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Behavioral and psychological determinants of pedestrian collisions on arterial roads with evidence from random parameter models

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Arterial roads, while comprising a small percentage of total roadway mileage in the U.S., contribute disproportionately to pedestrian fatalities. Focusing on the behavioral and psychological dimensions of crash risk, this study analyzes 1722 pedestrian crashes on principal arterials and 1614 on minor arterials in Louisiana from 2017 to 2021. A Random Parameter Multinomial Logit Model with Heterogeneity in Means and Variance captures the hidden variation in how individual behaviors and situational contexts affect injury outcomes. Results indicate that perceptual challenges (dark conditions without street lighting), driver decision errors (lane departures), and alcohol-impaired judgment are strong predictors of severe or fatal crashes. Marginal effects show elevated risk when pedestrians or drivers navigate low-visibility environments, single-vehicle settings that isolate responsibility, and scenarios involving Black pedestrians who may face systemic exposure and behavioral adaptation under stress. Conversely, proactive behaviors such as attentive movement before impact, lane keeping, and navigating mixed-use areas with higher driver expectancy can reduce the likelihood of severe injury. Psychological and situational determinants differ by arterial class: on principal arterials, perceptual load and alcohol impairment dominate, whereas on minor arterials, risk-taking maneuvers like midblock crossings and expectancy violations shape outcomes. These insights underscore the need for Safe System Approach (SSA) interventions that couple engineering fixes (street lighting, access control, enhanced midblock crossings) with behaviorally informed strategies such as targeted impaired-driving enforcement, perception-based educational campaigns, and context-specific outreach for at-risk demographic groups.

Keywords Arterial roads, Random parameter, Behavioral and psychological factors, Dark-no-streetlight, Lane departure

Based on data from the Fatality Analysis and Reporting System (FARS), 7,522 pedestrian deaths occurred in the U.S. in 2022, equating to roughly one fatality every 70 min and accounting for 18% of all traffic-related deaths that year[1]. While the number of pedestrian deaths in 2022 was roughly the same as in 1975, there has been an 83% increase since their lowest point (count = 4,109) in 2009[2]. This ongoing increasing trend in pedestrian fatalities highlights the urgent need for in-depth research to identify the critical factors contributing to these crashes. Understanding the critical nature of pedestrian safety is therefore urgently needed to meet the long-term goal of zero roadway fatalities on US roadways outlined by the National Roadway Safety Strategy (NRSS)[3]. Space and time are two critical components associated with pedestrian safety[4]. The spatial aspects involve the physical environment pedestrians navigate, including the design and layout of roadways, sidewalks, crosswalks, and pedestrian zones. In this context, the type of roadway (e.g., functional classification) significantly impacts pedestrian safety due to inherent differences in design and functionality. In the US, the classification system of roadways comprises five primary categories: interstates, freeways and expressways, other principal arterials,

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collectors, and local roads. Roadways are classified based on their primary function, from facilitating high-speed, long-distance travel to providing access to local neighborhoods. For instance, highways and arterial roads are designed to accommodate high-speed vehicular traffic with minimal interruptions, often featuring multiple lanes, limited access points, and higher posted speed limits. These characteristics can pose significant risks to pedestrians if appropriate safety measures, such as pedestrian overpasses or underpasses, crosswalk are not in place. The higher speeds and traffic volume make crossing these roads particularly risky, thus increasing the risk of fatal or severe injuries in such crashes. Despite accounting for a limited portion of the roadway network by functional classification, principal and minor arterial roads are associated with a disproportionately high number of pedestrian fatalities (See Fig. 1).

The FARS statistics indicate that out of the 34,203 pedestrian fatalities in the US between 2018 and 2022, arterial (primary and minor) roadways accounted for 61.83% (count = 21,148) of the total pedestrian fatalities. This is particularly concerning given that principal arterials, while comprising only 3.77% of the total miles by functional system, account for a significant 38.63% of pedestrian fatalities. Similarly, minor arterials, which comprise 5.91% of the total miles, are associated with 23.20% of pedestrian fatalities.

Evidence from the 'Pedestrian Safety Strategic Plan' indicates that pedestrian fatalities are particularly common on multilane arterial roads, largely due to elevated vehicle speeds and inadequate safety infrastructure[5]. In urban areas, these arterials often serve as key routes near transit stations, commercial hubs, and residential neighborhoods, resulting in higher pedestrian activity and greater exposure to traffic. Given their role as primary corridors for both vehicle and pedestrian movement, ensuring safety along these roads is essential. The typically higher speed limits on arterial roadways further amplify crash severity risks.

To address these challenges, it is essential to examine the underlying factors contributing to pedestrian-vehicle collisions along arterials. This study aims to analyze crashes on arterial roadways by incorporating a broad set of variables, spanning human behavior, vehicle characteristics, roadway features, environmental context, and temporal aspects, offering insights that can guide targeted safety policies and countermeasures for this roadway class. This research also seeks to support the broader goals of national safety initiatives such as the NRSS, Vision Zero, and Towards Zero Deaths (TZD) which strive for zero fatalities on roadways. By addressing the unique challenges posed by arterial roadways, the findings of this study are expected to contribute to creating safer environments for pedestrians and help achieve the long-term goal of zero roadway fatalities in the US. While this study does not primarily focus on extensively examining unobserved heterogeneity, it is important to acknowledge that crash risk factors may vary across different locations, populations, and conditions due to unobserved or latent factors not directly captured by the data. Accounting for such variability can improve the understanding of crash dynamics and enhance the effectiveness of targeted safety interventions.

Literature review

Pedestrian safety on arterial roadways is a critical issue due to the complex interplay of high traffic volumes, higher vehicle speeds, and mixed-use environments that often characterize these roadways. Combining these factors creates a hazardous walking environment for pedestrians and a greater likelihood of crash involvement. Previous studies have consistently shown that arterial roadways account for a significant portion of pedestrian fatalities, addressing many factors. For example, a previous research analyzed pedestrian collisions on urban arterial roads in Orange County, Florida, finding that strip commercial areas, especially those with alcohol-selling establishments, significantly contributed to pedestrian injuries and deaths[6]. They argued that the primary design and management of arterial roadways have historically prioritized the efficient movement of vehicular traffic over the safety of pedestrians. Another study examined vehicle speeds on low-speed urban arterials,

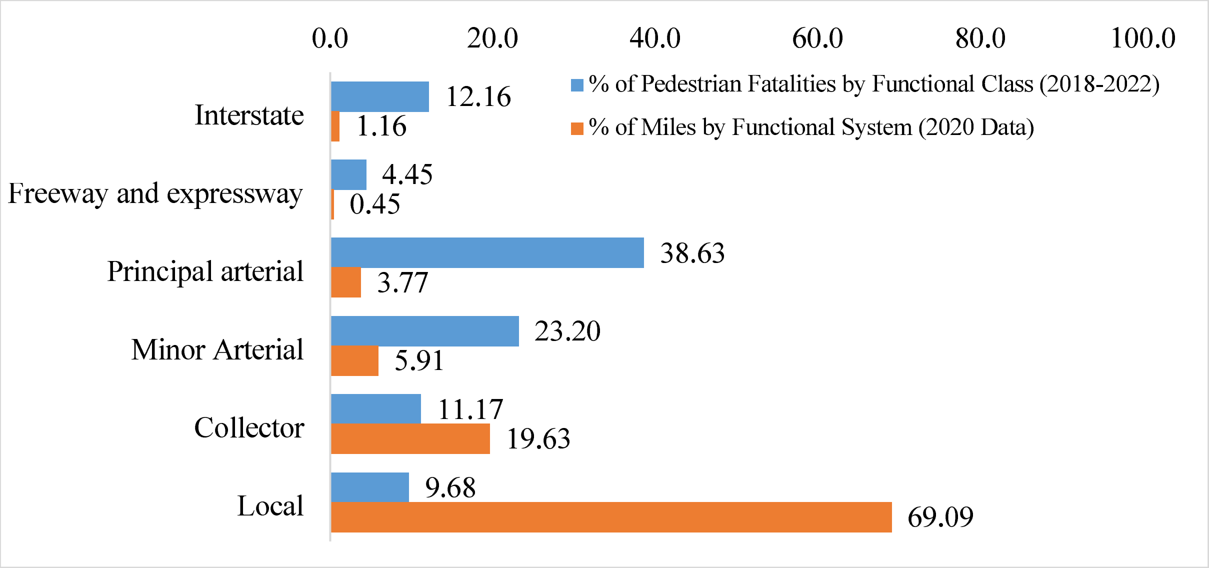

Fig. 1. Pedestrian fatalities according to the functional classification of roadways in the US.

finding that drivers often exceeded intended speeds, posing pedestrian safety risks[7]. Another study investigated drivers' yielding behavior at uncontrolled intersections (total = 20) along two-lane arterial and collector roads (25–30 mph) in Milwaukee, Wisconsin[8]. Observing 364 instances (i.e., pedestrians wished to cross), they found a low overall yielding rate of 16%, and yielding rates differed between intersections, ranging from a high of 60% to a low of 0%. Focusing on child pedestrian (0–14 years) crashes in Long Beach, California, a previous study conducted geographic analysis to identify high-risk areas[9]. The study reported that intersection crashes were significantly (p-value < 0.001) more likely to occur on major arterials and local streets, and drivers were the primary party at fault.

Another study analyzed the impact of community design on traffic-related crashes using GIS data and negative binomial models[10]. They found that urban arterials, arterial-oriented commercial developments, and big box stores were associated with an increased likelihood of traffic-related crashes and injuries. Previous research conducted a before-and-after crash analysis to evaluate safety improvements along a major arterial (5-mile corridor) in Sandy City, Utah[11]. They found that enhancements like raised medians, median barriers, right-turn lanes, street lighting, pedestrian access rams, and improved signage reduced crash severity and frequency by 40% annually. Previous research also emphasizes the critical role of built environment factors associated with arterial roadway design affecting pedestrian safety. For example, previous research used regression modeling, spatial analysis, and case studies with data from Columbus, Ohio, and found that pedestrians were more often at fault on fast, high-volume arterial roads with bus stops, but better crossing provisions led to fewer pedestrian-at-fault crashes at marked intersections[12]. Another study investigated the relationship between built environment characteristics and crash incidence involving motorists, pedestrians, and cyclists using a negative binomial regression model. They found that features such as miles of arterial roadways, four-leg intersections, strip commercial uses, and big box stores were associated with higher crash incidences, while pedestrian-scaled retail was linked to lower crash incidences[13]. Another study analyzed the relationship between built environment characteristics and pedestrian fatalities across the US using data (2012–2016) collected from FHWA, NHTSA, EPA, and the Census Bureau[14]. Using regression modeling techniques, they found strong associations between pedestrian fatalities and traffic density on non-access-controlled principal arterial and minor arterial roadways in urban areas. One of the recent AAA Foundation for Traffic Safety reports analyzed pedestrian fatalities in the U.S. from 2018–2021, finding that over three-quarters occurred on urban roads, most often on arterials and in dark conditions, with notable increases in fatalities among older pedestrians and in high-speed zones[15]. Another recent study applied a corridor-level approach to assess pedestrian and bicyclist crashes on urban and suburban arterial roads in multiple Florida counties[16]. By using negative binomial models, it identified roadway, traffic, and environmental factors that influence crash occurrence. This approach allows agencies to efficiently screen networks, pinpoint corridors with high crash potential, and recommend countermeasures such as adding bicycle lanes, improving lighting, and providing midblock crossings to enhance safety for vulnerable road users.

Several studies focused on improving safety on arterial roads, demonstrating the effectiveness of identifying and mitigating high-risk hot spot areas to reduce pedestrian fatalities and crashes. A research project by the Oregon Department of Transportation (ODOT) evaluated methods for setting safe speed zones on higher-speed roadways, particularly arterials with a history of severe injuries[17]. They found that modernizing speed-setting methods in urban areas improved safety for vulnerable users like pedestrians and cyclists, recommending further enhancements to reduce fatal and serious injury crashes. Another study addressed the rise in US pedestrian fatalities by identifying hot spot corridors (total = 65) with frequent fatal pedestrian crashes[18]. They analyzed data from 2001–2016, finding these hot spots typically on multilane roads with high-speed limits and traffic volumes, often near commercial areas and low-income neighborhoods. Another research focused on developing safety performance functions to identify crash hotspots based on the estimated exposure of vulnerable road users (pedestrians, bikes) at multilane arterial roads[19]. Utilizing big data sources and machine learning models, they revealed that (a) pedestrian and bike exposure during daytime is higher than that at nighttime, (b) the presence of high-frequency transit is associated with more crash potential, (c) the proportion of commercial land use and increase in the proportion of the population below the poverty line is positively associated with pedestrian crashes.

Some international studies also examined safety measures and risk factors on urban arterial roads, focusing on traffic patterns and median design. Research conducted in Beijing analyzed risk factors associated with severe crashes on urban arterial roads under mixed traffic, finding that heavier traffic volumes, multiple lanes, and higher speed limits increased severe crash risks, while the presence of medians reduced the risk of severe crash risk[20]. In the United Kingdom, one study analyzed urban pedestrian crashes using a Random Parameter Logit Model with Heterogeneity in Means and Variances, highlighting the influence of drivers' trip purposes and pre-crash maneuvers on injury severity[21]. They found that commuting and work-related trips, as well as maneuvers such as reversing, turning, and pedestrian crossings from the driver's offside, significantly affected crash outcomes, leading to recommendations for traffic management and awareness campaigns. Also using UK data, another study investigated rural pedestrian crashes at intersections and non-intersections through a Latent Class Clustering and Ordered Probit modeling framework[22]. Their results showed that factors such as pedestrian age, driver demographics, lighting conditions, heavy vehicle involvement, and higher speed limits influenced severity differently across crash types, underscoring the need for location-specific safety countermeasures like improved lighting and speed reduction in high-risk rural areas. In the Middle East, researchers conducted an observational study in Doha, Qatar, to examine illegal mid-block crossing behavior on a high-speed, six-lane divided arterial[23]. They documented that such crossings were predominantly undertaken by male pedestrians and were influenced by group size, the presence of other pedestrians, and approaching vehicles, with many using risky rolling gaps. These findings also point to the importance of infrastructure enhancements, pedestrian education, and enforcement to reduce unsafe crossing behaviors in high-speed urban settings.

Intersections with small angles, countdown signals, and high side-access densities had higher risks, but non-motorist protection facilities improved safety. Another study analyzed 32,894 vehicular and 1,012 pedestrian crashes in three cities on arterial roads, focusing on three median types (raised, flush, no median), finding that medians generally improve safety, though their effects vary, requiring careful design[24]. Few studies investigated the impact of lane reconfiguration and access management on arterial roadways to enhance safety and traffic flow. For example, converting 4-lane arterials to 3-lane roads with a center two-way left-turn lane in Burnsville, MN, and River Falls, WI, was associated with reduced likelihood of crashes and traffic volume[25]. Another study conducted in New Mexico evaluated pedestrian safety countermeasures on arterials, including a bus rapid transit (BRT) system, road diet, and High-Intensity Activated crosswalk (HAWK) signals[26]. Using crash data analysis, vehicle speed monitoring, and pedestrian behavior assessment, the study found these measures effectively reduced crash frequency and rates, especially noting changes in vehicle speeds and pedestrian behaviors. Another study assessed speed cameras on Roosevelt Boulevard, Philadelphia, using Bayesian negative binomial and Poisson models, finding significant reductions in crashes, injuries, and fatalities[27]. They recommend extending automated speed enforcement as economic benefits outweigh fines collected, though additional measures are needed. Another study investigated pedestrian crashes on state-owned highways and urban arterials, finding a strong association between bus stop usage and pedestrian collisions through logistic regression models[28]. They also identified associations with retail activity, housing concentrations, wide roadways, high traffic volumes, and high-speed limits, emphasizing the need for multi-modal facilities to ensure pedestrian safety in high bus rider activity areas.

