CPBS
Center for Pedestrian and Bicyclist Safety

A Tier-1 University Transportation Center

How Much Pedestrian Harm Can We Attribute to Larger Vehicles in the Fleet?

July 2024

A Report From the
Center for Pedestrian and Bicyclist Safety

Christopher R. Cherry
University of Tennessee-Knoxville

Saurav Parajuli
University of Tennessee-Knoxville

Kepler Barnhart
University of Tennessee-Knoxville

About the Center for Pedestrian and Bicyclist Safety (CPBS)

The Center for Pedestrian and Bicyclist Safety (CPBS) is a consortium of universities committed to eliminating pedestrian and bicyclist fatalities and injuries through cutting-edge research, workforce development, technology transfer, and education. Consortium members include: The University of New Mexico; San Diego State University; The University of California Berkeley; The University of Tennessee Knoxville; and The University of Wisconsin Milwaukee. More information can be found at: https://pedbikesafety.org

Disclaimer

Acknowledgments

This study was funded, partially or entirely, by a grant from the Center for Pedestrian and Bicyclist Safety (CPBS), supported by the U.S. Department of Transportation (USDOT) through the University Transportation Centers program. The authors would like to thank CPBS and the USDOT for their support of university-based research in transportation, and especially for the funding provided in support of this project. We thank the Tennessee Department of Transportation (TDOT) and the Tennessee Department of Safety and Homeland Security for providing the crash data.

TECHNICAL DOCUMENTATION

1. Project No.
23UTK03

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
How Much Pedestrian Harm Can We Attribute to Larger Vehicles in the Fleet?

5. Report Date
July 2024

6. Performing Organization Code
N/A

7. Author(s)
Christopher R. Cherry https://orcid.org/0000-0002-8835-4617
Saurav Parajuli https://orcid.org/0000-0003-4534-2832
Kepler Barnhart https://orcid.org/0009-0002-9585-1205

8. Performing Organization Report No.
N/A

9. Performing Organization Name and Address
Center for Pedestrian and Bicyclist Safety
Centennial Engineering Center 3020
The University of New Mexico
Albuquerque, NM 87131

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
69A3552348336

12. Sponsoring Agency Name and Address
United States of America
Department of Transportation
Office of Research, Development, and Technology (RD&T)

13. Type of Report and Period Covered
Final Report – June 2023 to May 2024

14. Sponsoring Agency Code
USDOT OST-R

15. Supplementary Notes
Report accessible via the CPBS website https://pedbikesafety.org and DOI https://doi.org/10.21949/jrmb-mq90

16. Abstract
Pedestrian fatalities in the U.S. have surged by 83 percent from 2009 to 2022, compared to a 25 percent increase in other traffic fatalities, coinciding with the boom of larger vehicles in the U.S. This study explores the impact of vehicle characteristics—including speed, size, weight, and design—on pedestrian injury outcomes, using Tennessee police crash data from 2009 to 2019, along with the vehicle details extracted using standardized Vehicle Identification Number (VIN) and Canadian Vehicle Specifications (CVS) dataset. The analysis, conducted using logistic and partial proportional odds models, revealed that higher speed limits, vehicle weights, and vehicle heights correlate with increased severity and fatality rates in pedestrian crashes. Key findings indicate that a 15 mph increase in speed limits results in a 50 percent rise in severe injury odds and a 150 percent rise in fatal injury odds, while vehicle heights significantly affect injury severity making pickup trucks 75.8 percent and compact SUVs 27.3 percent more dangerous than passenger cars for fatal pedestrian crashes. While newer vehicles are becoming more dangerous due to growing size, older vehicles were found to cause more pedestrian harm due to their age. The study also found that vehicle weight affects pedestrian safety more at lower speeds. The study recommends prioritizing speed management, implementing road design changes, encouraging pedestrian safety technologies, and regulating vehicle size and weight trends. The research highlights the need for future studies to examine actual vehicle speeds and weights, impact dynamics, and effects of electric and hybrid vehicles on pedestrian safety.

17. Key Words
Pedestrian safety; vehicle design; vehicle size; speed limits

18. Distribution Statement
No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	57	

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized.**

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

How Much Pedestrian Harm Can We Attribute to Larger Vehicles in the Fleet?

A Center for Pedestrian and Bicyclist Safety Research Report

July 2024

Christopher R. Cherry
Department of Civil Engineering
University of Tennessee-Knoxville

Saurav Parajuli
Department of Civil Engineering
University of Tennessee-Knoxville

Kepler Barnhart
Department of Civil Engineering
University of Tennessee-Knoxville

TABLE OF CONTENTS

List of Figures

List of Tables

Acronyms, Abbreviations, and Symbols

FHWA	Federal Highway Administration
NHTSA	National Highway Traffic Safety Administration
VIN	Vehicle Identification Number
CVS	Canadian Vehicle Specifications
TITAN	Tennessee Integrated Traffic Analysis Network
MMUCC	Model Minimum Uniform Crash Criteria
AIC	Akaike Information Criteria
SUV	Sport Utility Vehicle
SE	Standard Error
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
BTS	Bureau of Transportation Statistics
NACTO	National Association of City Transportation Officials
MUTCD	Manual on Uniform Traffic Control Devices
Freq.	Frequency
Coef.	Coefficient
R. Deviance	Residual Deviance
DoF	Degree of Freedom
Prob.	Probability
LR	Likelihood Ratio

Abstract

Pedestrian fatalities in the U.S. have surged by 83 percent from 2009 to 2022, compared to a 25 percent increase in other traffic fatalities, coinciding with the boom of larger vehicles in the U.S. This study explores the impact of vehicle characteristics—including speed, size, weight, and design—on pedestrian injury outcomes, using Tennessee police crash data from 2009 to 2019, along with the vehicle details extracted using standardized Vehicle Identification Number (VIN) and Canadian Vehicle Specifications (CVS) dataset. The analysis, conducted using logistic and partial proportional odds models, revealed that higher speed limits, vehicle weights, and vehicle heights correlate with increased severity and fatality rates in pedestrian crashes. Key findings indicate that a 15 mph increase in speed limits results in a 50 percent rise in severe injury odds and a 150 percent rise in fatal injury odds, while vehicle heights significantly affect injury severity making pickup trucks 75.8 percent and compact SUVs 27.3 percent more dangerous than passenger cars for fatal pedestrian crashes. While newer vehicles are becoming more dangerous due to growing size, older vehicles were found to cause more pedestrian harm due to their age. The study also found that vehicle weight affects pedestrian safety more at lower speeds. The study recommends prioritizing speed management, implementing road design changes, encouraging pedestrian safety technologies, and regulating vehicle size and weight trends. The research highlights the need for future studies to examine actual vehicle speeds and weights, impact dynamics, and effects of electric and hybrid vehicles on pedestrian safety.

