An Exploratory Analysis of Injury Severities in Crashes Involving Vulnerable Road Users: Evidence from Thessaloniki, Greece

Stavros Kontorinis, Athanasios Demiris, Grigorios Fountas(✉), and Socrates Basbas

Department of Transportation and Hydraulic Engineering, School of Rural and Surveying Engineering, Aristotle University of Thessaloniki (AUTh), Thessaloniki 54124, Greece
gfountas@topo.auth.gr

Abstract. Despite the urgent need to improve urban mobility and ensure the safer co-existence of vehicles and road users, significant challenges remain. In Greece, the persistently high number of severe road traffic crashes highlights the urgent need to better understand the factors contributing to crash severity, particularly among the most affected groups—vulnerable road users (VRUs). This group typically includes pedestrians and cyclists who frequently face elevated crash and injury risks in the event of a collision. In this context, this study examines injury severity outcomes in road traffic crashes involving pedestrians and cyclists in Thessaloniki, Greece. Utilizing historical crash data (2019–2021) derived from the Hellenic Statistical Authority, a total of 906 injury crashes were analyzed, involving 764 pedestrians and 142 cyclists. The dataset contains detailed information on vehicles, individuals involved, road and environmental conditions at the time of each crash. To identify the factors associated with injury severity, binary logistic regression was applied, using the Backward Likelihood Ratio (LR) method for variable selection. Road characteristics, driver socio-demographic characteristics, and driving behavior were identified as significant determinants of injury severities. Our work provides a robust analytical framework for enhancing road safety analysis and supporting policymakers in their efforts to protect vulnerable road users.

Keywords: Road Safety · Vulnerable Road Users · Binary Logistic Models

1 Introduction – Literature Review

Vulnerable road users refer to individuals who are particularly exposed to the risk of road traffic crashes, due to either the lack of protective equipment or their physical inability to safeguard themselves in the event of a collision. In cases where a city or region lacks the necessary infrastructure to support the safe coexistence of road users, it is expected that a disproportionately high number of crashes is likely to involve either cyclists or pedestrians. Such infrastructure, including sidewalks, bike lanes, and pedestrian signals, provides safer conditions for vulnerable users and contributes to reducing the severity of injuries in the event of an accident [1].

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1.1 Road Traffic Crashes and Vulnerable Road Users (VRUs)

Road traffic injuries remain a major public health concern, ranking among the leading causes of death worldwide despite continuous advancements in vehicle safety and traffic management systems [2]. Previous research indicates a persistent burden of road traffic crashes, with reported frequencies increasing by approximately 12% between 1992 and 2018 [3]. In 2021, road traffic fatalities reached the number of 1.19 million globally, with 21% of them being pedestrians and 5% cyclists [4]. Vulnerable road users, particularly pedestrians and cyclists, are disproportionately affected, accounting for nearly 46% of road fatalities in Europe as indicated by previous research findings [5]. Additionally, the growing popularity of alternative mobility solutions, such as e-scooters, constantly proposes road safety challenge for VRUs [6]. This kind of evidence has led to a growing shift in road safety research from crash frequency analysis to the examination of injury severity, which provides a meaningful dimension of traffic safety evaluation and its impact on public health and society overall. Moreover, road safety is explicitly embedded within the United Nations Sustainable Development Goals (SDGs), which aim to reduce fatalities and serious injuries obtained from road traffic crashes and promote safe and sustainable transport systems, highlighting the critical role of traffic safety in achieving broader sustainability objectives [7].

In road safety analysis, risk is conceptualized as a function of three key components: exposure, crash occurrence, and vulnerability. Exposure reflects the extent to which road users are present in the transport system, while occurrence captures the probability of a crash taking place. Vulnerability refers to the likelihood that a crash results in severe or fatal injuries. The present study focuses specifically on the vulnerability component, by modelling injury severity outcomes in crashes involving VRUs. Our analysis provides targeted insights into the factors that increase the probability of severe injury conditional on crash occurrence, thereby complementing existing research that primarily emphasizes crash frequency or exposure patterns. This severity-oriented perspective is particularly relevant in congested urban environments such as Thessaloniki, where detailed exposure data are often unavailable, yet understanding injury outcomes remains critical for effective road safety interventions.