Previous studies also highlighted the critical role of intersection design, residential street conditions, and crossing facilities in improving pedestrian safety on arterial roads. A previous study analyzed pedestrian crash risks at intersections (total = 81) along arterial and collector roadways in Alameda County, California, finding higher risks at intersections with more right-turn-only lanes, nearby non-residential driveways, and commercial properties, while raised medians reduced the likelihood of crashes[29]. A Louisiana study assessed pedestrian crossing facilities on high-speed urban arterials, finding correlations between pedestrian crash frequencies and roadway characteristics, providing a basis for statewide guidelines for pedestrian facilities on high-speed arterials[30]. Few studies highlight the impact of social and environmental factors on pedestrian safety, especially on arterial roads. Research conducted in Oregon focused on injury disparities of a specific demographic population, Black, Indigenous, and People of Color (BIPOC)[31]. The study found that increased pedestrian fatal and severe injuries were associated with an increase in vehicle miles traveled (VMT) on major arterials and an increase in the average width of arterials. A few other major findings from previous literature related to pedestrian safety on arterial roadways are summarized in Table 1.

Based on the review literature, it was identified that most of the previous research has addressed pedestrian safety on arterial roadways from a limited perspective. These studies often treated arterial roads as a single indicator variable in the modeling framework or focused on other contexts like specific safety countermeasures, such as improved crosswalk visibility or signal timing adjustments, without considering the broader range of factors influencing pedestrian safety. This limited approach fails to capture the complex and multifaceted nature of pedestrian-vehicle crashes on arterial roadways. To address this gap, it is necessary to assess how diverse contributing factors, including human behavior, vehicle type, roadway design, environmental conditions, and timing, affect pedestrian safety on these roads. This study adopts a comprehensive approach by analyzing these factors using an advanced random parameter modeling framework, with a specific emphasis on distinguishing between principal and minor arterials to uncover nuanced insights into crash dynamics. The findings are expected to inform the development of more effective and targeted safety countermeasures, contributing to improved pedestrian safety and advancing toward zero deaths on the nation's roads. This comprehensive approach not only addresses the gaps identified in previous research but is also expected to improve our understanding of the dynamics of pedestrian safety on arterial roadways.

Methodology

Dataset

Police reported pedestrian crash data was collected from the Louisiana Department of Transportation and Development (LaDOTD). The crash database was created by merging four data tables (vehicle table, crash table, road inventory table, and pedestrian table) and using Crash ID as a unique criterion. The primary database consists of 7,399 pedestrian crashes (KABCO severity level) in Louisiana during the (2017–2021) period. Based on the functional classification of roadways, a summary of the database is provided in Table 2.

A one-step filter criterion (roadway functional class = 3, 4) was used to prepare the final data for modeling purposes. The considered database includes 3,336 pedestrian-vehicle crashes on arterial roadways in Louisiana during the 2017–2021 period. This study considered KABCO scale to categorize pedestrian injury severity. Then these were regrouped into three types (KA, BC, O) to facilitate model development and interpretation as outlined by previous literature. Pedestrian crash severity distribution according to principal and minor arterial roadways is provided in Table 3.

Figure 2 illustrates the flowchart of the study design.

Based on a review of previous literature and availability in the Louisiana crash database, a wide range of variables covering roadway and vehicular characteristics, human factors, temporal and environmental factors were selected for analysis. Note that the variables were binary coded to identify their impact on pedestrian injury severity (1 for the presence of specific factors, 0 if that factor is not present). A summary of the selected variables is provided in Table 4.

References	Analysis type	Key findings related to pedestrian safety on arterial
32	Integrated choice and latent variables (ICLV) models	Pedestrians on principal urban arterials show low risk-taking behavior with high related exposure Pedestrians on minor arterials show more frequent risk-taking behavior with still high related exposure
33	Statistical model using GIS and crash data	The absence of sidewalks along urban arterials with four to six lanes significantly increases pedestrian crash likelihood Daily traffic volumes and roadway category impact crash likelihood on arterials Incident Risk Ratio (IRR) of pedestrian crashes is 1.67 times higher on arterials without sidewalks The likelihood of pedestrian crashes per mile is three times greater on arterials without sidewalks
34	Correlation analysis	Pedestrian crashes on multi-lane high-speed arterials are related to access density, transit stop density, and lighting level Countermeasures include engineering solutions, enforcement, and human behavior modification Recommendations are expected to be applicable to similar principal arterials
35	Random parameters multinomial logit models	The likelihood of pedestrian injury severity at high-speed limit zones is about 3.1 times higher for roadways with 40,000 vehicles per day, 3.2 times higher for two-way roads with a positive median barrier, and 1.7 times higher for urban principal roadways compared to medium-speed limit zones Higher likelihood of severe pedestrian injury in high-speed limit zones during afternoon peak, turn-lane, and dark conditions Crashes on urban principal arterials with 30–40 mph and 45–70 mph speed limits had a 0.0424 and 0.0254 higher probability of severe pedestrian injuries, respectively Crashes on urban major arterials with a 30–40 mph speed limit had a 0.0027 higher probability of severe pedestrian injury
18	Hierarchical clustering	Identified 60 unique fatal pedestrian crash hot spot corridors, primarily on multilane urban primary arterial roadways More than three-quarters had speed limits of 30 mph or higher, and 62% had traffic volumes exceeding 25,000 vehicles per day Hot spots classified into urban primary arterial roadways, requiring targeted safety strategies
36	Multilevel mixed effects Poisson models	Principal arterials have the highest pedestrian collision rates Collision rates increase by 9% per 10 feet of street width Intersections with traffic signals and marked crosswalks have higher collision rates
20	Generalized estimating equations with negative binomial link function	Heavier traffic volumes, more road lanes, and higher speed limits on arterial roads increase severe crash risk Medians reduce severe crash risk Higher risks of severe crashes are associated with intersections having small angles, countdown signals, and road segments with higher side-access densities and bus stops
14	Regression modeling	Strong associations between traffic on non-access-controlled principal arterial and minor arterial roadways and pedestrian fatalities Increase in traffic density on these arterial roads significantly raises pedestrian fatality risks Employment density in the retail sector is strongly associated with pedestrian fatalities in urban and rural tracts
37	Crash frequency and severity models	Increased pedestrian-vehicle crashes associated with higher travel demand and commute behaviors on arterial roads Network characteristics and sociodemographic features significantly impact crash frequency and severity
38	Log-linear regression for pedestrian exposure model	Developed a statewide model to estimate annual pedestrian crossing volumes at intersections on the California State Highway System Significant explanatory variables include intersections with principal arterial and minor arterial roadways Employment density, population density, and number of schools are key factors in pedestrian volumes
39	Safety performance functions (SPFs)	Pedestrian crashes at intersections on arterial roads are influenced by activity measures and intersection size/complexity Higher pedestrian volumes initially increase crash likelihood, but expected crashes decline above a certain threshold SPFs can help prioritize locations for safety improvements beyond high-crash areas

Table 1. Findings from key selected studies.

Code	Interpretation	Crash count	% of total
1	Interstate	268	3.62
2a	Principal Arterial—Other Freeways	30	0.41
2b	Principal Arterial—Other Expressways	22	0.30
3	*Principal Arterial*	*1,722*	*23.27*
4	*Minor Arterial*	*1,614*	*21.81*
5	Major Collector	1163	15.72
6	Minor Collector	374	5.05
7	Local	2,079	28.10
	Not available/Accessible	127	1.72
	Total	7,399	100%

Table 2. Distribution of pedestrian crash data according to functional classification.

Random parameter multinomial logit model

During the investigation of crash data, certain influential factors on injury severity may not be directly observed or measured. These unmeasured factors can cause variations in the effects of observed variables on injury outcomes, which is known as unobserved heterogeneity. While fully exploring unobserved heterogeneity is beyond the primary scope of this study, failure to account for it can lead to biased parameter estimates and less accurate predictions[40]. To address these challenges, this study employs an advanced random parameter multinomial logit model, which allows for variation in the influence of explanatory variables across individual observations. This approach captures not only differences in average effects but also allows for variability in both the magnitude and dispersion of these effects across individual crashes, thereby accounting for heterogeneity in how explanatory variables influence injury severity outcomes[41]. This research specifically focuses on analyzing the degree of injuries in crash situations as it explores three possible outcomes: fatal or severe injuries, moderate

Roadway type	Pedestrian injury severity distribution		
	Severity level	Frequency	Share of Total
Principal arterial	KA	467	27.12%
	BC	1,152	66.90%
	O	103	5.98%
	Total	1,722	100%
Minor arterial	KA	327	20.26%
	BC	1,196	74.10%
	O	91	5.64%
	Total	1,614	100%

Table 3. Pedestrian severity distribution for principal and minor arterial roadways.

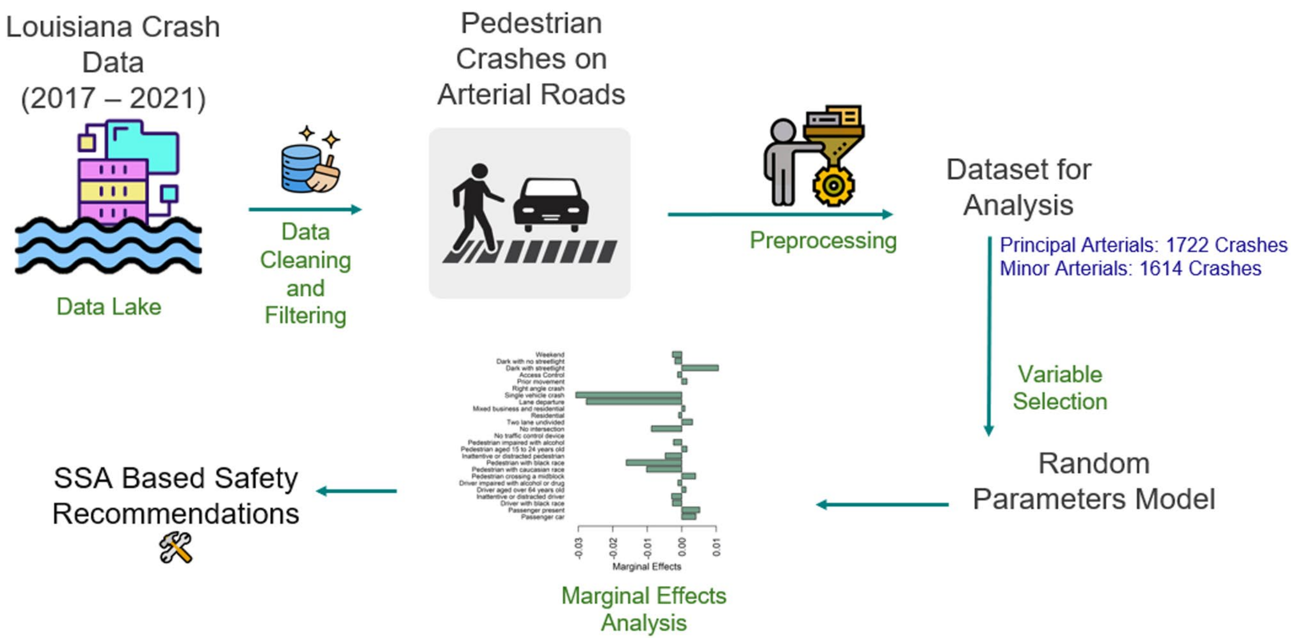

Fig. 2. Flowchart of study design.

or minor injuries, and no injuries or property damage. Expanding on previous studies, the modeling technique commences by constructing a function to evaluate the degree of injury severity[41].

$$S_{ij} = \boldsymbol{\beta}_i \boldsymbol{X}_{ij} + \varepsilon_{ij} \tag{1}$$

The symbol S_{ij} in the equation represents the probability that a vehicle designated as *j* experiences a level of severity represented by *i*, in an arterial roadway crash. On the other hand, $\boldsymbol{X}_{ij}$ denotes the variables that affect the degree of severity. The $\boldsymbol{\beta}_i$ parameters can be estimated and are associated with these factors, whereas ε_{ij} is the term for error. The standard multinomial logit model assumes that the errors terms follow extreme value distribution.

$$P_j\left(i\right) = \frac{EXP\left(\boldsymbol{\beta}_i \boldsymbol{X}_{ij}\right)}{\sum_{\forall I} EXP\left(\boldsymbol{\beta}_i \boldsymbol{X}_{ij}\right)} \tag{2}$$

$P_j\left(i\right)$ represents the likelihood of a vehicle *j* experiencing a certain level of injury severity, represented as *i*, inside a system with three possible severity outcomes. To facilitate flexible estimation of individual or multiple parameters within the set $\boldsymbol{\beta}_i$ over a wide range of crash events, Eq. (2) can be restated as[42]:

$$P_j\left(i\right) = \int \frac{EXP\left(\boldsymbol{\beta}_i \boldsymbol{X}_{ij}\right)}{\sum_{\forall I} EXP\left(\boldsymbol{\beta}_i \boldsymbol{X}_{ij}\right)} f\left(\beta|\varphi\right) d\beta \tag{3}$$

The function $f\left(\beta|\varphi\right)$ depicts the probability density function for $\boldsymbol{\beta}_i$, with $\boldsymbol{\varphi}_i$ being a collection of parameters that describe this function. These metrics encompass both the average value and the variances. The definitions

