warranties estimation of barrier type-specific models over each time period of analysis (herein, every one-two year).

Prospective future studies could delve into collisions encompassing supplementary types of roadside barriers, spanning both urban and rural contexts. Such research endeavors would offer a more holistic panorama of the variations in crash-injury severities associated with diverse roadside barrier options. This, in turn, would contribute to the development of suitable protective measures aimed at mitigating crash-injury severity within mountainous regions.

Data Availability

Access to data used to support the findings of this study is restricted.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was supported by the National Key R&D Program of China (no. 2021YFA1000304).

References

[1] Traffic Administration Bureau of Police Ministry (TABPM), *Road Traffic Accident Annual Census Report of China*, Traffic Management Bureau, Beijing, China, 2017.

[2] R. Yu, Y. Xiong, and M. Abdel-Aty, "A correlated random parameter approach to investigate the effects of weather conditions on crash risk for a mountainous freeway," *Transportation Research Part C: Emerging Technologies*, vol. 50, pp. 68–77, 2015.

[3] A. Mehrara Molan, M. Moomen, and K. Ksaibati, "Investigating the effect of geometric dimensions of median traffic barriers on crashes: crash analysis of interstate roads in Wyoming using actual crash datasets," *Journal of Safety Research*, vol. 71, pp. 163–171, 2019.

[4] A. Mehrara Molan, M. Moomen, and K. Ksaibati, "The impact of traffic barrier geometric features on crash frequency and injury severity of non-interstate highways," *Journal of Safety Research*, vol. 75, pp. 155–165, 2020a.

[5] A. Mehrara Molan, M. Rezapour, and K. Ksaibati, "Investigating the relationship between crash severity, traffic barrier type, and vehicle type in crashes involving traffic barrier," *Journal of Traffic and Transportation Engineering*, vol. 7, no. 1, pp. 125–136, 2020b.

[6] M. Rezapour, M. Moomen, and K. Ksaibati, "Ordered logistic models of influencing factors on crash injury severity of single and multiple-vehicle downgrade crashes: a case study in Wyoming," *Journal of Safety Research*, vol. 68, pp. 107–118, 2019.

[7] M. Rezapour, S. Wulff, and K. Ksaibati, "Examination of the severity of two-lane highway traffic barrier crashes using the mixed logit model," *Journal of Safety Research*, vol. 70, pp. 223–232, 2019.

[8] M. Rezapour, A. Mehrara Molan, and K. Ksaibati, "Analyzing injury severity of motorcycle at-fault crashes using machine learning techniques, decision tree and logistic regression models," *International Journal of Transportation Science and Technology*, vol. 9, no. 2, pp. 89–99, 2020.

[9] W. Hu and E. Donnell, "Median barrier crash severity: some new insights," *Accident Analysis and Prevention*, vol. 42, no. 6, pp. 1697–1704, 2010.

[10] B. Russo and P. Savolainen, "A comparison of freeway median crash frequency, severity, and barrier strike outcomes by median barrier type," *Accident Analysis and Prevention*, vol. 117, pp. 216–224, 2018.

[11] Y. Zou, A. Tarko, E. Chen, and M. Romero, "Effectiveness of cable barriers, guardrails, and concrete barrier walls in reducing the risk of injury," *Accident Analysis and Prevention*, vol. 72, pp. 55–65, 2014.

[12] J. Park, M. Abdel-Aty, and J. Lee, "Use of empirical and full bayes before–after approaches to estimate the safety effects of roadside barriers with different crash conditions," *Journal of Safety Research*, vol. 58, pp. 31–40, 2016.

[13] M. Hosseinpour and K. Haleem, "Examining crash injury severity and barrier-hit outcomes from cable barriers and strong-post guardrails on Alabama's interstate highways," *Journal of Safety Research*, vol. 78, pp. 155–169, 2021.