Executive Summary

Pedestrian deaths in the U.S. have surged by 83 percent from 2009 to 2022, while other traffic fatalities rose by only 25 percent, sparking concerns about pedestrian safety. This disproportionate increase is linked to distractions, intoxication, an aging population, and the growing prevalence of larger vehicles such as SUVs and pickup trucks. This study investigates the relationship between vehicle characteristics—including speed, size, weight, design, and their trends—and pedestrian injury outcomes using Tennessee police crash data, aligning with the Safe System approach. The existing literature on pedestrian safety often categorizes vehicles by body type, overlooking the separate impacts of vehicle weight and design, which have become more relevant with the rise of electric vehicles (EVs) and hybrid electric vehicles (HEVs). Previous studies have also largely ignored the combined effects of impact speed and vehicle weight on injury outcomes. This research fills these gaps by using detailed vehicle data, including curb weight and overall height, to understand better the relationship between vehicle characteristics and pedestrian injury outcomes while examining the influence of modern vehicle technologies and increasing vehicle sizes.

The study uses the Tennessee Integrated Traffic Analysis Network (TITAN) database, covering traffic crash data from 2009 to 2019, including details on individuals, crash circumstances, and vehicle specifics. The analysis focused on pedestrian crashes in urban areas, excluding interstate and rural incidents and multi-vehicle crashes, resulting in 16,626 pedestrian involvements. Additional data was obtained from the National Highway Traffic Safety Administration (NHTSA) VIN decoder and the Canadian Vehicle Specifications (CVS) dataset for accurate vehicle details. The methodology employed logistic regression models, including variables like speed limit, vehicle curb weight, vehicle age, and design features, with an interaction term for speed and weight. Partial proportional odds models were used to address the limitations of ordered logistic regression, allowing for variable coefficients. The analysis was conducted using Stata's 'gologit2' package, with model performance assessed using Akaike Information Criteria (AIC) and likelihood ratio tests.

The key findings of the study based on the partial proportional odds model are as follows:

- A 15 mph increase in speed limits correlates with a 50 percent increase in severe injury odds and a 150 percent increase in fatal injury odds in pedestrian crashes. A 5 mph reduction in speed limits could reduce severe injuries by 12.6 percent and fatal injuries by 26.6 percent.
- Vehicle curb weights are weakly related to injury severity, with variations in vehicle weight having minimal impact compared to impact speed. However, the combined effect of curb weights and speed limit suggests that vehicle weights significantly affect injury severity at lower speeds.
- For every 1-foot increase in vehicle height, there is a 0.152 increase in the long odds (16.4 percent in odds) of severe injuries and a 0.403 (49.6 percent in odds) increase in the log odds of fatal injuries.

- Minivans are 16.4 percent more likely to be involved in severe and 49.6 percent more likely to be involved in fatal pedestrian crashes compared to passenger cars. Pickup trucks and larger SUVs are 23.7 percent more likely to be involved in severe and 75.8 percent more likely to be involved in fatal pedestrian crashes compared to passenger cars. Compact SUVs have a 9.6 percent higher odds of severe pedestrian crashes and a 27.3 percent higher odds of fatal pedestrian crashes than passenger cars.
- The higher injury risk associated with higher vehicle height could be due to the increased front hood height, leading to variations in injury mechanisms and/or vicinity visibility issues associated with taller vehicles.
- Most common vehicles involved in pedestrian crashes in Tennessee from 2009 to 2019 ranged from 0 to 11 years in age, with vehicles aged 11 years having nearly 14percent higher odds of causing severe or fatal injuries compared to new vehicles. Older vehicles above 25 are 35 percent more likely to be associated with higher injury severity.
- Older vehicles are more dangerous to pedestrians, possibly due to wear and tear, ineffective brakes, lack of maintenance, rigid bodies, and lack of modern safety features.
- Increasing vehicle weight trends suggest that an increase in average curb weight from 3,800 lbs. to 4,800 lbs. could result in an 8.4 percent rise in fatalities and severe injuries on 15 mph roads and a 2.1 percent increase on 30 mph roads. Potential electrification of vehicle fleets poses significant risks on low-speed roads and during low-speed maneuvers.
- Increasing vehicle height trends suggest vehicles are becoming more dangerous to pedestrians. The 2019 Ford F-150 is almost 10 percent more dangerous than the 2008 model and about 20 percent more dangerous than the 1994 model, revealing that older vehicles are still more dangerous than the newer models.

The following recommendations were made based on the study findings.

- Countermeasures should prioritize speed management, such as reducing speed limits to 30 mph on roads with heavy pedestrian traffic. It is essential to ensure drivers do not unintentionally exceed the 30 mph limit; implementing complex road designs with traffic calming devices that can make it difficult to surpass this limit.
- Road design-related interventions to control vehicle impact speed are effective and can be implemented immediately, unlike adopting new technology to become widespread in the vehicle fleet.
- Manufacturers should be encouraged to include pedestrian safety technologies and adopt pedestrian-friendly designs in all models and trims for long-term benefits.
- Regulatory bodies should monitor vehicle size and weight trends and discourage excessive customizations that lead to higher hood and vehicle heights.

A major limitation of this study is the reliance on police crash data, which includes subjective bias. While standardized datasets for vehicle details helped reduce this bias, potential biases in control variables persist, along with reliance on curb weights and speed limits as proxies for actual vehicle and impact speeds. Future research should investigate actual speeds and weights, differences in impact manner, and the effects of EVs and HEVs on pedestrian safety.

Introduction

Pedestrian deaths in the United States (US) have risen disproportionately, with an 83 percent increase from 2009 to 2022, compared to a 25 percent increase in other traffic fatalities during the same period. The proportion of pedestrian deaths has also increased from 13 percent to 18 percent of all motor vehicle deaths over this timeframe (*IIHS-HLDI, 2022*). The steep rise in the pedestrian fatality, as seen in Figure 1, has led to various speculations about declining pedestrian safety in the US. News media and safety proponents often associate this increase with distractions in pedestrians and drivers, intoxication, an aging US population, and growth in vehicle size (*Schmitt, 2020*). The latter is particularly emphasized, as the trends in pedestrian fatalities and the sales of larger vehicles, such as SUVs and pickup trucks, align closely, garnering the attention of safety researchers. Several studies have explored the relationship between pedestrian crashes and vehicle characteristics, including size, type, design, and technology.