Variable	Principal arterial		Minor arterial	
	Mean	SD	Mean	SD
Environmental characteristics				
Spring (1 if the crash occurred in Spring, 0 if otherwise) [Principal: 1(n = 1269), 0 (n = 3896); Minor: 1(n = 1212), 0(n = 3630)]	0.246	0.431	0.250	0.433
Weekend (1 if the crash occurred on the weekend, 0 if otherwise) [Principal: 1(n = 1317), 0 (n = 3848); Minor: 1(n = 1152), 0(n = 3690)]	0.255	0.436	0.238	0.426
Dark with no streetlights (1 if the crash occurred at locations with dark-no-streetlights, 0 if otherwise) [Principal: 1(n = 636), 0 (n = 4529); Minor: 1(n = 741), 0(n = 4101)]	0.123	0.329	0.153	0.360
Dark with streetlights (1 if the crash occurred at locations dark with streetlights, 0 if otherwise) [Principal: 1(n = 2184), 0 (n = 2981); Minor: 1(n = 1653), 0(n = 3189)]	0.423	0.494	0.341	0.474
Rain (1 if the crash occurred in rainy weather conditions, 0 if otherwise) [Principal: 1(n = 378), 0 (n = 4787); Minor: 1(n = 330), 0(n = 4512)]	0.497	0.260	0.068	0.252
Crash Characteristics				
Access control (1 if the roadway has partial access control, 0 if otherwise) [Principal: 1(n = 525), 0 (n = 4640); Minor: 1(n = 444), 0(n = 4398)]	0.102	0.302	0.092	0.289
Prior movement (1 if driver deviated from going straight, 0 if otherwise) [Principal: 1(n = 681), 0 (n = 4484); Minor: 1(n = 651), 0(n = 4191)]	0.132	0.338	0.134	0.341
Hit and run (1 if the crash involved hit-and-run, 0 if otherwise) [Principal: 1(n = 1176), 0 (n = 3989); Minor: 1(n = 1293), 0(n = 3549)]	0.228	0.419	0.267	0.442
Right angle crash (1 if the crash involved right angle, 0 if otherwise) [Principal: 1(n = 366), 0 (n = 4799); Minor: 1(n = 366), 0(n = 4476)]	0.071	0.257	0.076	0.264
Single vehicle crash (1 if the crash involved a single vehicle, 0 if otherwise) [Principal: 1(n = 3828), 0 (n = 1338); Minor: 1(n = 3339), 0(n = 1503)]	0.741	0.438	0.690	0.463
Lane departure (1 if the crash involved lane departure of the vehicle, 0 if otherwise) [Principal: 1(n = 4800), 0 (n = 366); Minor: 1(n = 4491), 0(n = 351)]	0.929	0.257	0.928	0.259
Roadway Characteristics				
Mixed business and residential (1 if the crash occurred in mixed business and residential areas, 0 if otherwise) [Principal: 1(n = 2067), 0 (n = 3098); Minor: 1(n = 2211), 0(n = 2631)]	0.400	0.490	0.457	0.498
Residential (1 if the crash occurred in residential areas, 0 if otherwise) [Principal: 1(n = 291), 0 (n = 4874); Minor: 1(n = 867), 0(n = 3975)]	0.056	0.231	0.179	0.383
Two lanes undivided (1 if the crash occurred on two lanes undivided, 0 if otherwise) [Principal: 1(n = 2391), 0 (n = 2847); Minor: 1(n = 2817), 0(n = 2025)]	0.449	0.497	0.582	0.493
No intersection (1 if the crash occurred at segment, 0 if otherwise) [Principal: 1(n = 2859), 0 (n = 2307); Minor: 1(n = 2589), 0(n = 2253)]	0.553	0.497	0.535	0.499
Posted speed limit: 40–55 mph (1 if the crash occurred on roadways with a posted speed limit of 40–55 mph, 0 if otherwise) [Principal: 1(n = 2040), 0 (n = 3125); Minor: 1(n = 1227), 0(n = 3615)]	0.395	0.489	0.253	0.435
No traffic control device (1 if no traffic control device in place, 0 if otherwise) [Principal: 1(n = 669), 0 (n = 4496); Minor: 1(n = 654), 0(n = 4188)]	0.130	0.336	0.135	0.342
Traffic signal light (1 if the crash occurred at locations with signalized control, 0 if otherwise) [Principal: 1(n = 1110), 0 (n = 4055); Minor: 1(n = 801), 0(n = 4041)]	0.215	0.411	0.165	0.372
Pedestrian Condition and Characteristics				
Pedestrians impaired with alcohol (1 if alcohol-impaired pedestrian involved in the crash, 0 if otherwise) [Principal: 1(n = 513), 0 (n = 4652); Minor: 1(n = 360), 0(n = 4482)]	0.099	0.299	0.074	0.262
Pedestrians aged 15 to 24 years old (1 if 15–24 years old pedestrians involved in the crash, 0 if otherwise) [Principal: 1(n = 912), 0 (n = 4253); Minor: 1(n = 840), 0(n = 4002)]	0.177	0.381	0.173	0.379
Pedestrians aged 25 to 40 years old (1 if 25–40 years old pedestrians involved in the crash, 0 if otherwise) [Principal: 1(n = 1398), 0 (n = 3767); Minor: 1(n = 1482), 0(n = 3360)]	0.271	0.444	0.306	0.461
Pedestrians aged 41 to 64 years old (1 if 41–64 years old pedestrians involved in the crash, 0 if otherwise) [Principal: 1(n = 1995), 0 (n = 3171); Minor: 1(n = 1647), 0(n = 3195)]	0.386	0.487	0.340	0.474
Pedestrians aged over 64 years old (1 if older pedestrians were involved in the crash, 0 if otherwise) [Principal: 1(n = 462), 0 (n = 4703); Minor: 1(n = 459), 0(n = 4383)]	0.089	0.285	0.095	0.293
Pedestrians wearing dark clothes (1 if pedestrians in dark clothing were involved in the crash, 0 if otherwise) [Principal: 1(n = 2205), 0 (n = 2960); Minor: 1(n = 1953), 0(n = 2889)]	0.427	0.495	0.403	0.491
Inattentive or distracted pedestrian (1 if inattentive or distracted pedestrians involved in the crash, 0 if otherwise) [Principal: 1(n = 1317), 0 (n = 3848); Minor: 1(n = 1101), 0(n = 3741)]	0.255	0.436	0.227	0.419
Pedestrian physical impairment (1 if pedestrian with physical impairment involved in the crash, 0 if otherwise) [Principal: 1(n = 30), 0 (n = 5135); Minor: 1(n = 39), 0(n = 4803)]	0.006	0.076	0.008	0.089
Male pedestrian (1 if male pedestrians were involved in the crash, 0 if otherwise) [Principal: 1(n = 3420), 0 (n = 1746); Minor: 1(n = 3123), 0(n = 1719)]	0.662	0.473	0.645	0.479
Black pedestrian (1 if pedestrians with black demographics involved in the crash, 0 if otherwise) [Principal: 1(n = 2754), 0 (n = 2412); Minor: 1(n = 2361), 0(n = 2481)]	0.533	0.499	0.488	0.500
Caucasian pedestrian (1 if pedestrians with white demographics involved in the crash, 0 if otherwise) [Principal: 1(n = 2172), 0 (n = 2993); Minor: 1(n = 2244), 0(n = 2598)]	0.420	0.494	0.463	0.499
Pedestrian Actions				
Pedestrian crossing a midblock (1 if the crash occurred while pedestrian crossing at a midblock location, 0 if otherwise) [Principal: 1(n = 1755), 0 (n = 3410); Minor: 1(n = 1251), 0(n = 3591)]	0.340	0.474	0.258	0.438
Pedestrian walking against the traffic (1 if the crash occurred while pedestrian walking against the traffic, 0 if otherwise) [Principal: 1(n = 162), 0 (n = 5003); Minor: 1(n = 189), 0(n = 4653)]	0.031	0.174	0.039	0.194
Pedestrian walking along the traffic (1 if the crash occurred while pedestrian walking along the traffic, 0 if otherwise) [Principal: 1(n = 396), 0 (n = 4769); Minor: 1(n = 471), 0(n = 4371)]	0.077	0.266	0.097	0.296
Driver's Condition and Characteristics				
Driver impaired with alcohol or drug (1 if alcohol or drug-impaired drivers involved in the crash, 0 if otherwise) [Principal: 1(n = 279), 0 (n = 4886); Minor: 1(n = 177), 0(n = 4665)]	0.054	0.226	0.037	0.188
Driver aged over 64 years old (1 if older drivers involved in the crash, 0 if otherwise) [Principal: 1(n = 531), 0 (n = 4634); Minor: 1(n = 495), 0(n = 4347)]	0.103	0.304	0.102	0.303
Continued				

Variable	Principal arterial		Minor arterial	
	Mean	SD	Mean	SD
Driver aged 15 to 24 years old (1 if 15–24 years old drivers involved in the crash, 0 if otherwise) [Principal: 1(n = 678), 0 (n = 4487); Minor: 1(n = 648), 0(n = 4194)]	0.131	0.338	0.134	0.341
Inattentive or distracted driver (1 if inattentive or distracted drivers involved in the crash, 0 if otherwise) [Principal: 1(n = 759), 0 (n = 4406); Minor: 1(n = 819), 0(n = 4023)]	0.147	0.354	0.169	0.375
Driver with Black race (1 if drivers with black demographics involved in the crash, 0 if otherwise) [Principal: 1(n = 2055), 0 (n = 3111); Minor: 1(n = 1695), 0(n = 3147)]	0.398	0.489	0.350	0.477
Passenger present (1 if the crash involved vehicle includes passenger, 0 if otherwise) [Principal: 1(n = 750), 0 (n = 4415); Minor: 1(n = 753), 0(n = 4089)]	0.145	0.352	0.156	0.362
Vehicle Type				
Passenger car (1 if passenger car is involved in the crash, 0 if otherwise) [Principal: 1(n = 2241), 0 (n = 2925); Minor: 1(n = 2088), 0(n = 2754)]	0.434	0.496	0.431	0.495
Van or SUV (1 if Van or SUV involved in the crash, 0 if otherwise) [Principal: 1(n = 1323), 0 (n = 3842); Minor: 1(n = 1233), 0(n = 3609)]	0.256	0.437	0.255	0.436

Table 4. Descriptive statistics of key selected variables used in the modeling.

of all other terms remain unaltered. The variable $\boldsymbol{\beta}_{ij}$ refers to a set of measurable attributes that may vary across crash instances, reflecting potential heterogeneity in both the mean and variance of the random parameters[43,44].

$$\boldsymbol{\beta}_{ij} = \boldsymbol{\beta}_i + \boldsymbol{\Theta}_{ij}\boldsymbol{Z}_{ij} + \boldsymbol{\sigma}_{ij}EXP\left(\psi_{ij}\boldsymbol{Y}_{ij}\right)\upsilon_{ij} \tag{4}$$

$\boldsymbol{\beta}$, in this case, denotes the mean estimated parameters for all crashes. The term $\boldsymbol{Z}_{ij}$ captures observation-specific characteristics that help explain variations in the average effect on injury severity level *i*. $\boldsymbol{\Theta}_{ij}$ represents the quantifiable variables associated with these factors. $\boldsymbol{Y}_{ij}$ represents a separate group of variables that are specific to each observation. These variables help to explain the variations in the standard deviation $\boldsymbol{\sigma}_{ij}$, and their corresponding parameters are denoted as ψ_{ij}. Furthermore, υ_{ij} denotes the residual term. In addition, this study considers the possible association between random parameters[41,45]. When there are several random parameters that are recognized, the associated random parameters model is analyzed, as demonstrated in the study by[46]:

$$\beta_j = \beta + \boldsymbol{\eta}\boldsymbol{Z}_j + \Gamma\psi_j \tag{5}$$

In this context, β denotes the mean of the random parameter vector, while $\boldsymbol{Z}_j$ represents the explanatory variables influencing the average of β_j. The associated coefficients forThe associated coefficients for $\boldsymbol{Z}_j$ are denoted by η. The Cholesky decomposition matrix Γ is used to capture the standard deviation of random parameters. The term ψ_j accounts for the stochastic component, assumed to have a mean of zero and a variance of σ^2.

Model estimation was performed using simulated maximum likelihood with 1,000 Halton draws, following methodologies established in previous studies[40,42,47]. The normal distribution was selected for modeling random parameters due to its better performance compared to alternative distributions[48,49]. To interpret the results more effectively, marginal effects were computed to measure the impact of a one-unit change in each explanatory variable on the probability of different injury severity levels. These effects were calculated at the individual level and averaged across all observations to offer a comprehensive view of variable influence.

Results

The results obtained for principal and minor arterial roadways are discussed in this section. This study conducted a stepwise approach to facilitate the modeling process. First, a simple Multinomial Logit Model (MNL) was developed based on variables listed in Table 4, and only significant variables were carried out in the next step of the modeling process. Then, random parameters were set based on a trial-and-error process, and a simple Random Parameter Logit (RPL) model was developed. To add more complexity to the RPL framework, heterogeneity in the means (the random parameter means may be affected by the variables) and heterogeneity in variance (variables may affect the variance of the random parameter) were introduced in the model. Note that the Random Parameter Logit with Heterogeneity in Means and Variance (RPLHMV) performed better in terms of AIC and McFadden Pseudo R-squared measure, which is why it was chosen for explanation in this section (see Tables 4, 5, 6). Based on the final selected RPLHMV model, the value of the marginal effect of the significant variables is highlighted in Fig. 3.

Findings from the estimated models

Environmental characteristics

Dark with streetlights (1 if the crash occurred in the dark with streetlights condition, 0 otherwise) [BC]: For principal arterials, dark streetlight condition was identified as a random parameter, indicating variability in its influence on pedestrian injury outcomes. The estimated mean of the coefficient was – 0.60, with a standard deviation of 1.702, suggesting that approximately 63.8% of the distribution lies below zero, while 36.2% lies above. This indicates that in most cases, pedestrians were less likely to sustain BC-level injuries under dark conditions with streetlights, although in a smaller proportion of cases, the likelihood increased. This variability may stem from inconsistencies in streetlight placement and intensity, which can influence visibility[50]. In addition, pedestrians'

Variables	Principal—RPLHMV		Minor—RPLHMV	
	Coeff	t-stat	Coeff	t-stat
Environmental characteristics				
Weekend (1 if crash happened in weekend, 0 if no) [BC]	0.446	2.48	–	–
Dark with no streetlight (1 if yes, 0 if no) [KA]	1.686	7.63	0.565	1.78
Dark with streetlight (1 if yes, 0 if no) [BC]	− 0.600	− 2.65	− 0.715	− 2.34
St. dev. of dark with streetlight	1.702	2.37	–	–
Crash Characteristics				
Access control (1 if partial control, 0 if no) [KA]	0.478	2.02	–	–
Prior movement (1 if driver deviated from going straight, 0 if no) [KA]	− 0.504	− 1.95	− 0.568	− 1.73
Right angle crash (1 if yes, 0 if no) [O]	–	–	− 0.681	− 1.66
Single vehicle crash (1 if yes, 0 if no) [O]	− 1.191	− 5.32	− 2.126	− 9.40
Lane departure (1 if yes, 0 if no) [BC]	1.097	6.78	− 2.126	− 9.40
St. dev. of lane departure	–	–	2.984	2.22
Roadway Characteristics				
Mixed business and residential (1 if yes, 0 if no) [BC]	0.651	2.36	0.551	2.27
St. dev. of mixed business and residential	1.668	2.64	–	–
Residential (1 if yes, 0 if no) [BC]	0.636	2.01	–	–
Two lanes undivided (1 if yes, 0 if no) [KA]	− 0.324	− 2.11	–	–
No intersection (1 if crash occurred at segment, 0 if no) [O]	− 0.378	− 1.73	–	–
No traffic control device (1 if yes, 0 if no) [BC]	–	–	0.996	2.37
Pedestrian Condition and Characteristics				
Pedestrian impaired with alcohol (1 if yes, 0 if no) [O]	− 2.172	− 2.53	–	–
Pedestrian aged 15 to 24 years old (1 if yes, 0 if no) [KA]	− 0.530	− 2.07	− 1.517	− 4.57
Inattentive or distracted pedestrian (1 if yes, 0 if no) [BC]	0.725	3.85	–	–
Pedestrian with Black race (1 if yes, 0 if no) [O]	− 0.641	− 2.86	− 0.438	− 1.79
Pedestrian with Caucasian race (1 if yes, 0 if no) [O]	− 0.474	− 1.99	–	–
Pedestrian Actions				
Pedestrian crossing a midblock (1 if yes, 0 if no) [BC]	− 0.461	− 2.70	–	–
Driver's Condition and Characteristics				
Driver impaired with alcohol or drug (1 if yes, 0 if no) [KA]	2.558	5.20	–	–
Driver aged over 64 years old (1 if yes, 0 if no) [KA]	− 0.594	− 1.91	0.791	1.81
Inattentive or distracted driver (1 if yes, 0 if no) [BC]	0.635	2.97	0.738	2.39
Driver with Black race (1 if yes, 0 if no) [KA]	0.316	2.06	–	–
Passenger present (1 if yes, 0 if no) [O]	0.574	1.92	–	–
Vehicle Type				
Passenger car (1 if yes, 0 if no) [KA]	− 0.414	− 2.61	–	–
Heterogeneity in mean, Parameter:Variable				
Effect of rain on the mean of random parameter mixed business and residential area	− 1.224	− 2.05	–	–
Effect of pedestrian aged 15 to 24 years on the mean of random parameter mixed business and residential area	1.529	2.27	–	–
Effect of rain on the mean of random parameter dark with streetlight	0.956	1.73	–	–
Effect of pedestrian impaired with alcohol on the mean of random parameter dark with streetlight	− 1.084	− 2.37	–	–
Effect of dark with no streetlight on variance of lane departure	–	–	0.811	2.92
Effect of single vehicle crash on variance ofLane departure	–	–	0.376	2.33
Effect of driver aged 15 to 24 years old on variance of lane departure	–	–	0.482	2.37
Heteroscedasticity in random parameters				
Effect of posted speed limit 40–45 mph on the variance of Location type mixed business and residential area	0.797	2.32	–	–
Effect of driver impaired with alcohol or drug on the mean of random parameter lane departure	–	–	− 4.187	− 2.43
Effect of pedestrian aged 25–40 years old on the mean of random parameter lane departure	–	–	1.304	2.53
Effect of pedestrian impaired with alcohol on the mean of random parameter lane departure	–	–	− 1.638	− 1.81
Statistics				
Number of observations	1722		1614	
K	30		19	
Log likelihood at convergence	− 1176.952		− 1032.652	
Restricted log likelihood	− 1891.810		− 1773.160	
McFadden Pseudo R-squared	0.3779		0.4176	
Continued				