In crashes involving vulnerable road users, injury severity is mostly determined by the interaction of demographic characteristics, traffic conditions, roadway design, and behavioral nuances of the road users. VRUs are often road users with limited physical protection, and, as such, they are more exposed to high-speed traffic. This condition increases the likelihood of severe and fatal outcomes, particularly in the absence of dedicated infrastructure and effective speed management measures [1]. Recent studies tend to increasingly adopt severity-based analytical approaches to support targeted interventions aimed at reducing serious and fatal injuries rather than crash occurrence alone.

1.2 Pedestrian-Related Crashes and Injury Severity

Demographic Factors

Age is consistently identified as one of the strongest predictors of injury severity in pedestrian crashes. Elderly pedestrians are disproportionately affected, accounting for

42% of severe injuries and up to 71% of fatal pedestrian crashes on rural roads in Spain [8]. Several studies report that the average age of severely injured pedestrians exceeds 70 years [9], with individuals over 65 facing markedly increased fatality risk following both collisions and falls [10].

The continued ageing of the population contributes to the intensification of this trend. Head and neck injuries are particularly prevalent among elderly pedestrians and are significantly associated with fatal outcomes [11]. Moreover, delayed prioritization in emergency medical treatment often due to underestimation of injury severity has been shown to contribute to increased mortality among older pedestrians [12]. These findings highlight age as a critical determinant in injury severity modeling.

Gender-related disparities have also been observed as key determinants of crash injury severities. While male pedestrians are involved in a higher number of crashes overall, female pedestrians exhibit a higher propensity of sustaining severe injuries. Evidence from Sweden indicates that approximately 69% of injured pedestrians were women [10], suggesting that physiological vulnerability and higher exposure patterns may influence injury outcomes. In general, men tend to sustain a greater proportion of head and facial injuries, whereas women exhibit higher likelihood of lower-extremity fractures [9].

Speed, Temporal Factors and Visibility

Vehicle speed is a dominant factor affecting pedestrian injury severity. The risk of severe injury increases significantly at impact speeds exceeding 25 km/h, while fatal injury probability rises sharply beyond 40 km/h [13]. Notably, 63% of fatal pedestrian crashes occur on roads with speed limits above 30 km/h [13]. Crashes occurring during weekends are associated with increased injury severity, partly due to alcohol consumption, reduced lighting conditions, and altered traffic behavior [14]. Similarly, nighttime crashes present substantially higher severity levels, as reduced visibility impairs driver reaction times and pedestrian detection [15]. It is estimated that approximately 25% of pedestrian crashes result from drivers' failure to perceive pedestrians in time [16].

Vehicle Type and Roadway Characteristics

Heavy vehicles and freight trucks are particularly associated with severe and fatal pedestrian injuries due to their mass and longer stopping distances [17]. In this context, the type of intersection where the crash occurred also plays a critical role. Roundabouts have been associated with reductions in severe injuries and fatalities, whereas T-intersections exhibit increased probabilities of severe and fatal outcomes [18]. As for roadway geometry, signalized intersections demonstrate different risk profiles compared to unsignalized ones, with higher severity observed in environments with increased heavy vehicle presence and higher speed limits [19]. At unsignalized intersections, even small increases in speed limits markedly elevate the probability of severe pedestrian injury, while the presence of marked crosswalks has been shown to mitigate injury severity [19]. Additionally, wider roadways are consistently linked to more severe pedestrian injuries, primarily due to increased operating speeds [17]. However, drivers tend to overestimate their driving abilities and confidence and show less attention on familiar roads, a phenomenon

referred to as the JIMBY (Just in My Backyard) effect, which has been associated with an increased crash risk [20].

Pedestrian Behavior
Pedestrians often fail to comply with the traffic and road safety regulations. Signal violations, midblock crossings away from designated crosswalks, and walking along the carriageway are associated with increased crash severity [21, 22]. In Greece, risky pedestrian behaviors, particularly red-light violations and crossings more than 30 m away from crosswalks are commonly observed and strongly correlated with severe injury outcomes [23].

Contextual Factors
Factors such as inadequate lighting, obstructed visibility due to parked vehicles, and mobile phone use further exacerbate risk [24, 25]. These findings highlight the combined influence of behavioral and infrastructural deficiencies on pedestrian injury severity.