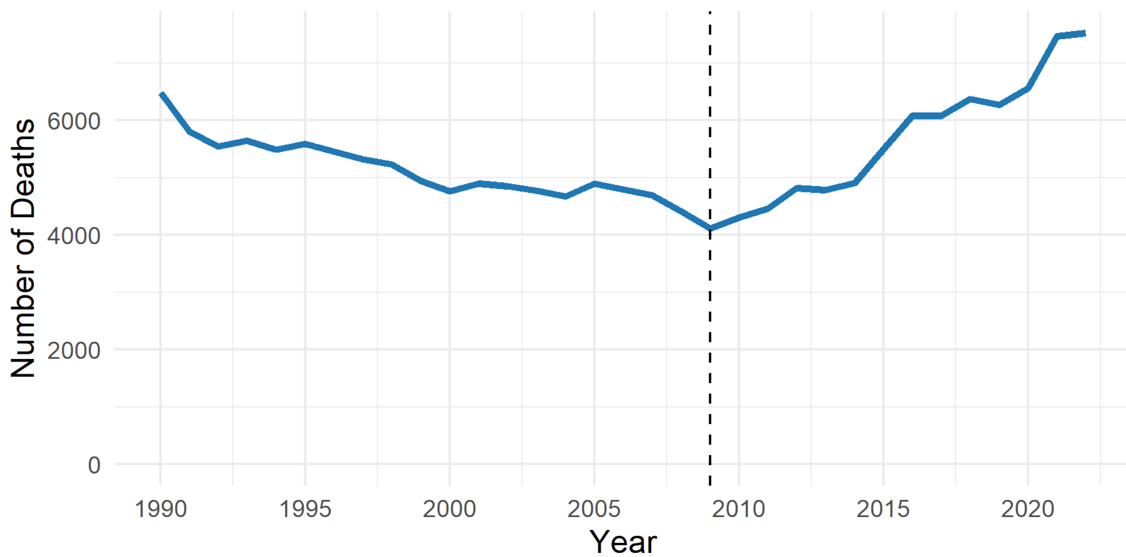

Figure 1. Pedestrian fatality trend in the US (1990 - 2022)

The injury outcomes of occupants in two-vehicle collisions are primarily determined by the transfer of kinetic energy from the crash, resulting in blunt trauma to critical body parts such as the head. When two vehicles collide, some kinetic energy is dissipated through friction, heat, sound, and vehicle deformation, which acts as a protective mechanism to reduce the force transmitted to the occupants (*Ballesteros et al., 2004; Sobhani et al., 2011*). However, pedestrians face significantly higher risks, as almost all the kinetic energy is transferred directly to their bodies, increasing the likelihood of severe or fatal injuries. The key factors contributing to kinetic energy transfer and subsequent trauma include the vehicle's speed, weight, and design. While a vehicle's speed and weight directly influence the impact force, design aspects such as hood height and point of impact can correlate with the trauma inflicted on a pedestrian's body and subsequent injury from falling on the road or being run over.

Recent research on pedestrian crashes has largely focused on vehicle sizes and types, often overlooking the combined impact of vehicle speed and weight. A comprehensive understanding of vehicle characteristics is crucial in the rapidly evolving vehicle landscape, with the advent of electric vehicles (EVs) and hybrid electric vehicles (HEVs) significantly heavier than conventional ones (while generally following the same shape). This research explores the relationship between various vehicle characteristics—such as weight, design, age and model year, and other factors—and pedestrian injury outcomes in pedestrian crashes, controlling for other crash features.

Background: Changing Vehicle Landscape

Using data from the Bureau of Transportation Statistics on the sales and leases of passenger cars and light trucks, Figure 2 illustrates that in 2009, the sales and leases of new light trucks dipped but began to rise steeply afterward (*Bureau of Transportation Statistics*). This trend mirrors the pedestrian fatality trend shown in Figure 1. From 2009 to 2022, the sales of SUVs and pickup trucks surged by 156 percent, while the sales of new passenger cars nearly halved. In 2022, consumer demand for larger vehicles allowed light trucks to make up 79 percent of new sales, with passenger cars making up just 21 percent. While these trends overlap, there is insufficient evidence to conclusively link the increase in vehicle weights and sizes to the rise in fatalities. For instance, a similar trend is also evident in the European Union (EU), where the annual share of SUV sales was less than 10 percent of all sales in 2009 but gradually increased to 40 percent in 2020 (*Vilchez et al., 2023*). By 2023, this number had risen to 51 percent (*Gibbs, 2024*). However, despite a similar vehicle sales trend as in the US, pedestrian deaths have continued to decrease over the years in the EU. Between 2012 and 2022, pedestrian fatalities in the EU decreased by 31 percent (*European Commission, 2024*), compared to a 56 percent increase in the US during the same period (*IIHS-HLDI, 2022*).

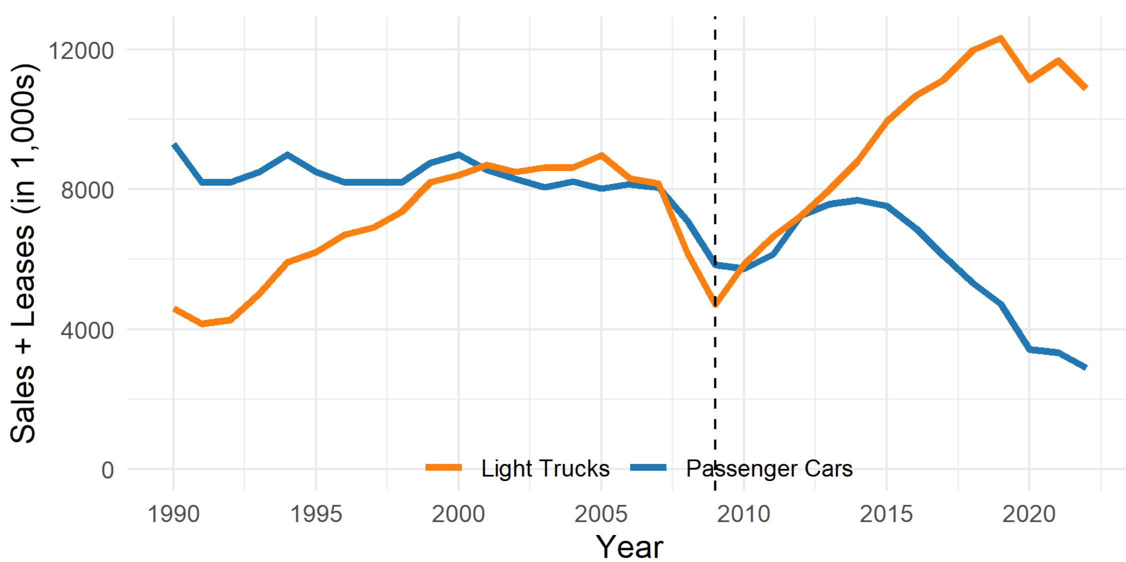

Figure 2. Yearly sales and leases of new passenger cars and light trucks in the US (1990 - 2022) as reported in the Bureau of Transportation Statistics (BTS) website

The increasing average vehicle weight is driven by the trend of newer pickup trucks becoming significantly larger and heavier than their predecessors, with SUV weights also varying widely (*Robertson, 2022*). As households choose larger and heavier cars for safety or comfort reasons, the fatality risk for those who are outside of their vehicle grows. White (*2004*) refers to this trend of American drivers buying increasingly large vehicles as an "arms race". This trend is further amplified by the rising sales of EVs in the U.S., which are on average 24 percent heavier than their conventional counterparts (*Timmers & Achten, 2016*). As EVs gain popularity, especially in the larger vehicle segments, they contribute to this weight increase. Notably, in 2023, 75 percent of EV sales in the U.S. were comprised of SUVs, pickups, or large cars (*International Energy Agency, 2024*). Consequently, vehicles on U.S. roads are becoming increasingly larger and heavier, driven by the confluence of electrification trends and evolving consumer preferences.