Variables	Principal—RPLHMV		Minor—RPLHMV	
	Coeff	t-stat	Coeff	t-stat
AIC	2413.9		2103.3	
AIC/N	1.402		1.303	

Table 5. Model estimation results for best models from each data subset.

perceived risk of safety and driver behavior can vary widely at night. Drivers' visibility and reaction time can also impact significantly, as adequate lighting generally improves these, but glare or distractions can counteract this benefit. The presence of rain was found to increase the mean of this variable to 0.956, suggesting that the combination of darkness with streetlighting and wet conditions elevates the probability of BC injuries on principal arterials. In addition to slippery road surfaces, rainy weather exacerbates visibility issues for drivers, thus increasing the risk of pedestrian injury in crashes. Additionally, both drivers and pedestrians may exhibit riskier behaviors under these conditions. Unlike random effects in the context of principal arterials, the fixed negative coefficient (-0.715) of this variable in minor arterials suggests a lower risk of BC injury. The marginal effects show different impacts across severity levels for principal arterials (KA = 0.0409, BC = − 0.0515, O = 0.0106) and minor arterials (KA = 0.0138, BC = − 0.0184, O = 0.0046). These results suggest that, despite the presence of streetlighting, limited visibility at night, along with elevated traffic volumes and vehicle speeds, continues to pose serious risks, particularly in terms of severe outcomes on both principal and minor arterials.

Dark with no streetlights (1 if the crash occurred in dark no streetlights condition, 0 otherwise) [KA]: The coefficient of this variable was identified as a fixed parameter for both principal and minor arterials. For the principal arterials, the fixed positive coefficient (1.686) of this variable suggests a higher likelihood of KA crash involvement under this specific condition. This impact can be explained by the poor visibility conditions in the dark conditions without streetlights, consistent with previous literature[51,52]. Due to reduced visibility, it is difficult for drivers to detect pedestrians in front from a safer distance[53]. Overall, the lack of visibility impacts drivers' ability to detect pedestrians, especially in high-speed and high-traffic environments typical of principal arterials are more likely to result in fatal or severe injuries to pedestrians. Similarly, this variable also shows a positive impact on minor arterials with a coefficient of 0.565, indicating that the dark condition without any streetlights increases the likelihood of KA injury. Although minor arterials generally have lower traffic volumes and speeds compared to principal arterials, the lack of streetlights still poses a significant risk. In these conditions, drivers are equally challenged by poor visibility, and the reduced reaction time can lead to fatal or severe outcomes. The marginal effect of this variable also clarifies its impact across different severity levels for the principal (KA = 0.0360, BC = − 0.0340, O = − 0.0020) and minor arterials (KA = 0.0063, − 0.0037, − 0.0027). These results indicate that the absence of streetlights at night disproportionately increases the risk of KA injuries. The negative marginal effects for BC and O crashes suggest that under dark conditions without streetlights, pedestrian-vehicle crashes are more likely to result in KA injuries rather than less severe outcomes (e.g., BC or O).

Weekend (1 if the crash occurred on weekends, 0 otherwise) [BC]: This indicator variable 'weekend' was found significant for principal arterial only. The fixed positive coefficient (0.446) indicates a higher likelihood of BC injury of pedestrians during weekends. This increased risk can be attributed to various factors, such as higher pedestrian activity during weekends, as pedestrians are more likely to be out for leisure activities, shopping, or social events, as documented in previous literature[54]. Additionally, weekends may see more drivers on the road, which may lead to more interactions, potentially leading to more crashes[55,56]. The marginal effect of this variable also reveals its impact across different severity levels for principal arterials (KA = − 0.0119, BC = 0.0147, O = − 0.0027). The slightly negative marginal effect for KA crashes (-0.0119) suggests a lower likelihood of KA injuries during weekends. This could be due to factors such as lower speeds in busy areas where pedestrians are present or more vigilant driving when drivers are aware of the increased activity. Similarly, the marginal effect for O crashes (-0.0027) might be due to the same factors contributing to the reduced likelihood of KA crashes.

Crash characteristics

Access control (1 if the crash occurred on partial access-controlled roads, 0 if otherwise) [KA]: The fixed positive coefficient (0.478) suggests that principal arterials with partial access control increased the likelihood of KA crashes. This increased risk can be attributed to several factors related to the nature of access-controlled roads. Roadways with partial access control are preferred through traffic movement where at-grade crossing may present[57]. However, on principal arterials, this can also result in higher speeds as drivers encounter fewer interruptions and may not be as vigilant about potential pedestrian crossings. The limited access points and other crossing environments might also create situations where pedestrians are forced to cross at unsafe locations, increasing the risk of severe crashes[58,59]. Examining the marginal effect of this variable reveals its impact across different severity levels for principal arterials (KA = 0.0073, BC = − 0.0061, O = − 0.0012). On the other hand, the marginal effects for BC and O crashes are negative, indicating a slight decrease in the likelihood of BC and O crashes. The reduced number of conflict points and more controlled traffic flow might lead to fewer minor crashes.

Prior movement (1 if driver deviated from going straight, 0 if otherwise) [KA]: The coefficient of this variable was found as a fixed parameter for both principal and minor arterials. Focusing on the principal arterials, the fixed negative coefficient (-0.504) suggests a lower likelihood of KA crashes when the driver deviates from going straight. When drivers deviate from going straight, they often slow down to make a turn or navigate

Variables	MNL		RPL		RPLHM		RPLHMV	
	Coeff	t-stat	Coeff	t-stat	Coeff	t-stat	Coeff	t-stat
Environmental characteristics								
Weekend (1 if crash happened on weekend, 0 if no) [BC]	0.370	2.86	0.439	2.52	0.474	2.58	0.446	2.48
Dark with no streetlight (1 if yes, 0 if no) [KA]	1.472	8.39	1.653	8.17	1.677	8.20	1.686	7.63
Dark with streetlights (1 if yes, 0 if no) [BC]	− 0.721	− 6.03	− 0.612	− 2.58	− 0.507	− 1.85	− 0.600	− 2.65
St. dev. of dark with streetlight	–	–	1.877	2.29	2.181	2.45	1.702	2.37
Crash Characteristics								
Access control (1 if partial control, 0 if no) [KA]	0.339	1.85	0.4519	2.03	0.465	1.99	0.478	2.02
Prior movement (1 if driver deviated from going straight, 0 if no) [KA]	− 0.391	− 2.07	− 0.542	− 2.36	− 0.529	− 2.23	− 0.504	− 1.95
Single vehicle crash (1 if yes, 0 if no) [O]	− 1.006	− 4.80	− 1.208	− 5.22	− 1.206	− 5.17	− 1.191	− 5.32
Lane departure (1 if yes, 0 if no) [BC]	0.947	7.23	1.069	6.75	1.094	6.73	1.097	6.78
Roadway Characteristics								
Mixed business and residential (1 if yes, 0 if no) [BC]	0.243	2.13	0.604	2.25	0.626	2.18	0.651	2.36
St. dev. of mixed business and residential	–	–	1.723	2.62	2.046	2.89	1.668	2.64
Residential (1 if yes, 0 if no) [BC]	0.536	2.13	0.634	2.15	0.668	2.22	0.636	2.01
Two lanes undivided (1 if yes, 0 if no) [KA]	− 0.293	− 2.46	− 0.286	− 1.97	− 0.294	− 1.95	− 0.324	− 2.11
No intersection (1 if crash occurred at segment, 0 if no) [O]	− 0.455	− 2.17	− 0.382	− 1.74	− 0.390	− 1.76	− 0.378	− 1.73
Traffic signal light (1 if yes, 0 if no) [BC]	0.235	1.65	–	–	–	–	–	–
Pedestrian Condition and Characteristics								
Pedestrian impaired with alcohol (1 if yes, 0 if no) [O]	− 1.864	− 2.56	− 2.007	− 2.67	− 2.184	− 2.91	− 2.172	− 2.53
Pedestrian aged 15 to 24 years old (1 if yes, 0 if no) [KA]	− 0.726	− 4.09	− 0.775	− 3.69	− 0.533	− 2.30	− 0.530	− 2.07
Inattentive or distracted pedestrian (1 if yes, 0 if no) [BC]	0.554	3.98	0.704	3.88	0.686	3.64	0.725	3.85
Pedestrian with Black race (1 if yes, 0 if no) [O]	− 0.815	− 3.74	− 0.697	− 2.90	− 0.621	− 2.56	− 0.641	− 2.86
Pedestrian with Caucasian race (1 if yes, 0 if no) [O]	− 0.660	− 2.93	− 0.505	− 2.01	− 0.434	− 1.70	− 0.474	− 1.99
Pedestrian Actions								
Pedestrian crossing a midblock (1 if yes, 0 if no) [BC]	− 0.405	− 3.31	− 0.468	− 2.90	− 0.430	− 2.54	− 0.461	− 2.70
Driver's Condition and Characteristics								
Driver impaired with alcohol or drug (1 if yes, 0 if no) [KA]	1.779	6.89	2.519	5.93	2.650	5.88	2.558	5.20
Driver aged over 64 years old (1 if yes, 0 if no) [KA]	− 0.477	− 2.16	− 0.612	− 2.33	− 0.645	− 2.39	− 0.594	− 1.91
Inattentive or distracted driver (1 if yes, 0 if no) [BC]	0.511	2.99	0.648	3.03	0.658	2.96	0.635	2.97
Driver with Black race (1 if yes, 0 if no) [KA]	0.252	2.11	0.321	2.18	0.333	2.19	0.316	2.06
Passenger present (1 if yes, 0 if no) [O]	0.587	2.18	0.577	2.00	0.569	1.96	0.574	1.92
Vehicle Type								
Passenger car (1 if yes, 0 if no) [KA]	− 0.344	− 2.87	− 0.399	− 2.75	− 0.416	− 2.78	− 0.414	− 2.61
Heterogeneity in mean, Parameter: Variable								
Effect of rain on the mean of random parameter mixed business and residential area	–	–	–	–	− 1.046	− 1.70	− 1.224	− 2.05
Effect of pedestrian aged 15 to 24 years on the mean of random parameter mixed business and residential area	–	–	–	–	1.177	2.14	1.529	2.27
Effect of rain on the mean of random parameter dark with streetlight	–	–	–	–	1.108	1.75	0.956	1.73
Effect of pedestrian impaired with alcohol on the mean of random parameter dark with streetlight	–	–	–	–	− 1.249	− 2.43	− 1.084	− 2.37
Heteroscedasticity in random parameters								
Effect of posted speed limit 40–45 mph on the variance of Location type mixed business and residential area	–	–	–	–	–	–	0.797	2.32
Statistics								
Number of observations	1,722							
K	24		25		29		30	
Log likelihood at convergence	− 1195.016		− 1189.749		− 1179.836		− 1176.952	
Restricted log likelihood	− 1891.810		− 1891.810		− 1891.810		− 1891.810	
McFadden Pseudo R-squared	0.3683		0.3711		0.3763		0.3779	
AIC	2438.0		2429.5		2417.7		2413.9	
AIC/N	1.416		1.411		1.404		1.402	

Table 6. Model estimation results for principal arterial roads.

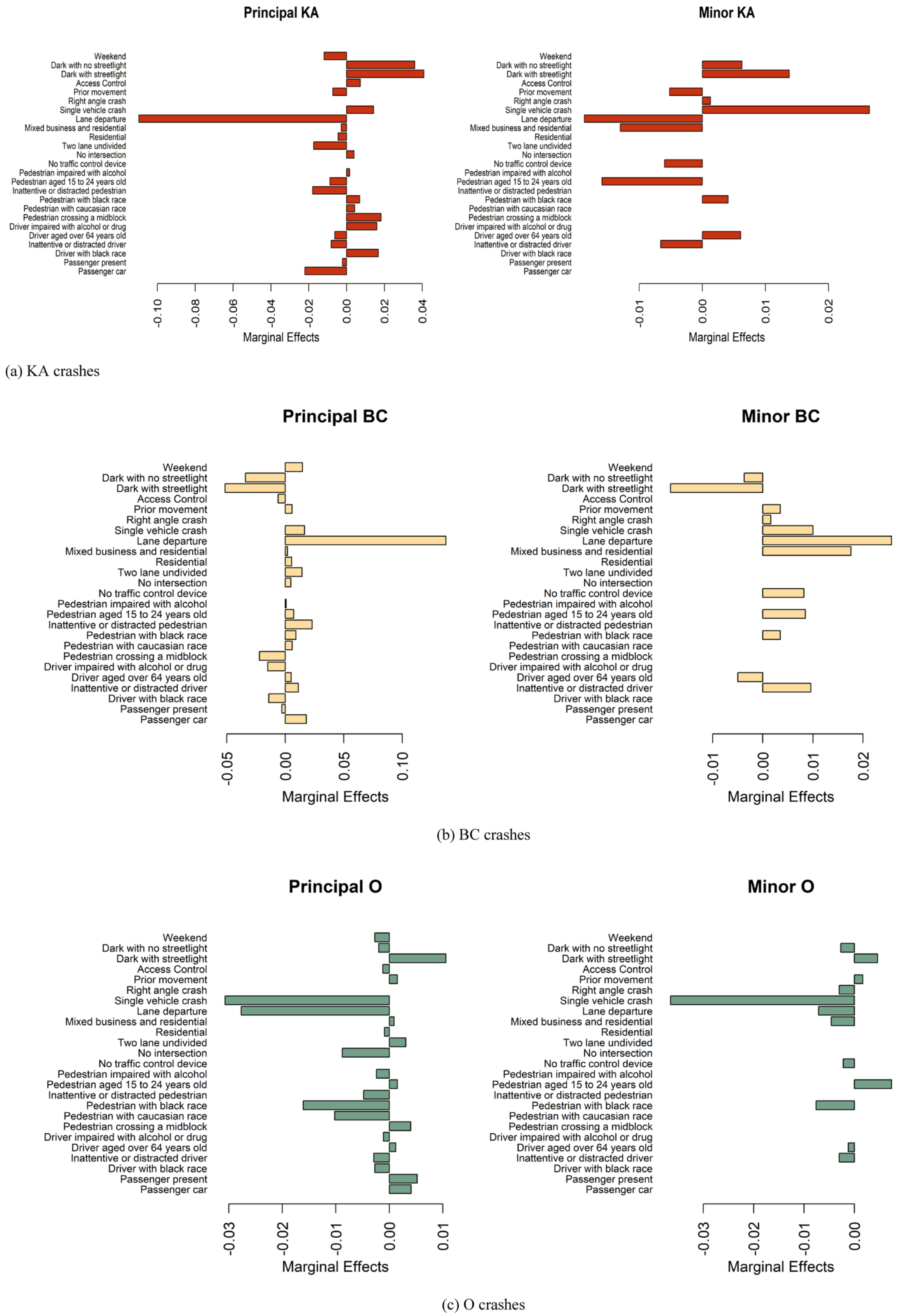

Fig. 3. Marginal effects of variables in principal and minor arterial roadways.