1.3 Cyclist-Related Crashes

Cycling is widely recognized as a sustainable and congestion reducing transport mode [26], actively promoted through European mobility policies [27]. Nevertheless, cyclists account for approximately 6% of fatal road traffic crashes in the EU [28], reflecting their high vulnerability in mixed-traffic environments. The global share of fatalities has risen up to 1% among cyclists since 2010 [6]. Unlike pedestrians, injured cyclists are typically younger, with most crash-involved cyclists aged between 34 and 54 years and an average age of approximately 44 years [29]. Most injured cyclists are male, a pattern consistent across multiple national datasets [29].

Protective Equipment and Visibility
As discussed previously, cyclists are particularly susceptible to injury in the event of a traffic crash due to their limited physical protection. In Italy, helmets were used in only 45.6% of recorded cycling crashes [30]. Helmet use is associated with a 32% reduction in severe facial and mandibular injuries [31]. Reduced nighttime visibility further increases injury severity, particularly when cyclists lack adequate lighting or reflective equipment [27].

Crash Type, Vehicle Interaction and Intersections
Single-bicycle crashes do not present consistent severity patterns. However, adverse weather and surface conditions increase the likelihood of severe injuries [32]. In multi-vehicle crashes, interaction with passenger cars significantly affects injury outcomes. Impact dynamics indicate that greater cyclist body mass may reduce post-impact velocity and injury severity, while larger collision angles are associated with less severe injuries [33].

The majority of cyclist–vehicle collisions occur during regular traffic flow, often involving turning vehicles and opposite-direction movements [29]. Collisions involving Sport Utility Vehicles (SUVs) are particularly severe. Due to their front-end design,

SUVs increase the likelihood of head injuries and fatal outcomes compared to conventional passenger cars [34]. Unsignalized intersections are linked to increased probabilities of both minor and severe cyclist injuries, as drivers frequently fail to decelerate adequately when approaching such locations [35]. This finding underscores the importance of traffic control and intersection design in mitigating injury severity among cyclists.

1.4 The Case of Thessaloniki

Urban environments with dense traffic, limited space allocation for active travel modes, and enforcement disparities present elevated risks for vulnerable road users. Thessaloniki exemplifies many of these challenges, including insufficient pedestrian infrastructure, fragmented cycling facilities, and high vehicle dominance. These conditions

Table 1. Summary of prior studies on VRUs safety.

Thematic Area	Peer-reviewed studies	Main Findings and Key Factors
Demographic related vulnerability	Casado-Sanz et al. (2019) [8] Gálvez-Pérez et al. (2023) [3] Etehad et al. (2015) [11] Ang et al. (2017) [12] Värnild et al. (2023) [9] Amin et al. (2022) [10]	Elderly pedestrians are disproportionately represented in severe/fatal crashes. Age-related physical frailty amplifies injury consequences even at low impact speeds. Gender and age interact with speed limit to determine serious injury risk.
Speed limit and road Infrastructure	Kröyer (2015) [13] Haleem et al. (2015) [19] Mokhtarimousavi et al. (2020) [14] Rifaat et al. (2011) [37] Zafri & Khan (2023) [39] Da Silva & Bezerra (2024) [1] Bassani et al. (2020) [2] Wennberg et al. (2024) [9] Tapp et al. (2015) [20]	Fatal pedestrian risk rises sharply above 30 km/h. Non-signalized locations carry significantly higher severe/fatal injury risk. Dedicated VRU infrastructure consistently reduces injury severity. Street pattern and spatial built environment impact crash severity. Public support for 20 mph limits is high but actual speed compliance remains inconsistent.
Behavioural factors and analytical methods	Alogaili & Mannering (2022) [15] Tamakloe et al. (2023) [25] Salehian et al. (2023) [18] Elalouf et al. (2023) [17] Nikolaou et al. (2023) [23] Raoniar & Maurya (2022) [22] Sheykhfard et al. (2023) [24]	Lighting conditions create distinct severity profiles. Random parameter & ML models outperform standard regression techniques. Safety attitudes and risk perception mediate self-declared pedestrian behaviour.