Simply associating the correlation between vehicle sales and the rise in pedestrian injuries without further statistical evidence could result in an illusory correlation bias. As a counter-example to this trend, while sales of larger vehicles in Europe are also trending upward, pedestrian safety has improved, unlike in the U.S. Additionally, as vehicles increase in size and weight, advancements in vehicle safety technology have also improved over time. Some contemporary vehicles now feature safety enhancements such as pedestrian emergency braking systems, which can detect pedestrians and apply brakes faster than a driver's perception-reaction time. This can greatly reduce the impact speed and, consequently, the impact force before hitting a pedestrian, potentially offsetting the increased impact due to the vehicle's increased weight. This scenario involves several confounding factors that could mitigate or exacerbate risks, such as vehicle weight, design, age, and speed, influencing the likelihood of serious or fatal pedestrian injuries.

Research Questions

This research will utilize Tennessee police crash data to examine the relationship between posted speed limits, vehicle weights, vehicle sizes, and pedestrian injury outcomes. Given the evolving vehicle landscape, this study aims to address the following key questions to understand better the correlation between fatal and serious outcomes and various vehicle characteristics in alignment with the safe system approach:

1. What is the relationship between speed limits and vehicle weights in terms of serious and fatal injury outcomes?
2. How will the increasing weights and sizes of vehicles across all body types impact pedestrian safety?
3. Despite modern vehicles becoming larger and heavier each year, how effective are they in ensuring safety by including advanced technologies?
4. How much pedestrian risk can we attribute to vehicles, and what are the relevant countermeasures to improve pedestrian safety?

Literature Review

Recent studies have examined the relationship between vehicle dynamics and pedestrian safety. Crash features, including vehicle speed, size, weight, design, lighting, demographics, pedestrian or driver behavior, distractions, and other factors, influence the likelihood of pedestrian injury or fatality in vehicle-to-pedestrian collisions. The following review of past literature explores how these factors, consolidated in broad groups, impact the outcomes of pedestrian crashes.

Vehicle Impact Speed

Safety literature focuses on impact speed, as it directly influences the injury outcomes and the effectiveness of most interventions and countermeasures for pedestrian crashes. Multiple studies have analyzed pedestrian safety risks as a function of impact speed, revealing a non-linear "S-curve" relationship between impact speed and fatality chances (*Davis, 2001; Han et al., 2012; Rosén & Sander, 2009; Tefft, 2013*). Using a meta-analysis of 20 pedestrian-vehicle impact speed studies, Hussain et al. (*2019*) visualized the relationship between fatality risk and vehicle impact speed, as shown in Figure 3. Based on this study's data and results, the curve indicates that the probability of pedestrian death is significantly low at lower speeds, with a 5 percent chance of death at 18.4 mph. The risk of death increases sharply with speed, especially in the mid-range, rising from 26 percent at 30 mph to 64.4 percent at 40 mph and over 80 percent at 45 mph. However, the curve flattens at higher speeds, indicating marginal increases in the probability of pedestrian death, reaching a 95 percent chance of death at 54.4 mph (*Hussain et al., 2019*). The curve can vary based on vehicle types and pedestrian demographics. For example, the curve for elderly pedestrians shifts to the left, indicating higher chances of fatality at relatively lower speeds than other pedestrians (*Davis, 2001*).

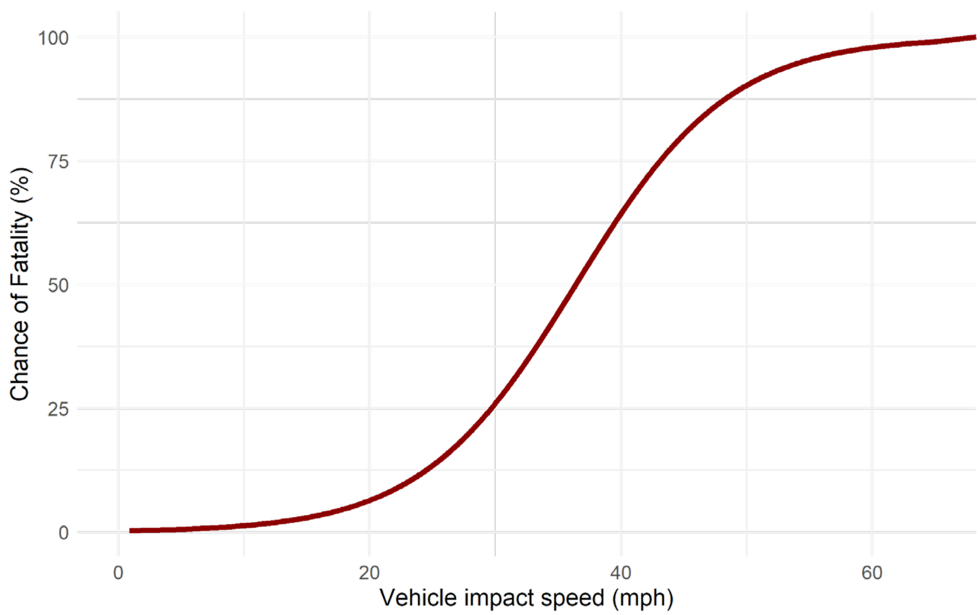

Figure 3. Relationship between fatality risk and impact speed based on Hussain et al. (2019) data and results

A significant challenge in crash data analysis is accurately determining impact speeds in traffic crashes, despite their association with injuries. This estimation often relies on crash reconstruction methods, including analyzing skid marks, deformations, and kinetics and kinematics calculations (*Rosén & Sander, 2009; Xu et al., 2009*). Alternatively, impact speeds can be obtained from event data recorders, although this method involves navigating privacy restrictions (*NHTSA, 2006*). As acquiring impact speeds data is difficult, with thousands of crashes reported daily, crash data recorders often do not include impact speeds, resulting in crash studies relying on other proxies such as posted speed limits instead (*Doecke et al., 2018; Islam, 2023; Zahabi et al., 2011*).

Moreover, directly regulating impact speeds is extremely challenging in a complex environment where drivers and pedestrians move freely. Therefore, researchers concentrate on controlling general driving speeds to some extent. They use various strategies to achieve this, such as implementing policy-related measures, making infrastructural improvements, and advancing vehicle technology to reduce impact speeds in pedestrian-vehicle crashes. Some of these methods are detailed below:

Impact Speeds and Posted Speed Limits

Setting speed limits on roads is the most popular policy-related intervention to regulate driving speeds. The 2009 edition of the Manual of Uniform Traffic Control Design (MUTCD) dictated that speed limits should be set within 5 mph of 85th percentile speeds during free flow conditions (*FHWA, 2009*). This method of setting speed limits results in a high correlation between actual driving speeds and posted speed limits. Elvik et al. (*2004*) also demonstrated that posted speed limits roughly correlate with vehicle impact speeds in vehicle-vehicle collisions. However, pedestrian safety studies present mixed results regarding posted speed limits and injury outcomes. Some researchers argue that the likelihood of fatal and severe injuries is higher on roads with higher speed limits (*Islam, 2023*). Others report that speed limits are not inherently linked to pedestrian injury outcomes. A study suggested that driving speeds are more influenced by road design and geometry, with posted speed limits having limited effects on speed reduction (*Zahabi et al., 2011*). Realizing the drawbacks of existing methods, the latest edition of MUTCD has also de-emphasized using the 85th percentile speed for the speed limit, hinting at using other context-sensitive methods to define the speed limit for the roads (*FHWA, 2023*).