an intersection[60,61], reducing their speed and, thus, the severity of potential crashes. Lower speeds generally lead to less severe outcomes[62], which explains the negative coefficient. Similarly, for the minor arterials, the negative coefficient (-0.568) also suggests a lower likelihood of KA injury under this condition. On minor arterials, deviations from going straight may occur more frequently due to the nature of these roads, which often have more intersections and access points. This frequent deviation involves lower speeds and increased driver attentiveness, contributing to reduced crash severity. These findings are consistent with a previous study that analyzed pedestrian crashes in the United Kingdom and found that certain pre-crash maneuvers, such as turning movements, were associated with reduced pedestrian injury severity compared to going straight, largely due to lower speeds and increased driver caution in these scenarios[21]. The marginal effects of this variable show similar effects in the crash severity levels for both principal (KA = − 0.0073, BC = 0.0058, O = 0.0015) and minor (KA = − 0.0052, BC = 0.0035, O = 0.0017) arterials. Overall, in the crash scenario in which the 'driver deviated from going straight', the likelihood of BC injury increases for both principal and minor arterials.

Right angle crash (1 if the crash involved right angle, 0 if otherwise) [O]: This variable was found significant in only minor arterials. The fixed negative coefficient (-0.681) for O injury indicates a higher likelihood of severe outcomes when they occur (KA = 0.0013, BC = 0.0016). Right-angle crashes typically occur at intersections or locations where vehicles cross paths perpendicularly[63]. These crashes often involve higher impact forces due to the impact angle, leading to more severe injuries[64]. On minor arterials, where traffic controls and speed limits are lower than on principal arterials, right-angle crashes can result in significant injuries due to the sudden and unexpected nature of pedestrian actions. Additionally, drivers may fail to notice pedestrians due to visual obstructions at intersections, leading to severe injuries[65].

Single vehicle crash (1 if the crash involved single vehicle, 0 if otherwise) [O]: This indicator variable was significant for both principal and minor arterials. The fixed negative coefficients for the principal (-1.191) and minor (-2.126) arterials indicate a lower likelihood of O crashes under this condition. Single-vehicle crashes often lead to more severe outcomes because of the unique nature of these incidents, as shown by the marginal effects (principal arterial: KA = 0.0143, BC = 0.0165, O = − 0.0307; minor arterial: KA = 0.0265, BC = 0.01, O = − 0.0365). The marginal effects for minor arterials demonstrate an even stronger impact, 1.85 times (0.0265/0.0143) higher likelihood of KA crashes (compared to principal arterial). These results suggest that such crashes on minor arterials have higher likelihood of resulting in severe injuries.

Lane departure (1 if the crash involved lane departure of vehicles, 0 if otherwise) [BC]: The indicator variable was significant for both principal and minor arterials illustrated by marginal effects (KA = − 0.1098, BC = 0.1374, O = − 0.0277) and minor (KA = − 0.0187, BC = 0.0257, O = − 0.0071). On principal arterials, it was modeled as a fixed parameter with a positive coefficient of 1.097, indicating an increased likelihood of BC-level injuries when crashes involve lane departures. Focusing on the minor arterials, the co-efficient for 'lane departure' variable has been identified as a random parameter with an estimated mean of − 2.126 and standard deviation of 2.984, suggesting that 76.19% of this distribution is below zero and 23.81% is above zero. This implies that in the case of lane departure crashes on minor arterials, a major proportion (76.19%) of pedestrian-vehicle crashes are less likely to result in BC crashes, and in 23.81% of cases, crashes have a higher probability of resulting in BC crash involvement. One key factor contributing to this heterogeneity is the location of the pedestrian relative to the vehicle during a lane departure. A pedestrian positioned on the left side of the vehicle's trajectory might experience different risks compared to one on the right side[66]. This variability is influenced by the driver's reaction, such as swerving or braking, which can change the impact dynamics[67]. Additionally, the specific trajectory of the vehicle during a lane departure plays a crucial role in determining whether the pedestrian is struck and, if so, the severity of the collision. Additional variability and complexity are observed for pedestrian-vehicle crashes involving lane departure collisions. Driver alcohol or drug impairment affected the mean of the random parameter 'lane departure', reducing it to − 4.187 and lowering the likelihood of pedestrian BC injuries. This counterintuitive finding highlights the complex dynamics of impaired driving and its impact on pedestrian crash severity on minor arterials. In addition, pedestrian alcohol/drug impairment also impacted the mean of this indicator variable by decreasing it to − 1.638. This suggests that the presence of impaired pedestrians in lane departure crashes has lower likelihood of resulting in BC injury crashes. While it might seem unexpected that impairment reduces the likelihood of BC injury severity, this could be due to impaired individuals' erratic behaviors leading to slower speeds or other evasive driving-related actions, which might reduce crash impact. Additionally, unobserved factors such as specific road conditions or traffic patterns on minor arterials might influence these outcomes, underscoring the need for further research to explore these interactions and their implications for pedestrian safety. Although pedestrian impairment has been a common influential factor contributing to pedestrian crashes[68–70], the specific event of lane departure may act differently in minor arterial settings. The upward shift in the indicator variable's mean (1.304) for 25–40-year-old pedestrians suggests a higher likelihood of BC crashes within this age group, potentially due to delayed reactions to unexpected scenarios. Middle-aged pedestrians may not respond as quickly as younger individuals, increasing their vulnerability in such crashes on minor arterials, where road conditions and traffic patterns may further complicate these events[71]. The positive coefficient (0.811) of the effect of 'dark with no streetlight' condition on the variance of lane departure indicates that the dark with no streetlight lighting condition increases the variance of 'lane departure' related crashes involving pedestrians. This suggests that the impact of lane departures on pedestrian injury severity is more variable when there is no streetlight in dark conditions. The manner of collision indicator variable 'single vehicle crash' also positively (0.376) influences the variance of lane departure crashes. Unlike multi-vehicle crashes where interactions between vehicles can moderate the impact, single-vehicle pedestrian crashes are often more unpredictable because they depend on the specific circumstances of the collision. Additionally, the pedestrian's actions, such as crossing behavior and attentiveness, add another layer of variability. Finally, the effect of drivers aged 15 to 24 years old is observed on the variance of pedestrian crashes in specific maneuvers of 'lane departure', with a positive coefficient of 0.482. This suggests that the impact of lane departures on crash severity is more variable when young drivers are involved. Inexperienced young drivers may be prone to risky behaviors, such as speeding, distraction, or overcorrection, which can potentially result in crash outcomes ranging from minor to severe or fatal (Tables 7, 8).

Variables	MNL		RPL		RPLHM		RPLHMV	
	Coeff	t-stat	Coeff	t-stat	Coeff	t-stat	Coeff	t-stat
Environmental characteristics								
Dark with no streetlight (1 if yes, 0 if no) [KA]	1.041	6.44	1.221	5.17	1.256	4.75	0.565	1.78
Dark with streetlights (1 if yes, 0 if no) [BC]	− 0.517	− 3.99	− 0.593	− 2.97	− 0.602	− 2.53	− 0.715	− 2.34
Crash Characteristics								
Prior movement (1 if driver deviated from going straight, 0 if no) [KA]	− 0.388	− 1.91	− 0.541	− 1.98	− 0.600	− 2.01	− 0.568	− 1.73
Right angle crash (1 if yes, 0 if no) [O]	− 0.757	− 2.08	− 0.786	− 2.01	− 0.764	− 1.90	− 0.681	− 1.66
Single vehicle crash (1 if yes, 0 if no) [O]	− 1.556	− 7.54	− 1.795	− 8.07	− 1.921	− 8.53	− 2.126	− 9.40
Lane departure (1 if yes, 0 if no) [BC]	− 1.556	− 7.54	− 1.795	− 8.07	− 1.921	− 8.53	− 2.126	− 9.40
St. dev. of lane departure	–	–	2.281	2.87	3.283	3.04	2.984	2.22
Roadway Characteristics								
Mixed business and residential (1 if yes, 0 if no) [BC]	0.383	3.32	0.571	3.09	0.599	2.89	0.551	2.27
No traffic control device (1 if yes, 0 if no) [BC]	0.437	2.32	0.773	2.33	0.858	2.23	0.996	2.37
Pedestrian Condition and Characteristics								
Pedestrian aged 15 to 24 years old (1 if yes, 0 if no) [KA]	− 0.757	− 3.86	− 1.171	− 3.93	− 1.349	− 4.48	− 1.517	− 4.57
Pedestrian aged 41 to 64 years old (1 if yes, 0 if no) [O]	− 0.412	− 1.75	–	–	–	–	–	–
Pedestrian with Black race (1 if yes, 0 if no) [O]	− 0.422	− 2.11	− 0.486	− 2.23	− 0.494	− 2.18	− 0.438	− 1.79
Driver's Condition and Characteristics								
Driver impaired with alcohol or drug (1 if yes, 0 if no) [KA]	1.093	3.89	1.317	3.30	–	–	–	–
Driver aged over 64 years old (1 if yes, 0 if no) [KA]	0.386	1.91	0.548	1.82	0.641	1.81	0.791	1.81
Inattentive or distracted driver (1 if yes, 0 if no) [BC]	0.332	2.06	0.601	2.35	0.692	2.39	0.738	2.39
Heterogeneity in mean, Parameter: Variable								
Effect of driver impaired with alcohol or drug on the mean of random parameter lane departure	–	–	-	–	− 3.270	− 2.80	− 4.187	− 2.43
Effect of pedestrian aged 25–40 years old on the mean of random parameter lane departure	–	–	–	–	0.920	2.66	1.304	2.53
Effect of pedestrian impaired with alcohol on the mean of random parameter lane departure	–	–	–	–	− 1.460	− 2.17	− 1.638	− 1.81
Heteroscedasticity in random parameters								
Effect of dark with no streetlight on variance of lane departure	–	–	–	–	–	–	0.811	2.92
Effect of single vehicle crash on variance of lane departure	–	–	–	–	–	–	0.376	2.33
Effect of driver aged 15 to 24 years old on variance of lane departure	–	–	–	–	–	–	0.482	2.37
Statistics								
Number of observations	1,614							
K	14		14		16		19	
Log likelihood at convergence	− 1061.955		− 1060.891		− 1046.158		− 1032.652	
Restricted log likelihood	− 1773.160		− 1773.160		− 1773.160		− 1773.160	
McFadden Pseudo R-squared	0.4011		0.4017		0.4100		0.4176	
AIC	2151.9		2149.8		2124.3		2103.3	
AIC/N	1.333		1.332		1.316		1.303	

Table 7. Model estimation results for minor arterial roads.

Roadway characteristics

Mixed business and residential areas (1 if the crash occurred in mixed business and residential areas, 0 if otherwise) [BC]: The indicator variable is significant for both principal and minor arterials. This variable has been identified as a random parameter for the principal arterials, with a mean of 0.651 and a standard deviation of 1.668. This indicates that 34.82% of this distribution is below zero, and 65.18% is above zero. This implies that, for crashes occurring on mixed business and residential roads on principal arterials, most pedestrians (65.18%) are highly likely to be involved in BC crashes, and 34.82% of pedestrians have less probability of BC crash involvement under these specific settings. These areas typically have high pedestrian activity due to the presence of both commercial and residential establishments[72,73]. However, the 34.82% below zero reflects that in a significant minority of cases, the conditions or specific circumstances may lead to less severe outcomes, possibly due to slower vehicle speeds, better visibility, or effective pedestrian safety measures in place. The weather condition indicator variable, 'rain' significantly impacts the mean of the random parameter, reducing it to − 1.224. This reduction suggests that during rainy conditions, the likelihood of BC crashes decreases in mixed business and residential areas. Rainy weather conditions may deter pedestrian activity[74], leading to fewer interactions with vehicles, or it may cause drivers to be more cautious, reducing the incidence of crashes. Conversely, the presence of 15 to 24 years old pedestrians positively impacts the mean of the random parameter by increasing it to 1.529. This age group is likely more active in mixed business and residential areas, increasing the risk of BC crashes due to higher pedestrian presence and potentially riskier behaviors such as jaywalking or inattentiveness[75]. The variable indicating a posted speed limit of 40–45 mph showed a positive effect (0.797) on the variance of the

Variable	Injury Severity	Principal Arterial	Minor Arterial
Environmental characteristics			
Weekend (1 if crash happened in weekend, 0 if no) [BC]	KA	−0.0119	–
	BC	0.0147	–
	O	−0.0027	–
Dark with no streetlight (1 if yes, 0 if no) [KA]	KA	0.0360	0.0063
	BC	−0.0340	−0.0037
	O	−0.0020	−0.0027
Dark with streetlight (1 if yes, 0 if no) [BC]	KA	0.0409	0.0138
	BC	−0.0515	−0.0184
	O	0.0106	0.0046
Crash Characteristics			
Access control (1 if partial control, 0 if no) [KA]	KA	0.0073	–
	BC	−0.0061	–
	O	−0.0012	–
Prior movement (1 if driver deviated from going straight, 0 if no) [KA]	KA	−0.0073	−0.0052
	BC	0.0058	0.0035
	O	0.0015	0.0017
Right angle crash (1 if yes, 0 if no) [O]	KA	–	0.0013
	BC	–	0.0016
	O	–	−0.0030
Single vehicle crash (1 if yes, 0 if no) [O]	KA	0.0143	0.0265
	BC	0.0165	0.0100
	O	−0.0307	−0.0365
Lane departure (1 if yes, 0 if no) [BC]	KA	−0.1098	−0.0187
	BC	0.1374	0.0257
	O	−0.0277	−0.0071
Roadway Characteristics			
Mixed business and residential (1 if yes, 0 if no) [BC]	KA	−0.0028	−0.0130
	BC	0.0019	0.0176
	O	0.0009	−0.0046
Residential (1 if yes, 0 if no) [BC]	KA	−0.0045	–
	BC	0.0054	–
	O	−0.0009	–
Two lanes undivided (1 if yes, 0 if no) [KA]	KA	−0.0174	–
	BC	0.0143	–
	O	0.0031	–
No intersection (1 if crash occurred at segment, 0 if no) [O]	KA	0.0040	–
	BC	0.0048	–
	O	−0.0088	–
No traffic control device (1 if yes, 0 if no) [BC]	KA	–	−0.0060
	BC	–	0.0082
	O	–	−0.0022
Pedestrian Condition and Characteristics			
Pedestrian impaired with alcohol (1 if yes, 0 if no) [O]	KA	0.0016	–
	BC	0.0008	–
	O	−0.0024	–
Pedestrian aged 15 to 24 years old (1 if yes, 0 if no) [KA]	KA	−0.0088	−0.0159
	BC	0.0072	0.0085
	O	0.0015	0.0074
Inattentive or distracted pedestrian (1 if yes, 0 if no) [BC]	KA	−0.0180	–
	BC	0.0229	–
	O	−0.0048	–
Pedestrian with Black race (1 if yes, 0 if no) [O]	KA	0.0070	0.0041
	BC	0.0091	0.0035
	O	−0.0161	−0.0076
Continued			