(*continued*)

Table 1. (*continued*)

Thematic Area	Peer-reviewed studies	Main Findings and Key Factors
Cyclist injury severity	Fountas et al. (2021) [32] Alnawmasi & Mannering (2023) [27] Bahrololoom et al. (2020) [33] Monfort & Mueller (2023) [34] Yang et al. (2021) [26] Wang et al. (2015) [35] Beck et al. (2016) [29] Levulytė et al. (2016) [28] Cittadini et al. (2024) [30] Stassen et al. (2024) [31] Kaya et al. (2021) [16] Marisamynathan & Vedagiri (2018) [21] Shinar (2012) [5] WHO (2023) [4] Fountas et al. (2026) [6]	Vehicle speed and mass jointly determine cyclist fatality risk; SUVs cause significantly worse injuries than cars. Nighttime crashes are consistently more severe. Junction type, road surface, and lighting are top risk contributors. Helmet use reduces injury severity in bicycle and e-scooter crashes. Driver scanning failures are a primary cause of VRUs crashes at intersections.

intensify exposure and amplify injury severity when crashes occur, reinforcing the need for severity-focused analyses rather than crash frequency alone.

In many developing countries, road traffic crashes are a major contributor to global deaths and injuries. Vulnerable road users are unable to protect themselves in the event of a collision, meaning not only drivers and passengers are at risk of sustaining an injury during a collision event [36]. It is emphasized that vulnerable road users are exposed to a higher level of risk on streets where vehicles travel at high speeds [37]. This highlights the importance of implementing speed limits as a traffic calming measure to, among others, mitigate the risk of hazardous incidents and associated injuries.

Although extensive research has studied injury severity in traffic crashes involving vulnerable road users and motorized vehicles, empirical evidence at the city level remains limited, particularly for Greek urban environments that exhibit unique challenges as far as the interactions between motorized and non-motorized users are concerned. In our study, we investigated the determinants of injury severity in Thessaloniki, using Binary Logistic Regression models, to estimate the probability of severe or fatal outcomes, based on crash-specific characteristics. A data-driven, severity-oriented assessment for Thessaloniki is provided, facilitating a better understanding of the factors associated with serious and fatal injuries among vulnerable road users. Table 1 summarizes the reviewed studies and their findings.

In this context, the findings of this study are relevant to a wide range of local stakeholders involved in urban mobility and road safety. Public authorities can utilize these results to design targeted interventions aimed at protecting VRUs and transport planners may benefit from the identification of high-risk infrastructural characteristics. In addition, enforcement authorities can use these insights to prioritize monitoring of traffic

violations, while private stakeholders, including mobility service providers and insurance companies, may leverage the results to better assess and mitigate risk associated with VRUs.

Our study is organized as follows: Sect. 2 presents the data collection process and the main characteristics of the study area, Sect. 3 describes the methodological framework and the statistical models used for the analysis of injury severity, Sect. 4 reports the empirical results and discusses the key findings for both pedestrian- and bicyclist-involved crashes and Sect. 5 summarizes the main conclusions, outlines policy implications, and highlights limitations and directions for future research.

2 Data

For the crash analysis, data obtained from the public database of the Hellenic Statistical Authority covering the period between 2019 to 2021. The dataset comprised traffic crashes recorded by police authorities within the regional unit of Thessaloniki, Greece including detailed information about the vehicles involved (type of vehicle, vehicle maneuvering during the crash, driver's license), the persons involved (age, gender, injury severity, travel purpose), roadway and environmental characteristics at the time of the crash. Crashes resulting in no injuries are not reported in the public crash dataset.

During the three-year span, 4,366 accidents occurred in our case study area, while 906 involved at least one vulnerable road user, pedestrian or cyclist. Specifically, out of the total crashes analyzed, 142 involved at least one cyclist, highlighting the significant presence of cycling-related incidents within the dataset. Meanwhile, 764 crashes involved at least one pedestrian, underscoring the vulnerability of pedestrians in traffic accidents. These figures reflect the considerable risks faced by vulnerable road users, which became a central focus of the analysis in order to better understand the dynamics and factors contributing to such incidents. Information relating to the exposure of vulnerable road users (e.g., traffic volumes for pedestrians and cyclists) was not available in the dataset. Regarding the severity of injuries observed, a composite indicator was created in Microsoft Excel that takes into consideration all the individuals injured by each accident provides the more severe injury outcome observed in the crash. Working through the environment of IBM SPSS Statistics, two separate datasets, and subsequently, statistical models were developed, one focusing on traffic crashes involving pedestrians and the other on crashes involving bicyclists.