Impact Speeds and Road Infrastructure

In its *Urban Street Design Guide*, the National Association of City Transportation Officials (NACTO) advocates for an active approach to speed design. Rather than relying solely on speed limit signs and current operating speeds, NACTO recommends using road geometry and design elements, supplemented by traffic calming devices, to maintain safe driving speeds (*NACTO, 2013*). Traditional road design prioritizes speed and throughput, allowing drivers to exceed speed limits without infrastructural restrictions. At higher speeds, a driver's peripheral vision narrows to an angle of only 2-4 degrees of accurate vision (*AASHTO*), limiting their ability to see pedestrians and respond effectively. This can result in higher impact speeds and increased risk of pedestrian injury. Conversely, setting a safer design speed, achieved using infrastructural and design elements (*Zahabi et al., 2011*), can significantly reduce the likelihood of speeding and exceeding speed limits, which can be fatal for pedestrians. This approach also enhances drivers' peripheral vision, improving their ability to detect and react to pedestrians (*NACTO, 2013*).

Impact Speed and Effective Braking

Road design elements can naturally reduce vehicle speeds without requiring drivers to intervene consciously. However, in many situations, drivers must make a conscious effort to brake to avoid pedestrian crashes. The reaction time or stopping distance is often insufficient to effectively brake before reaching the pedestrian, resulting in fatal impact speeds. Factors such as a driver's age (*Lerner, 1993*), intoxication levels (*Calhoun et al., 2004*), drowsiness (*Daviaux et al., 2014; Van Den Berg & Neely, 2006*), and other personal conditions like illness can significantly affect cognitive abilities, delaying perception-reaction times and braking, with higher chances of fatal injuries to pedestrians. Additionally, visibility issues during darkness and the pedestrian clothing choices can further hinder effective braking by delaying the driver's perception times (*Feng et al., 2012; Plainis & Murray, 2002*). In addition to visibility issues and delayed perception-reaction times, inclement weather conditions, such as rain and snow resulting in wet and slippery roads, reduce road friction and extend stopping distances, thereby posing significant safety risks for pedestrians (*El-Shawarby et al., 2013*).

Some modern vehicles have automatic emergency braking systems that apply hard brakes when a pedestrian is detected. Others use alert technologies to warn drivers upon pedestrian detection. These systems are designed to reduce impact speeds or prevent crashes, minimizing the risk of severe and fatal pedestrian injuries. A study found that shown that vehicles using this technology could potentially lower the crash involvement of pedestrians by 60 to 70 percent (*Strandroth et al., 2014*) and pedestrian injury risk by almost 30 percent (*Cicchino, 2022*). However, while these technologies present promises of improving pedestrian safety, they are still in development and may not function optimally under challenging conditions, such as nighttime, high-speed roads, and during turning maneuvers (*Cicchino, 2022*).

Vehicle Weights

Following the theoretical framework of kinetic energy transfer in a collision, vehicle weights contribute to the energy transfer after the squared impact speeds. In a vehicle-to-vehicle collision, the likelihood of sustaining a fatal injury increases by 40-50 percent when struck by a vehicle that is 1,000 pounds heavier (*Anderson & Auffhammer, 2014*). A study examining the effects of commercial vehicles on pedestrian safety found that the odds of fatal injury for pedestrians are 4.37 times higher when struck by lighter commercial vehicles, such as SUVs, pickup trucks, and passenger cars, compared to when they are hit by heavier commercial vehicles, such as heavy trucks and tractor-trailers (*Wang et al., 2022*).

While there is a clear distinction of pedestrian injury outcomes between heavier vehicles and other vehicles in pedestrian safety, most safety research has not implemented the vehicle weights to analyze the relationship between pedestrian crash outcomes and private vehicle types, despite the rise in average vehicle weights over the years in the US (*Tyndall, 2021*). Recent research efforts have settled on using vehicle types, such as passenger cars, SUVs, pickup trucks, and minivans, as a proxy for vehicle weights to study their relationship with pedestrian crash outcomes. Studies unanimously agree that heavier consumer vehicles, such as pickup trucks and SUVs, are more likely to be associated with more fatal and severe pedestrian crashes than passenger cars (*Desapriya et al., 2010; Edwards & Leonard, 2022; Liu et al., 2019; Tyndall, 2021*). A meta-analysis of 11 studies revealed that the probability of a pedestrian being fatally injured when hit by a light truck vehicle is 50 percent more than when hit by a passenger car (*Desapriya et al., 2010*).

Only a few studies have attempted to attribute these risks separately to vehicle weight and design. Tyndall (*2024*) studied the relationship between vehicle front-hood height and pedestrian injury outcomes, controlling for vehicle weights. The findings revealed that vehicle weights had an insignificant impact on pedestrian injuries once front-end height was accounted for. Other studies have concentrated more on the relationship between injury mechanisms and vehicle designs than on these categories, which will be discussed in greater detail in the following section. Despite the increasing trend in vehicle weights, policy interventions regulating vehicle weights for consumer vehicles are rarely implemented.

Vehicle Designs and Injury Mechanisms

One of the Safe Systems principles is "Humans are vulnerable." This is especially true for pedestrians, as the outcomes of crashes heavily depend on the specific points of impact or where they experience blunt trauma in a pedestrian-vehicle collision. For instance, injuries can be more severe if pedestrians are struck in the head or chest, whereas impacts to the legs or arms might result in less critical injuries. Limited studies have analyzed the relationship between vehicle parameters such as designs and pedestrian injuries (*Han et al., 2012; Hu et al., 2024; Tyndall, 2024*). Extant literature has primarily focused on frontal collisions and the initial and subsequent blunt trauma sustained by pedestrians.

Han et al. (*2012*) analyzed the impact of vehicle velocity on pedestrian injury risk at various speeds, focusing on dynamic responses and injury risks to different body parts using parameters like head injury criteria and chest deflection. They concluded that impact velocity is the most significant factor in injury severity, with vehicle front-end shape also playing a critical role. The study found higher risks of head and lower extremity injuries with medium-size sedans and SUVs, increased chest injuries with single unit truck vehicles, and a higher risk of pelvis fractures with both single unit truck vehicles and SUVs, while minicars posed a lower overall injury risk. A 2006 study reported similar head injury profiles for pedestrians struck by both cars and SUVs but significantly more severe lower body injuries when hit by an SUV compared to a passenger car. The study suggested that this difference may be due to the front-end shape of SUVs, which provides a larger impact area, is associated with less body rotation, and is more related to impact speed than to the mass difference between cars and SUVs (*Simms & Wood, 2006*).