Variable	Injury Severity	Principal Arterial	Minor Arterial
Pedestrian with Caucasian race (1 if yes, 0 if no) [O]	KA	0.0043	–
	BC	0.0059	–
	O	− 0.0102	–
Pedestrian crossing a midblock (1 if yes, 0 if no) [BC]	KA	0.0182	–
	BC	− 0.0221	–
	O	0.0040	–
Driver's Condition and Characteristics			
Driver impaired with alcohol or drug (1 if yes, 0 if no) [KA]	KA	0.0160	–
	BC	− 0.0150	–
	O	− 0.0011	–
Driver aged over 64 years old (1 if yes, 0 if no) [KA]	KA	− 0.0063	0.0061
	BC	0.0050	− 0.0050
	O	0.0012	− 0.0012
Inattentive or distracted driver (1 if yes, 0 if no) [BC]	KA	− 0.0082	− 0.0066
	BC	0.0111	0.0096
	O	− 0.0029	− 0.0030
Driver with Black race (1 if yes, 0 if no) [KA]	KA	0.0168	–
	BC	− 0.0141	–
	O	− 0.0027	–
Passenger present (1 if yes, 0 if no) [O]	KA	− 0.0022	–
	BC	− 0.0030	–
	O	0.0052	–
Vehicle Type			
Passenger car (1 if yes, 0 if no) [KA]	KA	− 0.0221	–
	BC	0.0180	–
	O	0.0041	–

Table 8. Marginal effect results based on the RPLHMV model for principal and minor arterial roads.

corresponding random parameter. This suggests that crash severity outcomes in mixed business and residential areas become more variable under these speed conditions. The increased variability likely comes from the elevated risks posed by higher travel speeds in areas with substantial pedestrian presence, where interactions between vehicles and pedestrians are more frequent and unpredictable. For minor arterials, this variable was treated as a fixed parameter and yielded a positive coefficient of 0.551. Similar to principal arterials, areas characterized by both residential and commercial activity tend to have increased interactions between pedestrians and vehicles, raising the likelihood of BC-level injuries. The marginal effects for minor arterials indicate variation across injury severity levels: KA = − 0.0130, BC = 0.0176, and O = − 0.0046. The positive effect for BC injuries supports the finding that such environments are associated with a higher chance of moderate injuries, while the negative effects for KA and O outcomes point to a lower probability of both severe/fatal and no-injury crashes in these settings.

Residential areas (1 if the crash occurred in residential areas, 0 if otherwise) [BC]: The fixed positive coefficient (0.636) suggests that on residential roads, the likelihood of BC crashes is higher. Examining the marginal effects of this variable reveals its varied impacts on crash severity levels for principal arterials (KA = − 0.0045, BC = 0.0054, O = − 0.0009). The positive marginal effect for BC crashes indicates a higher probability of possible injury crashes in residential areas. This increase is likely due to the higher number of pedestrians, including children and elderly individuals, who are more vulnerable to being involved in crashes[76]. The negative marginal effect for KA crashes suggests a slightly lower likelihood of fatal or severe injuries in residential areas. This may be due to lower vehicle speeds typically enforced in residential zones, which can reduce the severity of crashes when they occur. Additionally, traffic calming measures such as speed bumps, stop signs, and pedestrian crossings in residential areas can help mitigate the severity of crashes[77].

Two lanes undivided (1 if the crash occurred on two-lane undivided roads, 0 if otherwise) [KA]: This indicator variable was found significant for principal arterials, suggesting a notable impact of roadway lane configuration on pedestrian safety. The fixed negative coefficient (-0.324) signifies a lower likelihood of KA injury on a two-lane undivided roadway. This reduced likelihood can be attributed to several factors associated with the characteristics of two-lane undivided roads. On two-lane undivided roadways, traffic is typically slower due to narrow lanes and the potential for head-on collisions, which may prompt more cautious driving[78]. Additionally, these roadways often have fewer lanes for pedestrians to cross, reducing their exposure to moving vehicles. The absence of a median or divider might also encourage drivers to be more vigilant, knowing that oncoming traffic is closer. Examining the marginal effects of this variable reveals its varied impact on crash severity levels for principal arterials (KA = − 0.0174, BC = 0.0143, O = 0.0031).

Not at intersection (1 if the crash occurred at segment, 0 if otherwise) [O]: This indicator variable was found significant for principal arterials. The fixed negative coefficient (-0.378) indicates a lower likelihood of O crashes when the crash occurs at a road segment rather than an intersection. This suggests that pedestrian crashes occurring at road segments are generally more severe, aligned with our common expectations[79]. Examining the marginal effects of this variable reveals its varied impact on crash severity levels for principal arterials (KA = 0.0040, BC = 0.0048, O = − 0.0088). The positive marginal effects for KA and BC crashes suggest an increased likelihood of severe injuries at road segments. This pattern can be attributed to several factors. At road segments, vehicles are typically traveling at higher speeds compared to intersections, where they must slow down or stop. Higher speeds increase the impact of a crash, leading to more severe injuries. Additionally, the absence of intersections might reduce driver vigilance, as drivers may be less likely to anticipate sudden stops or the presence of pedestrians.

No traffic control device (1 if no traffic control device in place, 0 if otherwise) [BC]: This indicator variable was found significant for minor arterials, indicating a substantial impact on pedestrian safety due to the absence of traffic control devices. The fixed positive coefficient (0.996) suggests a higher likelihood of BC crashes when there is no traffic control device present on minor arterial roads. This increased risk can be attributed to the lack of regulated traffic flow with no traffic control device in place, leading to more frequent interactions between vehicles and pedestrians[80]. Examining the marginal effects of this variable reveals its varied impact on crash severity levels for minor arterials (KA = − 0.0060, BC = 0.0082, O = − 0.0022). The positive marginal effect for BC crashes indicates a higher probability of moderate/complaint injury crashes under this condition. The absence of traffic control devices, such as stop signs or traffic lights, can result in unpredictable driver behavior and increased pedestrian exposure to moving vehicles, leading to a greater likelihood of BC injuries.

Pedestrian condition and characteristics

Pedestrian impaired with alcohol (1 if alcohol impaired pedestrian involved in the crash, 0 if otherwise) [O]: This indicator variable was found significant for principal arterials, with a fixed negative coefficient of − 2.172, suggesting that alcohol impairment in pedestrians increases the severity of crashes, resulting in more severe outcomes (KA = 0.0016, BC = 0.0008, O = − 0.0024). It has been well established that alcohol impairment in pedestrians is associated with increased probabilities of severe injury crashes mainly due to impaired judgment and reduced reaction capabilities, which compromise a pedestrian's ability to safely navigate complex traffic environments on principal arterials making them more vulnerable to dangerous and consequential crash scenarios[81,82].

Pedestrians aged 15 to 24 years old (1 if 15–24 years old pedestrian involved in the crash, 0 if otherwise) [KA]: This variable was found significant for both principal and minor arterial roads. The fixed negative coefficients of − 0.530 for principal arterial roads and − 1.517 for minor arterial roads suggest that pedestrians aged 15 to 24 years old are associated with a decreased likelihood of KA injury. This decreased likelihood can be attributed to better physical resilience and quicker reaction times typical of this age group, which help them avoid the most severe consequences of crashes. Analyzing the marginal effects of this variable reveals its impact across different severity levels for the principal (KA = − 0.0088, BC = 0.0072, O = 0.0015) and minor arterial roads (KA = − 0.0159, BC = 0.0085, O = 0.0074). This pattern suggests that younger pedestrians may have a lower risk of fatal or severe injuries; their higher physical resilience and quicker reaction times result in more minor or no injuries in crashes.

Inattentive or distracted condition of pedestrian (1 if inattentive or distracted pedestrian involved in the crash, 0 if otherwise) [BC]: The inattentive or distracted pedestrian variable was statistically significant for principal arterial roads. A fixed positive coefficient of 0.725 indicates that distracted pedestrians are more likely to be involved in BC-level injury crashes along these corridors. This increased risk is likely due to reduced situational awareness and slower response times, which heighten vulnerability during crossing or roadside interactions. These findings align with earlier studies noting that pedestrians using electronic devices in residential settings face a greater chance of sustaining moderate injuries[83]. The marginal effects for principal arterials further demonstrate its influence across injury severity categories (KA = − 0.0180, BC = 0.0229, O = − 0.0048).

Black pedestrian (1 if Black pedestrian is involved in the crash, 0 if otherwise) [O]: This variable was found to be significant for both principal and minor arterials, emphasizing the role of pedestrian race in influencing crash severity outcomes. The fixed negative coefficients -0.641 for principal arterials and -0.438 for minor arterials indicate that crashes involving Black pedestrians are less likely to result in no-injury outcomes. The marginal effects also demonstrate variation across injury levels: for principal arterials, KA = 0.0070, BC = 0.0091, and O = − 0.0161; for minor arterials, KA = 0.0041, BC = 0.0035, and O = − 0.0076. These findings point to a greater likelihood of injury when Black pedestrians are involved. Overall, the increased risk (resulting in KA and BC injuries) on principal and minor arterials can be explained by the higher exposure of Black pedestrians to risky environments and less immediate medical response, increasing the probability of KA and BC. This is consistent with the finding that Black pedestrians were significantly overrepresented in terms of fatalities[84]. This increased severity can be attributed to the higher likelihood of encountering hazardous conditions and less access to safe pedestrian infrastructure possibly contributing to more serious crash outcomes.

Caucasian pedestrian (1 if Caucasian pedestrian is involved, 0 if otherwise) [O]: This variable is significant for principal arterial roads, with a fixed negative coefficient of − 0.474 suggesting that Caucasian pedestrians are associated with an increased likelihood of KA and BC injuries (KA = 0.0043, BC = 0.0059, O = − 0.0102). This heightened risk can be attributed to a combination of factors, including the higher exposure of Caucasian pedestrians to principal arterial roads, which often feature higher speeds and traffic volumes, making any vehicle–pedestrian interactions more dangerous. Note that the risk is higher for Black pedestrians compared to Caucasian pedestrians on principal arterials.

Pedestrian crossing at midblock locations (1 if the crash occurred while pedestrian crossing at midblock, 0 if otherwise) [BC]: This variable is found significant for principal arterial roads. The fixed negative coefficient of − 0.461 for principal arterial roads suggests that pedestrians crossing at a midblock are associated with a decreased likelihood of BC crashes on these roads. Examining the marginal effects of this variable shows its varied impact across different severity levels for principal arterial roads (KA = 0.0182, BC = − 0.0221, O = − 0.0040). The positive marginal effect for KA indicates an increased likelihood of KA injury for pedestrians crossing at midblock. A previous analysis revealed that the likelihood of pedestrian fatalities is greater at midblock locations compared to intersections[85]. The increased severity can be attributed to the unpredictability of midblock crossings, where drivers may not expect pedestrians, leading to higher impact speeds and more severe crash outcomes.

Drivers's characteristics

Driver impaired with alcohol or drug (1 if alcohol or drug involved drivers involved in the crash, 0 if otherwise) [KA]: This variable was significant for principal arterials, indicating that driver impairment plays a critical role in pedestrian crash severity. The fixed positive coefficient of 2.558 implies a strong association between alcohol or drug impairment and a higher probability of crashes resulting in KA injuries (KA = 0.0160, BC = − 0.0150, O = − 0.0011). Previous research also suggests that alcohol involvement is more likely to increase the probability of severe injury outcomes[86,87]. This increased likelihood can be attributed to the significant reduction in reaction time, coordination, and judgment that impairment causes, leading to more severe pedestrian crash outcomes.

Driver aged over 64 years old (1 if older drivers involved in the crash, 0 if otherwise) [KA]: Pedestrian crashes involving older drivers were found to have contrasting impacts on pedestrian injury severity for the principal (KA = − 0.0063, BC = 0.0050, O = 0.0012) and minor arterial roads (KA = 0.0061, BC = − 0.0050, O = − 0.0012). The lower likelihood of KA injury on principal arterial may be attributed to older drivers being more cautious and driving at lower speeds on principal arterial roads, leading to less severe pedestrian injury outcomes. The higher likelihood of pedestrian KA injuries on minor arterial roads involving older drivers, as opposed to principal arterials, can be attributed to the more complex and unpredictable driving conditions on these roads. Minor arterials often lack the design standards and traffic controls of principal arterials, resulting in more variable traffic patterns and unexpected situations, such as pedestrians crossing at non-designated areas. While older drivers tend to be cautious with defensive driving style[88,89], the challenges posed by minor arterials, such as frequent stops, starts, and turns, can lead to slower reaction times and less controlled maneuvers. Additionally, the lack of adequate pedestrian infrastructure on minor arterials further exacerbates the risk, contributing to more severe injury outcomes in these environments.

Inattentive or distracted driver (1 if inattentive or distracted drivers involved in the crash, 0 if otherwise) [BC]: This variable was significant for both principal and minor arterial roadways. On principal arterials, the fixed positive coefficient of 0.635 indicates that crashes involving inattentive or distracted drivers are more likely to result in BC injuries. A similar trend was observed on minor arterials, where the coefficient of 0.738 also points to an increased risk of BC injuries under driver distraction. This elevated risk can be attributed to reduced driver awareness, which increases the chance of collisions with pedestrians. The marginal effects further illustrate this pattern: for principal arterials (KA = − 0.0082, BC = 0.0111, O = − 0.0029) and for minor arterials (KA = − 0.0066, BC = 0.0096, O = − 0.0030). Interestingly, the negative marginal effects for KA crashes suggest that distraction may be associated with a reduced likelihood of severe injuries, a finding that warrants further investigation. Factors such as roadway design and surrounding land use may influence how driver distraction translates into crash severity[90].

Black driver (1 if Black driver is involved in the crash, 0 if otherwise) [KA]: This variable was significant for principal arterial roads, highlighting the influence of driver race on pedestrian injury outcomes. A fixed coefficient of 0.316 indicates that crashes involving Black drivers are more likely to result in KA injuries. The associated marginal effects, KA = 0.0168, BC = − 0.0141, and O = − 0.0027, illustrate this increased risk for severe outcomes. This pattern may reflect broader socioeconomic and environmental disparities that shape driving behavior and exposure to hazardous traffic conditions, as noted in earlier studies[91].