The main reason for conducting two separate statistical analyses was that certain covariates may influence injury severity differently in bicycle-related crashes compared to pedestrian-related crashes, due to the distinct mobility and physical protection characteristics of each user group. In the pedestrian model, 93.5% of the crashes were slight injuries, 2.2% severe injuries and 4.3% fatal. Additionally, for cyclist-involved crashes, 95.1% were slight injuries, 2.1% severe injuries and 2.8% were fatal. In Tables 2 and 3, some key descriptive statistics are illustrated.

Table 2. Distribution of Injury Severity in crashes involving Vulnerable Road Users.

	Slight	Serious	Fatal
Accidents involving Pedestrians	(714) 93.5%	(17) 2.2%	(33) 4.3%
Accidents involving Bicyclists	135 (95.1%)	3 (2.1%)	4 (2.8%)

Table 3. Age Group of Vulnerable Road Users involved in accidents

	0–14	15–30	31–45	46–60	61+
Pedestrians	11.8%	19.7%	13.7%	16.5%	38.3%
Bicyclists	15.9%	30.4%	26.8%	17.4%	9.4%

3 Methodology

Prior to estimating the statistical models for crash injury severities, non-parametric inferential statistical analyses were conducted to explore the relationships between variables and identify pairs of variables that may exhibit statistically significant associations, thus warranting further statistical investigation.

To understand how multiple variables in the sample influence injury severity, we estimated a Binary Logistic Regression model. Binary Logistic Regression is a statistical modeling technique used when the dependent variable is binary (i.e., takes values of 0 or 1). It estimates the probability of a specific outcome, making it particularly suitable for analyzing relationships where the response variable represents two possible categories [38]. For the purposes of the analysis, serious and fatal injuries were combined into a single outcome category. The equation that best describes the model is as follows [39]:

$$\log\left(\frac{P}{1-P}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n \tag{1}$$

Where $\log\left(\frac{P}{1-P}\right)$ is the probability of the event occurring, meaning the higher value P gets, the likelihood of a serious or fatal injury increases [39]; β_0 is the constant; $\beta_1 + \beta_2 + \ldots + \beta_n$ are the regression coefficients; and $X_1 + X_2 + \ldots + X_n$ are the independent variables that affect the injury severity probability. This model is employed to evaluate the statistical significance of the independent variables in relation to injury severity and to quantify both the direction and magnitude of their effects. Specifically, the exponentiated coefficient (exp (β)) provides the multiplicative change in the odds of the injury outcome for a one-unit change of the independent variable. Furthermore, it enables the identification of the most influential predictors based on estimated coefficients. Models' performance was evaluated using goodness-of-fit measures: Hosmer and Lemeshow Test, Cox and Snell R Square, Nagelkerke R Square and log-likelihood values. Every variable included in the models was statistically significant at a confidence level of at least 90%.

4 Results and Analysis

4.1 Inferential Statistics

In the context of a preliminary investigation of possible statistical relationships among injury severity and various potential explanatory factors, a series of inferential analyses were conducted, with the findings summarized in Table 4. Inferential statistical analysis was conducted to investigate the presence of statistically significant relationships between injury severity and a wide range of variables describing the characteristics of vulnerable road users, roadway infrastructure, and accident conditions. Given that injury severity constitutes an ordinal variable and that normality assumptions were not satisfied, non-parametric statistical tests were used. Specifically, the Mann–Whitney U test, the Kruskal–Wallis H test, and the Friedman test were applied, depending on the nature and grouping of the examined variables. Statistical significance was assessed at the 5% level ($p < 0.05$), and all analyses were performed using IBM SPSS Statistics.

The results of the inferential analysis revealed that injury severity is significantly associated with several demographic, spatial, and roadway-related factors. In particular, the age group of involved pedestrians and vehicle drivers exhibited statistically significant differences in injury severity outcomes ($p < 0.05$), indicating an increased vulnerability among older groups. Furthermore, roadway characteristics such as road width and road type were found to be significantly related to injury severity, with wider road sections and arterial roads being associated with a higher likelihood of severe or fatal injuries. Variables capturing the overall crash context and user behavior, including pedestrian position and movement at the time of the accident, also demonstrated statistically significant relationships with injury severity.