Hu et al. (*2024*) examined the influence of vehicle front-end geometry on pedestrian fatality risks in motor vehicle crashes, analyzing 17,897 crash reports. They found that tall and blunt, tall and sloped, and medium-height and blunt front ends increased pedestrian fatality risks by 43.6, 45.4, and 25.6 percent, respectively, with flat hoods contributing to a 25.1 percent increase, while longer hoods and larger windshield angles showed increased risks but were not statistically significant. After merging crash data with the Canadian Vehicle Specifications (CVS) data containing vehicle dimensions, Tyndall (*2024*) found that the likelihood of pedestrian fatalities increases by 22 percent for every 10 cm increase in the front-end height of the striking vehicle. The study also noted a higher risk for elderly and child pedestrians.

Studies have also examined the effect of pedestrian kinematics and the nature of subsequent impacts after being struck by the front end of a vehicle. For heavy vehicles like trucks and buses, the likelihood of pedestrians being run over is higher than for lighter vehicles, even at low speeds (*Schubert et al., 2023*). A qualitative comparison of secondary impacts found that vehicles with lower hoods, such as compact cars, sedans, vans, and sports cars, presented “moderate” to “critical” risks. In contrast, secondary impacts from SUVs and larger vehicles were “very critical.” Child pedestrian impacts were also “very critical” for vans, unlike adults, for whom the impacts were “critical” (*Hamacher et al., 2012*). Another study analyzed ground contact mechanisms in pedestrian crashes and concluded that high-fronted vehicles cause more significant ground-related injuries (*Simms et al., 2011*).

In conclusion, the literature review revealed that impact speed, vehicle weight, vehicle design, and injury mechanisms primarily influence pedestrian injury outcomes. Multiple studies agree that vehicle impact speed is the most critical factor in causing pedestrian injuries (*Hamacher et al., 2012; Han et al., 2012; Saadé et al., 2020*). They found that vehicle impact speeds below 30 km/h can significantly reduce injuries and fatalities across all vehicle types. Most countermeasures focus on preventing crashes or reducing vehicle impact speeds, such as setting and enforcing speed limits, designing roads to inhibit unsafe driving speeds, and implementing efficient braking technologies in vehicles. Additional countermeasures, like improved lighting and pedestrian infrastructure (signals and crosswalks), help attract drivers’ attention and prompt them to brake or avoid crashes. Studies on vehicle design recommend that manufacturers adopt features such as lower and sloped front ends, wide windshield areas, and reduced hood stiffness to lower injury risks to pedestrians (*Han et al., 2012; Hu et al., 2024; Simms & Wood, 2006*).

Literature Gaps and Research Contributions

Pedestrian safety research based on police crash data has often utilized categorical vehicle body types to examine the combined effects of vehicle weight and design. The existing literature typically categorizes vehicle types in econometric models, grouping SUVs and pickup trucks as heavier vehicles and sedans and coupes as lighter ones. However, this classification approach has limitations, particularly with the rise of electric vehicles. For instance, the 2024 Tesla Model 3, classified as a sedan, is 300 kg (661.4 lbs.) heavier than the base 2024 Toyota RAV4, a midsize SUV (*Canadian Vehicle Specifications (CVS), 2024*). Moreover, significant weight variations can occur within the same model year, make, and model. For example, the heaviest trim of the 2024 Ford F-150 truck is 785 kg (1730.6 lbs.) heavier, or 41 percent heavier, than the base trim of the same model. This research accounts for curb weight variations at the trim level by mapping weight ratings using Vehicle Identification Number (VIN) data combined with clustering algorithms.

Additionally, accounting for vehicle design elements, such as front-end height in pedestrian crashes, poses challenges since VIN information and the CVS dataset do not provide front-hood height data. Hu et al. (*2024*) attempted to measure front hood height using vehicle profile photos manually, but this method becomes impractical for police crash databases with thousands of different vehicle combinations of model year, model, and make. Tyndall (*2024*) used the difference between a vehicle's overall height and window height to estimate the front-end height. However, this method may not be consistent across all vehicle types, as it fails to account for variations in front-end heights, such as between the 2021 Ford F-150 and the 2008 Ford F-150. To streamline the analysis and maintain consistency across all vehicles, we used the vehicle's overall height as a proxy for controlling vehicle design aspects. This approach is novel and is based on the rationale that vehicles with higher front hood designs typically have elevated driver seating positions for improved visibility, leading to greater overall height.

Although studies consistently identify kinetic energy transfer from vehicles to pedestrians as a primary cause of injury outcomes, there is a notable gap in the literature regarding the combined effects of impact speed and vehicle weight—two major factors influencing this energy transfer. This research, based on police crash data, aims to explore the relationship between impact speed, represented by speed limit, and vehicle weight, represented by curb weight, by including an interaction term for speed limit and curb weight in the analysis. This term will also determine whether vehicle weights significantly impact injury outcomes separately on low-speed and high-speed roads.

Over the past few decades, research has demonstrated that consumer vehicles have become safer for drivers and passengers, as seen in features like reduced stiffness and improved impact absorption in newer models (*Ryb et al., 2009*). Manufacturers also assert that these vehicles are now safer for other road users, including pedestrians. However, as consumer vehicles have also become larger and heavier, the potential injury burden on pedestrians has increased. While some studies have examined the effectiveness of specific technologies, such as automatic emergency braking, in preventing pedestrian crashes (*Cicchino, 2022*), very few have comprehensively accounted for technological advancements over the years using pedestrian data. This study will address this gap using a vehicle age variable (closely correlated with model year due to a relatively small study period of 2009-2019) to explore the combined effects of advancements in vehicle technology and the potential degradation of safety due to wear and tear on pedestrian safety. This study will also be among the first ones to compare the advantages of modern vehicle technologies with the adverse effects of increasing vehicle size trends.

Lastly, as a study centered on pedestrian safety using crash data, this research will significantly contribute to the safety literature by thoroughly examining various vehicle features in the context of severe and fatal injury outcomes. These features include curb weight as a proxy for vehicle weight, speed limit as a proxy for vehicle impact speed, vehicle age as a proxy for the combined effects of technological advancements and wear and tear over the years, and vehicle height as a proxy for vehicle design and body types.

Data and Methodology

Data

This research uses the Tennessee Integrated Traffic Analysis Network (TITAN) database with traffic crashes recorded by law enforcement in Tennessee from 2009 to 2019 (*Tennessee Highway Safety Office, 2021*). With the TITAN dataset, we also used the National Highway Traffic Safety Administration (NHTSA) VIN decoder to acquire more accurate information about the model year, make, and model of vehicles involved in the pedestrian crashes (*NHTSA*). Finally, we used the Canadian Vehicle Specification (CVS) dataset for the information about vehicle weights and dimensions, such as vehicle heights (*Canadian Vehicle Specifications (CVS), 2024*).

TITAN Crash Database

The TITAN database contains all traffic safety-related information and is managed by the Tennessee Department of Safety and Homeland Security. TITAN records injuries in a KABCO scale, following the Model Minimum Uniform Crash Criteria (MMUCC) for uniform record keeping across different jurisdictions across the states (*NHTSA, 2017*). The K in KABCO stands for "killed" or fatal crash outcomes, A stands for serious or incapacitating injuries, B stands for minor or non-incapacitating injuries, C stands for possible, and O stands for property damage only (*Federal Highway Administration*). This research aligns with the Safe Systems Principle: "Death and serious injuries are unacceptable." In the following sections, the term "severe injuries" is repeatedly used to collectively represent fatal (K) and serious or incapacitating (A) injuries.