Passenger present (1 if the crash involved vehicle involves passenger, 0 if no passenger) [O]: This variable was significant for principal arterial roads and was associated with a positive estimated coefficient of 0.574, indicating the influence of passenger presence on pedestrian crash severity. The result suggests that vehicles carrying passengers are more likely to be involved in pedestrian crashes that result in no injuries on these roadways. In other words, drivers with passengers are more likely to avoid KA pedestrian crashes on principal arterials outlined by the marginal effects (KA = − 0.0022, BC = − 0.0030, O = 0.0052). This could be attributed to drivers being more cautious when carrying passengers, leading to safer driving behavior and less severe pedestrian crash outcomes consistent with previous literature[92,93].

Passenger car (1 if passenger car is involved in crash, 0 if otherwise) [KA]: This variable was significant for principal arterial roads, with a negative estimated coefficient of − 0.414, indicating that crashes involving passenger cars are less likely to result in KA-level pedestrian injuries on these roadways. The marginal effects reveal the varied impact of this variable across different severity levels (KA = − 0.0221, BC = 0.0180, O = 0.0041). Passenger cars, being smaller and lighter than larger vehicles like trucks or SUVs, tend to cause less severe impacts, resulting in a lower probability of fatal or severe injuries. Their greater maneuverability and better driver visibility also contribute to a reduced likelihood of KA crashes, as drivers can more effectively avoid or mitigate collisions compared to other vehicle types like trucks or SUV consistent with previous literature[94].

Conclusions

This study makes a novel contribution by applying a random parameter modeling framework with heterogeneity in both means and variance to analyze pedestrian crashes on principal and minor arterial roads in Louisiana.

A total of 3,336 pedestrian-vehicle crashes from 2017 to 2021 were examined to explore the factors influencing injury severity. The modeling approach is essential for addressing unobserved heterogeneity within the data, enabling a more accurate assessment of how various factors affect crash outcomes. Marginal effects revealed notable differences between principal and minor arterials in the determinants of pedestrian injury severity, offering valuable insights for developing safety strategies.

Pedestrian-related factors significantly influence crash outcomes. For instance, alcohol or drug impairment among pedestrians markedly elevates the risk of severe injuries (KA or BC) on principal arterial roadways. The minimal impact on no injuries (O) indicates that impaired pedestrians are at a higher risk of severe outcomes in crashes, likely due to reduced cognitive skills, and decision-making ability in complex traffic environments on principal arterials. The lack of significant impact on minor arterial roads suggests that pedestrian impairment may not be as critical a factor in these settings, or other factors may dominate in contributing to crash severity. The impact of pedestrian races also varies across road types. For pedestrians of the Black race, the likelihood of KA injuries is higher on both principal and minor arterial roads compared to pedestrians of the Caucasian race. This indicates that racial disparities in pedestrian safety need to be addressed through targeted interventions that consider the specific vulnerabilities faced by Black race pedestrians, including but not limited to, community-specific education and infrastructure improvements. Pedestrians crossing a midblock on principal arterial roads experience an increased likelihood of KA injuries. This highlights the need for enhanced midblock crossing safety measures, such as pedestrian crosswalks with adequate lighting and signage. The research also identifies those pedestrian demographics, such as age have varying impacts on injury severity across road types. For instance, younger pedestrians (aged 15 to 24 years) are less likely to experience KA injuries on both principal and minor arterials, but the effect is more substantial on minor arterials. This suggests that targeted safety measures, such as education campaigns and infrastructure improvements, should consider the demographic profile of pedestrians frequenting these roads.

Roadway characteristics also significantly influence crash severity. Access control, indicating partial access control on principal arterial roads, increases the likelihood of KA injuries. This suggests that while access control can reduce conflict points, it may not be sufficient alone to mitigate severe pedestrian crash risk. Environmental factors play a crucial role as well. For principal and minor arterial roads, the presence of streetlights in dark conditions increases the likelihood of KA injuries while reducing the likelihood of BC and O injuries. This suggests that while streetlights improve visibility, they may also indicate higher traffic volumes or more complex driving conditions that increase severe crash risk. Additionally, dark conditions without streetlights increase the likelihood of KA injuries on principal and minor arterials. This underscores the critical need for adequate lighting on these roads to enhance pedestrian safety and mitigate crash severity. Overall, dark conditions (with or without streetlights) increase the likelihood of KA injuries on principal and minor arterials, emphasizing the importance of adequate lighting on all arterial roads. The analysis of crash characteristics reveals that single-vehicle crashes significantly increase the likelihood of KA injuries on both principal and minor arterials. However, the impact is more pronounced on minor arterials, suggesting that single-vehicle crashes on these roads may involve higher speeds or more severe impacts. Driver alcohol or drug involvement, along with distractions found to play a critical role in KA or BC injury of pedestrians. This finding highlights the critical role of addressing driver distraction and impairment to improve pedestrian safety on minor arterials.

Temporal factors, such as the time of day and day of the week, also influence crash severity. Weekend crashes, for instance, show distinct patterns in terms of crash severity compared to weekday crashes. Understanding these temporal variations is essential for developing targeted interventions that address specific high-risk periods. Lane departure crashes significantly increase the likelihood of BC injuries on both principal and minor arterials. However, the impact is more pronounced on principal arterials, indicating that measures to prevent lane departures, such as rumble strips or improved lane markings, could be particularly beneficial on these roads. The higher traffic volumes and speeds on principal arterials may exacerbate the consequences of lane departures, making this a priority area for intervention.

Practical applications

The findings support the broader goals of national safety initiatives, such as the NRSS and Vision Zero, aiming to reduce pedestrian fatalities and achieve zero roadway deaths. This study highlighted the importance of developing safety measures that reflect the distinct conditions of principal and minor arterial roads. By targeting the specific factors linked to pedestrian crash severity on each road type, transportation agencies can implement more effective interventions to improve pedestrian safety. Ultimately, the insights gained from this study emphasized the importance of implementing comprehensive safety measures that address the diverse risk factors identified. Such measures could include enhanced street lighting, stricter enforcement of driving under the influence (DUI) laws, improved signage and crosswalks at midblock locations, and targeted education and outreach programs for unobserved communities. In addition, the findings of this study advocated the implementation of Safe System Approach (SSA) principles to facilitate the philosophical shift from reactive to proactive countermeasures. While this study primarily aligns with the Safer People element among SSA's core elements (safer people, safer vehicles, safer speeds, safer roads, and post-crash care), it also underscores the interconnected nature of pedestrian-vehicle crashes with all SSA elements. Based on the results, this study focused on the most critical factors increasing the likelihood of fatal/severe injury in pedestrian crashes (based on positive marginal effects of KA). Based on the context (first column), we provided connections with the Safe System Roadway Design Hierarchy (tier 1: remove severe conflicts, tier 2: reduce vehicle speed, tier 3: manage conflicts in time, tier 4: increase attentiveness and awareness) that can be integrated into the approach. Note that, the hierarchy depends on the previous work by Austroads[95] and is consistent with the Safe System Pyramid[96]. Several countermeasures and policy level implications are summarized in Table 9.

v. Study limitations.

Context (crash scenario)	Safe system roadway design hierarchy	Countermeasure/policy level implications
Dark lighting conditions (with and without streetlights)	Tier 4: increase attentiveness and awareness	Enhance roadway visibility through the installation of additional streetlights, reflective road markings, and pedestrian-activated flashing beacons. Introduce public campaigns to encourage wearing reflective clothing and improve driver attentiveness during low-light conditions
Access control	Tier 2: reduce vehicle speed	Implement measures to reduce vehicle speeds, such as speed humps, chicanes, and dynamic speed limit signs. Enhance access control through the construction of pedestrian-only zones or controlled crossings at high-risk locations
Single vehicle crash	Tier 3: manage conflicts in time	Design interventions to manage conflicts in time, including installing advanced pedestrian detection systems at crossings and adjusting signal timings to allow for safe pedestrian movement
Segment crashes	Tier 4: increase attentiveness and awareness	Install warning signs and midblock crossings with flashing pedestrian beacons in high-crash segments
Pedestrian alcohol impairment	Tier 4: increase attentiveness and awareness	Launch programs to discourage impaired walking through public service announcements. Introduce dedicated late-night transit options to reduce pedestrian exposure and partner with local bars to provide safe transport initiatives
Pedestrian with Black demographics	Tier 4: increase attentiveness and awareness	Address potential inequities by prioritizing safety enhancements in underserved neighborhoods
Driver alcohol or drug involvement	Tier 4: increase attentiveness and awareness	Enhance enforcement of impaired driving laws, increase checkpoints, and integrate pedestrian detection technologies at critical crossings to prevent impaired-driver-related crashes
Driver with black demographics	Tier 4: increase attentiveness and awareness	Conduct equity-based assessments to ensure fair distribution of safety measures. Increase educational efforts and targeted enforcement in high-risk communities to mitigate crash risk

Table 9. Countermeasures and policy level implications based on safe system roadway design hierarchy.

Although this study offers important insights into pedestrian crashes on arterial roads, it is based on historical crash data, which may not account for dynamic elements like real-time environmental conditions or fluctuations in driver behavior. While the random parameter approach helps account for unobserved heterogeneity, it may still fall short in fully representing the complexity of pedestrian lane departure crashes, which are often shaped by sudden and unpredictable factors. There is a need for more advanced methodologies, such as integrating real-time data streams and machine learning models, to better understand and predict these crashes. Future research should explore the interaction between driver impairment, pedestrian behavior, and road design in lane departure incidents, particularly in urban settings where traffic patterns are less predictable. This could lead to more interventions that address the specific conditions contributing to these high-severity pedestrian crashes on arterial roads. Furthermore, future research could explore the role and effectiveness of vehicle–pedestrian crash avoidance systems in reducing the frequency and severity of pedestrian crashes. While such information was not available in the crash data used in this study, incorporating data from connected vehicle systems, advanced driver assistance systems (ADAS), or vehicle manufacturers could allow for a more detailed assessment of how these technologies influence pedestrian safety outcomes. Examining the interaction between roadway characteristics, pedestrian behavior, and crash avoidance technologies would provide a more comprehensive understanding of potential countermeasures and support the development of integrated safety strategies. In addition, the dataset spans 2017–2021 and therefore includes the period affected by COVID-19 lockdowns. Travel demand, pedestrian activity, and driver behavior during this time may have deviated substantially from pre-pandemic patterns due to stay-at-home orders, reduced traffic volumes, and altered trip purposes. Although these potential effects could not be directly quantified with the modeling approach used in this study, acknowledging them as a contextual factor is important, and future research should investigate how pandemic-related disruptions influence pedestrian crash frequency, patterns, and injury severity. It is also important to acknowledge that the effects of some variables on pedestrian injury severity may vary over time due to temporal instability, which is an important and current topic in crash analysis research. Although this study does not explicitly model temporal changes, recognizing this limitation highlights a potential are for future research to better capture evolving crash dynamics.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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References

1. Fatality and Injury Reporting System Tool (FIRST). https://cdan.dot.gov/query.
2. Fatality Facts 2022: Pedestrians. *IIHS-HLDI crash testing and highway safety* https://www.iihs.org/topics/fatality-statistics/detail/pedestrians.
3. National Roadway Safety Strategy | US Department of Transportation. https://www.transportation.gov/NRSS.
4. Hamdane, H., Serre, T., Masson, C. & Anderson, R. Issues and challenges for pedestrian active safety systems based on real world accidents. *Accid. Anal. Prev.* **82**, 53–60 (2015).
5. Zegeer, C. V., Nabors, D., Gelinne, D., Lefler, N. & Bushell, M. *Pedestrian Safety Strategic Plan: Recommendations for Research and Product Development*. https://rosap.ntl.bts.gov/view/dot/49260 (2010).
6. Miles-Doan, R. & Thompson, G. The planning profession and pedestrian safety: Lessons from Orlando. *J. Plan. Educ. Res.* **18**, 211–220 (1999).