Table 4. Inferential tests conducted among variables and crash injury severity

Independent Variables	Inf. Test
Age group of pedestrians involved	Friedman
Age group of drivers	Friedman
Residential area	Mann-Whitney U
Road type	Kruskal Wallis H
Lighting conditions	Friedman
Road width	Friedman
Age of driver when driver licence obtained	Friedman
Vehicle's time of first registration	Friedman
Breathalyzer test type	Friedman
Breathalyzer test result	Friedman
Position and movement of pedestrian	Friedman

4.2 Model Estimation Results for Pedestrian-Involved Crashes

The binary logistic regression model for injury severity in pedestrian-involved crashes was estimated following variable selection using the Backward Likelihood Ratio method. The dependent variable is binary: 1 = serious or fatal injury as the most severe outcome observed in the crash, 0 = slight injury. The model results, together with goodness-of-fit measures and key descriptive statistics of the independent variables, are presented in Table 5.

Table 5. Estimation results of the Binary Logistic model for pedestrian-involved crashes.

Variable Description	Coeff.	Std. Error	p-value	Exp.B
Constant	−5.505	0.824	0.000	0.004
Gender (1 if Female, 49.35%, 0 otherwise)	−1.091	0.358	0.002	0.336
Age group of pedestrian involved (1 if driver aged 61+, 38.30%, 0 otherwise)	0.359	0.131	0.006	1.432
Road width (if road width was 5 to 7 m, 22.30%, 0 otherwise)	0.404	0.123	0.001	1.498
Vehicle maneuver (if vehicle moved normally, 54.30%, 0 otherwise)	0.889	0.510	0.081	2.433
Traffic violation (1 if there was a violation of a traffic light or of a STOP sign, 5.10%, 0 otherwise)	2.908	0.606	0.000	18.315
Speed limit violation (1 if there was a speed limit violation, 6.30%, 0 otherwise)	2.669	0.895	0.003	14.429
Pedestrian position (1 if pedestrian moved regularly, 18.50%, 0 otherwise)	−1.923	0.748	0.010	0.146
Heavy vehicle involved (if heavy vehicle involved, 0 otherwise)	1.371	0.498	0.006	3.938
Goodness-of-fit measures				
Hosmer and Lemeshow test	Chi-square	Deg. Of freedom	Sig.	
	8.778	8	0.361	
−2 Log Likelihood	293.307			
Cox and Snell R Square	0.095			
Nagelkerke R Square	0.247			

Results of the pedestrian model indicate that several factors significantly influence the probability of serious or fatal injury outcomes in crashes involving pedestrians. Female pedestrians have substantially lower likelihood of sustaining serious or fatal injuries compared to males, a finding that has been also documented in previous studies [40]. Additionally, older pedestrians, aged more than 61 years old, are more likely to sustain severe pedestrian injury outcomes, potentially due to slower reaction times [41]. Road width is also found to be correlated with severe injuries, indicating that crashes

occurring on narrower road sects. (5–7 m), are linked to serious or fatal injuries for pedestrians. Narrower roads can sometimes be more hazardous, because of the limited space for pedestrians to comfortably move. Even though vehicles' speed is usually lower in these cases, the limited space makes it more difficult for road users to safely interact [42]. Moreover, the involvement of heavy vehicles in a road crash was found to increase the likelihood of serious pedestrian injuries, possibly capturing complex interaction mechanisms among road users [43].

Regarding road users' behavior, we found that even normal driving maneuvers can contribute to elevated injury severity, when combined with additional crash risk factors. This outcome may be attributable to pedestrians' non-compliant road behavior, a factor that has also been highlighted in existing literature [44]. It is also in line with the variable of pedestrian position, that was also found to be statistically significant in our first model, indicating that when pedestrians adhere to regular crossing or walking positions, the likelihood of serious or fatal injury related to a road crash is importantly reduced. Traffic violations, in particular violations of a traffic light or of a STOP sign, dramatically increase the possibility of severe injury. Similar effects are also observed for speed limits violations from the side of vehicle drivers; the latter result underscores the critical importance of driver compliance with traffic controls and speed limits in protecting vulnerable road users. This finding also suggests that policymakers should move beyond infrastructure interventions only and invest in targeted educational campaigns, which reinforce the legal and ethical responsibility of drivers toward pedestrian safety.

4.3 Model Estimation Results for Bicyclist-Involved Crashes

A separate binary logistic regression model was developed for bicyclist-involved crashes using the same Backward Likelihood Ratio approach for variable selection. The dependent variable again distinguishes serious or fatal injury from slight injury outcomes. Estimation results and goodness-of-fit statistics are presented in Table 6.