TITAN comprises three main datasets: person, crash, and vehicle (unit).

- Person Dataset: Contains details on all individuals involved in the crash, including demographics, intoxication status, actions during the crash, and injury severity outcome.
- Crash Dataset: Includes date, time, location, collision type, lighting conditions, and other infrastructure-related details, including whether the crash occurred in parking lots and private properties.
- Vehicle Dataset: Provides information on each vehicle involved, including details about the vehicle's characteristics and maneuvers and some built-environment information like posted speed, road profile, alignment, surface type, number of lanes, travel direction, etc.

We merged these datasets into a comprehensive dataset and removed personally identifiable information before proceeding with the analyses. For this report, we excluded interstate crashes and those identified by police as rural area crashes. Interstate highways have fully controlled access and restrict pedestrian presence, while rural areas might have different crash dynamics compared to urban areas, where pedestrians are at higher risk (*Parajuli et al., 2023*). Additionally, we excluded pedestrian crashes involving multiple vehicles to avoid potential confounding due to differing crash dynamics. We also excluded cars with trailers, as they do not accurately represent standard weights or dimensions. Finally, we were left with 16,626 pedestrians involved from January 1, 2009, to September 30, 2019.

NHTSA VIN Decoder

Although TITAN categorizes vehicles according to their body type and notes their year, model, and make, it also records the Vehicle Identification Number (VIN) for each vehicle involved in crashes. Using VIN information, we can accurately determine the model year, model, make, and other vehicle information using the NHTSA VIN decoder. Although VIN information is generally more uniform and accurate than subjective reporting of vehicle characteristics, there can still be instances where VINs are missing or inaccurate. By excluding crashes with incorrect or missing VINs, we retrieved 10,772 crashes, constituting a subset of the initially filtered data.

Table 1 compares the initial filtered data and data with the VIN information. The latter is roughly similarly distributed to the initial dataset, with notable differences. One major difference is the hit-and-run indicator, where the dataset with recorded VINs is more associated with non-hit-and-run crashes and has a slightly higher proportion of fatal crashes. Another difference is in driver characteristics, with the initial dataset having more unknowns. Additionally, there are minor discrepancies, such as data related to White pedestrians and male drivers being slightly more likely to have their VINs reported in the TITAN dataset than Black pedestrians and female drivers. For the purposes of our investigation, we assume that VIN reporting is random based on the evidence presented in Table 1. This assumption will be maintained throughout the remainder of the report and analyses.

Table 1. Comparison of non-interstate urban single-vehicle pedestrian crashes with and without VIN Information Reported for Vehicles

Variables	Value	Overall		Reported VINs	
		Freq.	%	Freq.	%
Time of Day	6 am-noon	3,260	19.6	2,208	20.5
	6 pm-midnight	5,459	32.8	3,452	32.0
	Midnight - 6am	1,597	9.6	810	7.5
	noon - 6 pm	6,310	38.0	4,302	39.9
Lighting Condition	Dark-Lighted	4,860	29.23	3,009	27.93
	Dark-Not Lighted	1,399	8.41	861	7.99
	Dawn/Dusk	588	3.54	364	3.38
	Daylight	9,779	58.82	6,538	60.69
Weather	Clear	13,232	79.6	8,483	78.8
	Cloudy	1,251	7.5	915	8.5
	Other	359	2.2	190	1.8
	Rain	1,784	10.7	1,184	11.0

Variables	Value	Overall		Reported VINs	
		Freq.	%	Freq.	%
Police reported Vehicle Category	Heavy Truck	199	1.2	130	1.2
	Medium Truck	411	2.5	280	2.6
	Motorcycle	79	0.5	63	0.6
	Other/ unknown	1,609	9.7	941	8.7
	Passenger car	8,228	49.5	5,252	48.8
	SUV/Pickup/Minivan	6,100	36.7	4,106	38.1
Driver Race	Hispanic	470	2.8	350	3.2
	Non-Hispanic Black	4,544	27.3	3,442	32.0
	Non-Hispanic White	7,862	47.3	6,255	58.1
	Other/ Unknown	3,750	22.6	725	6.7
Pedestrian Race	Hispanic	481	2.9	326	3.0
	Non-Hispanic Black	5,112	30.7	3,075	28.5
	Non-Hispanic White	7,183	43.2	5,112	47.5
	Other	3,850	23.2	2,259	21.0
Pedestrian Alcohol	No or Unknown	15,689	94.4	10,140	94.1
	Yes	937	5.6	632	5.9
Pedestrian Drug	No or Unknown	16,498	99.2	10,686	99.2
	Yes	128	0.8	86	0.8
Driver Alcohol	No or Unknown	16,293	98.0	10,517	97.6
	Yes	333	2.0	255	2.4
Driver Drug	No or Unknown	16,476	99.1	10,652	98.9
	Yes	150	0.9	120	1.1
Pedestrian Gender	Female	6,973	41.9	4,679	43.4
	Male	9,653	58.1	6,093	56.6
Driver Gender	Female	9,075	54.6	5,086	47.2
	Male	7,551	45.4	5,686	52.8
Land Use	Non-residential	12,040	72.4	7,954	73.8
	Residential	4,586	27.6	2,818	26.2
Hit and run	No	11,602	69.8	9,628	89.4
	Yes	5,024	30.2	1,144	10.6
Low-Speed Maneuver	No	8,038	48.3	5,431	50.4
	Yes	8,588	51.7	5,341	49.6
Weekend	No	12,708	76.4	8,302	77.1
	Yes	3,918	23.6	2,470	22.9
Location of Crash	Trafficway	11,476	69.0	7,301	67.8
	Parking lot	4,210	25.3	2,870	26.6
	Private Roads	940	5.7	601	5.6

Variables	Value	Overall		Reported VINs	
		Freq.	%	Freq.	%
Pedestrian Age Category	15 and younger	2,658	15.99	1,827	16.96
	16-34	5,509	33.13	3,262	30.28
	35-49	3,327	20.01	2,129	19.76
	50-64	3,450	20.75	2,273	21.10
	65 and above	1,664	10.01	1,269	11.78
	unknown	18	0.11	12	0.11
Driver Age Category	15-24	2,371	14.26	1,980	18.38
	25-54	6,658	40.05	5,478	50.85
	55 and above	3,501	21.06	2,907	26.99
	Unknown	4,096	24.64	407	3.78
Posted Speed Limit	15 mph or lower	4,947	29.75	3,320	30.82
	20, 25, or 30 mph	4,786	28.79	3,074	28.54
	35 or 40 mph	5,226	31.43	3,264	30.30
	45 mph or higher	1,667	10.03	1,114	10.34
Year	2009	1,326	7.98	762	7.07
	2010	1,362	8.19	832	7.72
	2011	1,450	8.72	931	8.64
	2012	1,602	9.64	1,003	9.31
	2013	1,465	8.81	922	8.56
	2014	1,480	8.90	984	9.13
	2015	1,628	9.79	1,115	10.35
	2016	1,682	10.12	1,147	10.65
	2017	1,692	10.18	1,144	10.62
	2018	1,679	10.10	1,094	10.16
	2019	1,260	7.58	838	7.78
Pedestrian Injury Outcome	No Injury (O)	1,300	7.8	813	7.5
	Possible (C)	6,609	39.8	4,131	38.3
	Minor (B)	5,407	32.5	3,488	32.4
	Serious (A)	2,624	15.8	1,841	17.1
	Fatal (K)	686	4.1	499	4.6
Total		16,626	100	10,772	100

Canadian Vehicle Specifications (CVS)

Although the NHTSA VIN decoder provides accurate and uniform information on year, make, model, and body type, it does not consistently offer vehicle weight information such as curb weight, vehicle trims, and dimensions. On the other hand, the CVS dataset provides standard vehicle weights and sizes at the year, make, model, and trim level, but we are missing the trim information. Using the CVS dataset without including trim information would not be ideal, as curb weights can vary significantly even within the same year, make, and model, as discussed earlier.