7. Dixon, K. K., Hunter, M. P., Wang, J., Boonsiripant, S. & Wu, S. *Effects of Urban Street Environment on Operating Speeds*. 156p https://rosap.ntl.bts.gov/view/dot/49731 (2008).
8. Schneider, R. J., Sanatizadeh, A., Shaon, M. R. R., He, Z. & Qin, X. Exploratory analysis of driver yielding at low-speed, uncontrolled crosswalks in Milwaukee, Wisconsin. *Transp. Res. Rec. J. Transp. Res. Board* **2672**, 21–32 (2018).
9. Lightstone, A. S., Dhillon, P. K., Peek-Asa, C. & Kraus, J. F. A geographic analysis of motor vehicle collisions with child pedestrians in Long Beach, California: Comparing intersection and midblock incident locations. *Injury Prev.* **7**, 155–160 (2001).
10. Dumbaugh, E. & Rae, R. Safe urban form: Revisiting the relationship between community design and traffic safety. *J. Am. Plann. Assoc.* **75**, 309–329 (2009).
11. Kump, R., Nuesmeyer, R., Harris, K. & Hanks, K. Calculating the value of arterial safety improvements: Before and after study shows safety improvements reduced crashes by 40 Percent. *ITE J.* **86**, 34–39 (2016).
12. Stiles, J. & Miller, H. J. The built environment and the determination of fault in urban pedestrian crashes: Toward a systems-oriented crash investigation. *J. Transp. Land Use* **17**, 97–113 (2024).
13. Dumbaugh, E. & Li, W. Designing for the safety of pedestrians, cyclists, and motorists in urban environments. *J. Am. Plann. Assoc.* **77**, 69–88 (2011).
14. Mansfield, T. J., Peck, D., Morgan, D., McCann, B. & Teicher, P. The effects of roadway and built environment characteristics on pedestrian fatality risk: A national assessment at the neighborhood scale. *Accid. Anal. Prev.* **121**, 166–176 (2018).
15. Arnold, L. S. *et al.* Pedestrian Fatalities on Urban Arterial Roads at Night: An In-Depth Crash Analysis and Three Case Studies—AAA Foundation for Traffic Safety. (2025).
16. McCombs, J., Al-Deek, H. & Sandt, A. Network screening and analysis of pedestrian and bicyclist crashes on Florida arterials using a corridor-level approach. *IATSS Res.* **48**, 574–583 (2024).
17. ODOT. *Validation of the New Speed Zoning Method for Urban Arterials and High-Speed Roadways in Terms of Speed Compliance and Safety Outcomes [Project]*. https://trid.trb.org/view/1897046 (2021).
18. Schneider, R. J., Sanders, R. L., Proulx, F. R. & Moayyed, H. United States fatal pedestrian crash hot spot locations and characteristics. *J. Transp. Land Use* **14**, 1–23 (2021).
19. Mahmoud, N., Abdel-Aty, M., Cai, Q. & Zheng, O. Vulnerable road users' crash hotspot identification on multi-lane arterial roads using estimated exposure and considering context classification. *Acc. Anal. Prev.* **159** (2021).
20. Ma, M., Yan, X., Abdel-Aty, M., Huang, H. & Wang, X. Safety analysis of urban arterials under mixed-traffic patterns in Beijing. *Transp. Res. Record J. Transp. Res. Board* (2010). https://doi.org/10.3141/2193-13.
21. Sadeghi, M., Aghabayk, K., Seyfi, M. & Shiwakoti, N. Drivers' trip purpose and pre-crash maneuvers as determinants of pedestrian injury severity: Insights and policy recommendations. *Transp. Policy* **170**, 58–74 (2025).
22. Salehian, A., Aghabayk, K., Seyfi, M. & Shiwakoti, N. Comparative analysis of pedestrian crash severity at United Kingdom rural road intersections and Non-Intersections using latent class clustering and ordered probit model. *Accid. Anal. Prev.* **192**, 107231 (2023).
23. Shaaban, K., Muley, D. & Mohammed, A. Analysis of illegal pedestrian crossing behavior on a major divided arterial road. *Transport. Res. F Traffic Psychol. Behav.* **54**, 124–137 (2018).
24. Bowman, B. L. & Vecellio, R. L. Effect of urban and suburban median types on both vehicular and pedestrian safety. *Transp. Re. Record* 169–179 (1994).
25. Sohrweide, T. A., Buck, B., Wronski, R., & Institute of Transportation Engineers (ITE). Arterial Street Traffic Calming with Three-Lane Roads. in 9p (2002).
26. NMDOT. *NMDOT Pedestrian Safety on Arterials*. http://www.pedbikesafety.org/23unm01 (2024).
27. Guerra, E. et al. Evaluating the effectiveness of speed cameras on Philadelphia's Roosevelt Boulevard. *Transp. Res. Record J. Transp. Res. Board* https://doi.org/10.1177/03611981241230320 (2024).
28. Moudon, A. V. & Hess, P. M. *Pedestrian Safety and Transit Corridors*. 48. http://www.wsdot.wa.gov/research/reports/fullreports/556.1.pdf (2003).
29. Schneider, R. J. *et al.* Association between roadway intersection characteristics and pedestrian crash risk in Alameda County, California. *Transp. Res. Rec. J. Transp. Res. Board* (2010). https://doi.org/10.3141/2198-06.
30. Codjoe, J. *et al. Evaluating Pedestrian Crossings on High-Speed Urban Arterials*. 140p https://www.ltrc.lsu.edu/pdf/2021/FR_641.pdf (2021).
31. Roll, J. & McNeil, N. *Understanding Pedestrian Injuries and Social Equity*. 128p https://www.oregon.gov/odot/Programs/ResearchDocuments/SPR%20841Injuries-Equity.pdf (2021).
32. Cord, A. F. et al. Towards systematic analyses of ecosystem service trade-offs and synergies: Main concepts, methods and the road ahead. *Ecosyst. Serv.* **28**, 264–272 (2017).
33. Abou-Senna, H., Radwan, E. & Mohamed, A. Investigating the correlation between sidewalks and pedestrian safety. *Accid. Anal. Prev.* **166**, 106548 (2022).
34. Zhou, H., Miller, D. & Hsu, P. A case study of pedestrian safety on multi-lane high-speed arterials (2011).
35. Islam, M. An exploratory analysis of the effects of speed limits on pedestrian injury severities in vehicle-pedestrian crashes. *J. Transp. Health* **28**, 101561 (2023).
36. Quistberg, D. A. et al. Multilevel models for evaluating the risk of pedestrian–motor vehicle collisions at intersections and mid-blocks. *Accid. Anal. Prev.* **84**, 99–111 (2015).
37. Sener, I. N., Lee, K., Hudson, J. G., Martin, M. & Dai, B. The challenge of safe and active transportation: Macrolevel examination of pedestrian and bicycle crashes in the Austin District. *J. Transp. Saf. Secur.* **13**, 525–551 (2021).
38. Griswold, J. B. et al. A pedestrian exposure model for the California state highway system. *Transp. Res. Rec.* **2673**, 941–950 (2019).
39. Thomas, L. et al. Changing the future? Development and application of pedestrian safety performance functions to prioritize locations in Seattle, Washington. *Transp. Res. Record* **2659**, 212–223 (2017).
40. Behnood, A. & Mannering, F. The effect of passengers on driver-injury severities in single-vehicle crashes: A random parameters heterogeneity-in-means approach. *Anal. Methods Acc. Res.* **14**, 41–53 (2017).
41. Washington, S., Karlaftis, M. G., Mannering, F. & Anastasopoulos, P. *Statistical and Econometric Methods for Transportation Data Analysis*. (CRC Press, 2020).
42. McFadden, D. & Train, K. Mixed MNL models for discrete response. *J. Appl. Econ.* **15**, 447–470 (2000).
43. Seraneeprakarn, P. et al. Occupant injury severities in hybrid-vehicle involved crashes: A random parameters approach with heterogeneity in means and variances. *Anal. Methods Acc. Res.* **15**, 41–55 (2017).
44. Yu, M., Zheng, C. & Ma, C. Analysis of injury severity of rear-end crashes in work zones: A random parameters approach with heterogeneity in means and variances. *Analytic Methods in Accid. Res.* **27**, 100126 (2020).
45. Saeed, T. U., Hall, T., Baroud, H. & Volovski, M. J. Analyzing road crash frequencies with uncorrelated and correlated random-parameters count models: An empirical assessment of multilane highways. *Anal. Methods Accid. Res.* **23**, 100101 (2019).
46. Se, C., Champahom, T., Jomnonkwao, S., Karoonsoontawong, A. & Ratanavaraha, V. Temporal stability of factors influencing driver-injury severities in single-vehicle crashes: A correlated random parameters with heterogeneity in means and variances approach. *Anal. Methods Accid. Res.* **32**, 100179 (2021).
47. Bhat, C. R. Simulation estimation of mixed discrete choice models using randomized and scrambled Halton sequences. *Transp. Res. Part B Methodol.* **37**, 837–855 (2003).
48. Damsere-Derry, J. et al. Evaluation of the effectiveness of traffic calming measures on vehicle speeds and pedestrian injury severity in Ghana. *Traffic Inj. Prev.* **20**, 336–342 (2019).

49. Li, Y., Song, L. & Fan, W. (David). Day-of-the-week variations and temporal instability of factors influencing pedestrian injury severity in pedestrian-vehicle crashes: A random parameters logit approach with heterogeneity in means and variances. *Anal. Methods Accid. Res.* **29**, 100152 (2021).
50. Bhagavathula, R. & Gibbons, R. B. Lighting strategies to increase nighttime pedestrian visibility at midblock crosswalks. *Sustainability* **15**, 1455 (2023).
51. Fountas, G., Fonzone, A., Gharavi, N. & Rye, T. The joint effect of weather and lighting conditions on injury severities of single-vehicle accidents. *Anal. Methods Accid. Res.* **27**, 100124 (2020).
52. Jägerbrand, A. K. & Sjöbergh, J. Effects of weather conditions, light conditions, and road lighting on vehicle speed. *Springerplus* **5**, 505 (2016).
53. Hossain, A., Sun, X., Thapa, R., Hossain, Md. M. & Das, S. Exploring association of contributing factors to pedestrian fatal and severe injury crashes under dark-no-streetlight condition. *IATSS Res.* **47**, 214–224 (2023).
54. Miranda-Moreno, L. F. & Lahti, A. C. Temporal trends and the effect of weather on pedestrian volumes: A case study of Montreal, Canada. *Transp. Res. Part D Transp. Environ.* **22**, 54–59 (2013).
55. Payyanadan, R. P., Sanchez, F. A. & Lee, J. D. Influence of familiarity on the driving behavior, route risk, and route choice of older drivers. *IEEE Trans. Hum.-Mach. Syst.* **49**, 10–19 (2019).
56. Wen, H. & Xue, G. Exploring the relationships between single-vehicle traffic accident and driver's route familiarity on the mountainous highways. *Cogn Tech. Work* **22**, 815–824 (2020).
57. FHWA. Model Inventory of Roadway Elements. https://safety.fhwa.dot.gov/tools/data_tools/mirereport/22.cfm (2014).
58. Kwayu, K. M., Kwigizile, V. & Oh, J.-S. Evaluation of pedestrian crossing-related crashes at undesignated midblock locations using structured crash data and report narratives. *J. Transp. Saf. Secur.* **14**, 1–23 (2022).
59. Zheng, Y., Chase, T., Elefteriadou, L., Schroeder, B. & Sisiopiku, V. P. Modeling vehicle–pedestrian interactions outside of crosswalks. *Simul. Model. Pract. Theory* **59**, 89–101 (2015).
60. Björklund, G. M. & Åberg, L. Driver behaviour in intersections: Formal and informal traffic rules. *Transp.. Res. F Traffic Psychol. Behav.* **8**, 239–253 (2005).
61. Choi, J., Tay, R., Kim, S. & Jeong, S. Turning movements, vehicle offsets and ageing drivers driving behaviour at channelized and unchannelized intersections. *Accid. Anal. Prev.* **108**, 227–233 (2017).
62. Tefft, B. C. Impact speed and a pedestrian's risk of severe injury or death. *Accid. Anal. Prev.* **50**, 871–878 (2013).
63. Wang, X. & Abdel-Aty, M. Right-angle crash occurrence at signalized intersections. *Transp. Res. Rec.* **2019**, 156–168 (2007).
64. Jin, Y., Wang, X. & Chen, X. Right-angle crash injury severity analysis using ordered probability models. in *2010 International Conference on Intelligent Computation Technology and Automation* vol. 3 206–209 (2010).
65. Habibovic, A., Tivesten, E., Uchida, N., Bärgman, J. & Ljung Aust, M. Driver behavior in car-to-pedestrian incidents: An application of the driving reliability and error analysis method (DREAM). *Accid. Anal. Prev.* **50**, 554–565 (2013).
66. Bastien, C., Wellings, R. & Burnett, B. An evidence based method to calculate pedestrian crossing speeds in vehicle collisions (PCSC). *Accid. Anal. Prev.* **118**, 66–76 (2018).
67. Liu, W. et al. Study on pedestrian thorax injury in vehicle-to-pedestrian collisions using finite element analysis. *Chin. J. Traumatol.* **18**, 74–80 (2015).
68. Batouli, G., Guo, M., Janson, B. & Marshall, W. Analysis of pedestrian-vehicle crash injury severity factors in Colorado 2006–2016. *Accid. Anal. Prev.* **148** (2020).
69. Das, S., Ashraf, S., Dutta, A. & Tran, L.-N. Pedestrians under influence (PUI) crashes: Patterns from correspondence regression analysis. *J. Saf. Res.* **75**, 14–23 (2020).
70. Hossain, A., Sun, X., Mahmud Zafri, N. & Codjoe, J. Investigating pedestrian crash patterns at high-speed intersection and road segments: Findings from the unsupervised learning algorithm. *Int. J. Transp. Sci. Technol.* https://doi.org/10.1016/j.ijtst.2023.04.007 (2023).
71. Dommes, A. & Cavallo, V. The role of perceptual, cognitive, and motor abilities in street-crossing decisions of young and older pedestrians. *Ophthal. Physiol. Opt.* **31**, 292–301 (2011).
72. Letchworth, W. E. Identification of Zones with High Pedestrian Activity Using GIS (2004).
73. Pulugurtha, S. S. & Repaka, S. R. An assessment of models to estimate pedestrian demand based on the level of activity. *J. Adv. Transp.* **47**, 190–205 (2013).
74. Aultman-Hall, L., Lane, D. & Lambert, R. R. Assessing impact of weather and season on pedestrian traffic volumes. *Transp. Res. Rec.* **2140**, 35–43 (2009).
75. Shiwakoti, N., Tay, R. & Stasinopoulos, P. Development, testing, and evaluation of road safety poster to reduce jaywalking behavior at intersections. *Cogn. Tech. Work* **22**, 389–397 (2020).
76. Niebuhr, T., Junge, M. & Rosén, E. Pedestrian injury risk and the effect of age. *Accid. Anal. Prev.* **86**, 121–128 (2016).
77. Lee, G., Joo, S., Oh, C. & Choi, K. An evaluation framework for traffic calming measures in residential areas. *Transp. Res. Part D Transp. Environ.* **25**, 68–76 (2013).
78. Al-Bdairi, N. S. S., Zubaidi, S. L., Zubaidi, H. & Obaid, I. Injury severity of single-vehicle weather-related crashes on two-lane highways. *J. Transp. Saf. Secur.* **0**, 1–21 (2023).
79. Afghari, A. P., Haque, M. M. & Washington, S. Applying a joint model of crash count and crash severity to identify road segments with high risk of fatal and serious injury crashes. *Accid. Anal. Prev.* **144**, 105615 (2020).
80. Bryden, J. E., Andrew, L. B. & Fortuniewicz, J. S. Work zone traffic accidents involving traffic control devices, safety features, and construction operations. *Transp. Res. Rec.* **1650**, 71–81 (1998).
81. Dultz, L. A. & Frangos, S. G. The impact of alcohol in pedestrian trauma. *Trauma* **15**, 64–75 (2013).
82. Oxley, J., Lenné, M. & Corben, B. The effect of alcohol impairment on road-crossing behaviour. *Transport. Res. F Traffic Psychol. Behav.* **9**, 258–268 (2006).
83. Hossain, M. M., Zhou, H., Sun, X., Hossain, A. & Das, S. Crashes involving distracted pedestrians: Identifying risk factors and their relationships to pedestrian severity levels and distraction modes. *Accid. Anal. Prev.* **194**, 107359 (2024).
84. Sanders, R. L. & Schneider, R. J. An exploration of pedestrian fatalities by race in the United States. *Transp. Res. Part D: Transp. Environ.* **107**, 103298 (2022).
85. Siddiqui, N. A., Chu, X. & Guttenplan, M. Crossing locations, light conditions, and pedestrian injury severity. *Transp. Res. Rec.* https://doi.org/10.3141/1982-19 (2006).
86. Adanu, E. K., Lidbe, A., Tedla, E. & Jones, S. Factors associated with driver injury severity of lane changing crashes involving younger and older drivers. *Accid. Anal. Prev.* **149** (2021).
87. Li, Z. et al. Examining driver injury severity in intersection-related crashes using cluster analysis and hierarchical Bayesian models. *Accid. Anal. Prev.* **120**, 139–151 (2018).
88. Donorfio, L. K. M., D'Ambrosio, L. A., Coughlin, J. F. & Mohyde, M. Health, safety, self-regulation and the older driver: It's not just a matter of age. *J. Saf. Res.* **39**, 555–561 (2008).
89. Keskinen, E., Hiro, O. & Katila, A. Older drivers fail in intersections: Speed discrepancies between older and younger male drivers. *Accid. Anal. Prev.* **30**, 323–330 (1998).
90. Khan, N. A. & Habib, M. A. Exploring the impacts of built environment on pedestrian injury severity involving distracted driving. *J. Saf. Res.* **80**, 97–108 (2022).
91. Guerra, E., Dong, X., Lin, L. & Guo, Y. Temporal analysis of predictors of pedestrian crashes. *Transp. Res. Rec.* **2674**, 252–263 (2020).

92. Lee, C. & Abdel-Aty, M. Presence of passengers: Does it increase or reduce driver's crash potential?. *Accid. Anal. Prev.* **40**, 1703–1712 (2008).
93. Orsi, C., Marchetti, P., Montomoli, C. & Morandi, A. Car crashes: The effect of passenger presence and other factors on driver outcome. *Saf. Sci.* **57**, 35–43 (2013).
94. Hu, W. & Cicchino, J. B. Relationship of pedestrian crash types and passenger vehicle types. *J. Saf. Res.* **82**, 392–401 (2022).
95. McTiernan, D. & Rensen, A. The Safe System hierarchy of control framework for local roads. in *Proceedings of the 2016 Australasian Road Safety Conference* 6–8 (2016).
96. Ederer, D. J., Panik, R. T., Botchwey, N. & Watkins, K. The Safe Systems Pyramid: a new framework for traffic safety. *Transp. Res. Interdiscip. Perspect.* **21**, 100905 (2023).

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Author contributions
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Declarations

Competing interests
The authors declare no competing interests.

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