[14] F. Mannering, "Temporal instability and the analysis of highway accident data," *Analytic Methods in Accident Research*, vol. 17, pp. 1–13, 2018.
[15] Q. Hou, X. Huo, J. Leng, and F. Mannering, "A note on out-of-sample prediction, marginal effects computations, and temporal testing with random parameters crash-injury severity models," *Analytic Methods in Accident Research*, vol. 33, Article ID 100191, 2022.
[16] S. Washington, M. Karlaftis, F. Mannering, and P. Anastasopoulos, *Statistical and Econometric Methods for Transportation Data Analysis*, CRC Press, Taylor and Francis Group, New York, NY, USA, 3rd edition, 2020.
[17] P. Anastasopoulos and F. Mannering, "An empirical assessment of fixed and random parameter logit models using crash- and non-crash-specific injury data," *Accident Analysis and Prevention*, vol. 43, no. 3, pp. 1140–1147, 2011.
[18] S. Ahmed, J. Cohen, and P. Anastasopoulos, "A correlated random parameters with heterogeneity in means approach of deer-vehicle collisions and resulting injury-severities," *Analytic Methods in Accident Research*, vol. 30, Article ID 100160, 2021.
[19] F. L. Mannering and C. R. Bhat, "Analytic methods in accident research: methodological Frontier and future directions," *Analytic Methods in Accident Research*, vol. 1, pp. 1–22, 2014.
[20] G. Fountas and P. Anastasopoulos, "A random thresholds random parameters hierarchical ordered probit analysis of highway accident injury-severities," *Analytic Methods in Accident Research*, vol. 15, pp. 1–16, 2017.
[21] G. Fountas, P. Anastasopoulos, and M. Abdel-Aty, "Analysis of accident injury-severities using a correlated random parameter ordered probit approach with time variant covariates," *Analytic Methods in Accident Research*, vol. 18, pp. 57–68, 2018.
[22] F. Mannering, V. Shankar, and C. Bhat, "Unobserved heterogeneity and the statistical analysis of highway accident data," *Analytic Methods in Accident Research*, vol. 11, pp. 1–16, 2016.
[23] F. Ye, C. Wang, W. Cheng, and H. Liu, "Exploring factors associated with cyclist injury severity in vehicle-electric bicycle crashes based on a random parameter logit model," *Journal of Advanced Transportation*, vol. 2021, Article ID 5563704, 12 pages, 2021.
[24] C. Wang, P. Zhang, F. Chen, and J. Cheng, "Modeling injury severity for nighttime and daytime crashes by using random parameter logit models accounting for heterogeneity in means and variances," *Journal of Advanced Transportation*, vol. 2022, Article ID 7871338, 12 pages, 2022.
[25] M. A. Seyfi, K. Aghabayk, A. M. Karimi Mamaghan, and N. Shiwakoti, "Modeling the motorcycle crash severity on nonintersection urban roadways in the Australian state of victoria using a random parameters logit model," *Journal of Advanced Transportation*, vol. 2023, Article ID 2250590, 12 pages, 2023.
[26] D. Mcfadden and K. Train, "Mixed MNL models for discrete response," *Journal of Applied Econometrics*, vol. 15, no. 5, pp. 447–470, 2000.
[27] A. Behnood and F. L. Mannering, "The temporal stability of factors affecting driver-injury severities in single-vehicle crashes: some empirical evidence," *Analytic Methods in Accident Research*, vol. 8, pp. 7–32, 2015.
[28] A. Behnood and F. Mannering, "Determinants of bicyclist injury severities in bicycle-vehicle crashes: a random parameters approach with heterogeneity in means and variances," *Analytic Methods in Accident Research*, vol. 16, pp. 35–47, 2017.
[29] A. Behnood and F. Mannering, "The effect of passengers on driver-injury severities in single-vehicle crashes: a random parameters heterogeneity-in-means approach," *Analytic Methods in Accident Research*, vol. 14, pp. 41–53, 2017.
[30] A. Behnood and F. Mannering, "Time-of-day variations and temporal instability of factors affecting injury severities in large-truck crashes," *Analytic Methods in Accident Research*, vol. 23, Article ID 100102, 2019.
[31] Q. Wu, D. Song, C. Wang et al., "Analysis of injury severity of drivers involved different types of two-vehicle crashes using random-parameters logit models with heterogeneity in means and variances," *Journal of Advanced Transportation*, vol. 2023, Article ID 3399631, 15 pages, 2023.
[32] C. Wang, S. M. Easa, D. Song, F. Chen, F. Xiao, and J. Cheng, "Alternative unobserved heterogeneity models to analyze injury severity of expressway crashes in different tunnel types," *Tunnelling and Underground Space Technology*, vol. 140, Article ID 105245, 2023.
[33] D. Song, X. Yang, P. C. Anastasopoulos, X. Zu, X. Yue, and Y. Yang, "Temporal stability of the impact of factors determining drivers' injury severities across traffic barrier crashes in mountainous regions," *Analytic Methods in Accident Research*, vol. 39, Article ID 100282, 2023.
[34] H. Wen and G. Xue, "Injury severity analysis of familiar drivers and unfamiliar drivers in single-vehicle crashes on the mountainous highways," *Accident Analysis and Prevention*, vol. 144, Article ID 105667, 2020.
[35] M. Yu, C. Ma, and J. Shen, "Temporal stability of driver injury severity in single-vehicle roadway departure crashes: a random thresholds random parameters hierarchical ordered probit approach," *Analytic Methods in Accident Research*, vol. 29, Article ID 100144, 2020.