Table 6. Estimation results of Binary Logistic Model for bicyclist-involved accidents.

Variable Description	Coeff.	Std. Error	p-value	Exp.B
Constant	−3.976	0.701	0.000	0.019
Road width (if road width was 5 to 7 m, 22.3%, 0 otherwise)	1.863	0.840	0.027	6.441
Traffic violation (1 if there was a traffic violation of a traffic light or of a STOP sign, 5.10%, 0 otherwise)	1.639	0.959	0.087	5.150
Goodness-of-fit measures				
Hosmer and Lemeshow test	Chi-square	Deg. Of freedom		Sig.
	0.080	1		0.778
−2 Log Likelihood	49.138			
Cox and Snell R Square	0.046			
Nagelkerke R Square	0.141			

This model is more parsimonious in terms of the number of independent variables, which is expected given the smaller sample of bicyclist crashes. In line with our previous pedestrian-focused statistical model, road width emerges as the main influential predictor, as also suggested by the exponentiated coefficient. Crashes occurring on narrow road sections are associated with higher likelihood of serious or fatal injury for cyclists. This pronounced effect, likely stems from limited lateral space for evasive actions and, as such, higher conflict frequency and severity in mixed traffic environments [45]. Additionally, drivers' failure to comply with traffic signals or STOP signs increases the likelihood of severe cyclist injury [46]. This finding reinforces the importance of junction control and driver awareness, at locations where cyclists and motorized traffic frequently interact.

5 Discussion and Conclusion

This study examined injury severity outcomes among vulnerable road users, in particular pedestrians and cyclists, in Thessaloniki, Greece, by analyzing police-reported crash data, through separate binary logistic regression models. By focusing on the probability of serious or fatal injuries rather than crash frequency alone, the analysis contributes to evidence-based road safety research that supports the integration of road safety goals, in line with the Safe System approach [47], and the Greek National Road Safety Strategic Plan [48].

The results of the pedestrian-focused model show that several socio-demographic, infrastructural and behavioral factors significantly influence injury severity. Behavioral factors proved particularly influential; illegal driver's behavior was found to dramatically increase severe injury probability (increasing the odds of severe or fatal injury by more than 18 times in the case of signal or STOP violations and 14 times in the case of speed limit violation), while regular pedestrian positioning appears to reduce risk.

The bicyclist-focused model further reinforced the importance of infrastructural characteristics and of compliance with key traffic regulations. Narrow road widths play a key role in bicyclists' injury severity (increasing the odds of severe injury by more than six times), reflecting limited cycling space and higher conflict potential in mixed-traffic settings. The overlapping influence of road width and road users' behavior across both models underscores the existence of shared issues for vulnerable road users, while the more pronounced effect for cyclists emphasizes their greater sensitivity to limited road space in the absence of dedicated infrastructure.

Overall, our study provides a city-level, severity-oriented analysis of vulnerable road user crashes, in a Greek urban context, delivering empirical insights that can directly inform targeted interventions in similar geographical contexts. Study's findings highlight the urgent need for improved compliance with traffic controls, better management of urban streets, and complex interactions among road users and different type of vehicle, in order to protect vulnerable users. While our research provides valuable insights, several limitations should be acknowledged. The relatively small number of cyclist crashes in our sample maybe limits model's statistical robustness and police-reported data may under-represent minor injuries, due to subjective police's assessments. Moreover, another limitation is that the use of the 2019–2021 dataset may affect the robustness of the statistical inferences because of the unique traffic patterns and behavioral shifts induced by

the COVID-19 pandemic. Future research should use data from a longer, post-pandemic, period, to better understand the factors that influence bicyclist injury severity relevant to road crashes and integrate police-reported data with hospital records for more accurate severity assessment. Extending the analysis to a national scale would further strengthen the evidence base for safer mobility in Greece. In addition, the integration of emerging Information and Communication Technologies (ICT) could offer significant potential to enhance the understanding of VRUs safety. The availability of real-time traffic data, connected vehicle systems and sensor-based monitoring offers new opportunities to capture exposure and behavioral patterns. Such data sources could enable the joint modelling of crash occurrence and injury severity, providing a more comprehensive assessment of road safety risk. Furthermore, the use of machine learning techniques could support the development of proactive safety management systems, allowing for dynamic risk prediction and targeted interventions.

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