Fortunately, the NHTSA VIN decoder does provide gross vehicle weight ratings (GVWR) for most vehicles, which could vary within the trim level. We mapped the GVWR from the NHTSA VIN decoder to the vehicle curb weights of trims in the CVS dataset to better estimate vehicle dimensions using a hierarchical clustering algorithm. This method allowed us to more accurately estimate curb weights, particularly for vehicles with significant trim-level variation, such as pickup trucks and some SUVs, rather than averaging weights and other dimensions across the year, make, and model without considering trim differences.

Logistic Regressions

Logistic regression models are widely used for analyzing crash data and injury outcomes. In this study, we trained multiple binary logit models to superficially examine the relationship between crash features and severe and fatal injury outcomes. Then, we trained more complex partial proportional odds models to understand the relationship between fatal, serious, and non-severe crashes.

Firstly, we narrowed the dataset with reported VINs containing only passenger cars, SUVs, pickups, and minivans, resulting in 10,436 entries of pedestrian involvement in crashes with these vehicles from 2009 to 2019. These vehicles are also the most popular consumer vehicle categories in the US. Additionally, given the detailed numerical data for vehicle attributes such as weights, sizes, and ages, we utilized the numerical values of posted speed limits. For crashes occurring in parking lots and driveways, where no posted speed limit is assigned, we applied a nominal speed limit of 5 mph. Likewise, to better understand the relationship between crash mechanisms and vehicle characteristics, we consolidated low-speed vehicle movements like turning, braking, slowing down, and backing up into a single variable called low-speed maneuvers.

$$Logit\left(Prob(Z_i = 1)\right) = \ln\left(\frac{P(Z)}{1 - P(Z)}\right) = \boldsymbol{X_i^T \beta} \ldots (1)$$

$$Prob(Z_i = 1) = \frac{e^{\boldsymbol{X_i^T \beta}}}{1 + e^{\boldsymbol{X_i^T \beta}}} \ldots (2)$$

In the above equations (1) and (2), Z represents the dependent variable, either a fatal or severe outcome in a pedestrian crash. $\boldsymbol{X}_{\boldsymbol{i}}^{\boldsymbol{T}}$ is a vector of independent variables, including the speed limit, vehicle weights, the interaction term for speed limit and vehicle weight, vehicle age, vehicle design features, pedestrian and driver controls, year-fixed effects, and a 1 for the intercept. $\boldsymbol{\beta}$ is the vector of corresponding coefficients.

The binary logit modeling in R language compared fatal versus non-fatal and severe versus non-severe outcomes using predictor variables such as speed limit, vehicle curb weight, vehicle age, vehicle design features, and other relevant factors in pedestrian crashes involving consumer vehicles. Model 1 is the simplest, excluding vehicle design factors, to observe if variations in curb weight alone account for differences in injury outcomes. Model 2 included a categorical vehicle body type variable (pickups, SUVs, minivans, and passenger cars). Model 3 replaced these categorical variables with a continuous vehicle height variable to capture design aspects. Each model introduced a speed limit × curb weight interaction variable to study the combined effect of vehicle weight and speed limit. Models 1A, 2A, and 3A are non-interaction models, while Models 1B, 2B, and 3B include the interaction. This modeling approach was applied to both fatal vs. non-fatal and severe vs. non-severe outcomes, resulting in two sets of six models each. The crash year fixed effects and controls for pedestrian and driver features were applied to all models. We used Akaike Information Criteria (AIC) to test the goodness of fit for the models.

Partial Proportional Odds Model

The outcomes of our interest, fatal and serious crash outcomes, follow a specific order and can be arranged as an ordinal variable: fatal (K), serious (A), and other outcomes comprising BCO ratings of the KABCO scale. Thus, this presents an avenue for fitting an ordered logistic regression model to understand the relationship between the ordinal dependent variable and other independent variables. However, the simplest ordered logistic regression model features "parallel lines assumptions," which assume constant odds ratios for the independent variables between different outcome levels. This assumption is overly restrictive and can often be violated, and it is also true for safety studies. For instance, speed could violate the parallel lines assumption because its impact on crash severity is not uniform across all levels of injury outcomes; higher speeds might drastically increase the odds of severe crashes more than minor ones. To overcome this issue, we selected the partial proportional odds model to model our injury outcome variable, which relaxes the parallel lines assumptions to specific variables that violate it.

The partial proportional odds model is a specific type of generalized ordered logit model where certain β coefficients for independent variables can vary across different levels of the outcome variable, while others remain constant. As illustrated by Williams (2006) in equation (3), for an ordinal variable with M different categories, the β coefficients for vectors X_1 and X_2 are constant, while the β coefficients for vector X_3 can differ for different values of j (*Williams, 2006*).

$$P(Y_i > j) = \frac{e^{(\beta 0_j + X1_i\beta 1 + X2_i\beta 2 + X3_i\beta 3_j)}}{1 + e^{(\beta 0_j + X1_i\beta 1 + X2_i\beta 2 + X3_i\beta 3_j)}}, j = 1,2, \dots, (M-1) \dots (3)$$

We used Stata's 'gologit2' package to fit two partial proportional odds models (*Williams, 2006*), one with and the other without the interaction term between the speed limit and vehicle weights. We tested the parallel lines assumption at a 0.001 significance level to achieve a less restrictive model and avoid potential overfitting. The independent variables are identical to those of the corresponding best-performing logit regression models. We tested goodness of fit using the likelihood ratio tests provided by the Stata output.

Results

In this section, we will discuss the descriptive statistics of the variables used in model training and are relevant to the subsequent discussion. Following the presentation of descriptive statistics, we will interpret the results of the binary logit model and the proportional odds model with appropriate visualizations.

Descriptive Statistics

We prepared a frequency table, Table 2, for the categorical variables. We also prepared a descriptive statistics table, Table 3, for relevant continuous variables, reporting the statistics like mean, median, standard deviation, minimum, and maximum.

Categorical variables

Table 2 depicts a descriptive frequency summary of the categorical variables used in the study. The dataset includes vehicle characteristics derived from VIN information, supplemented by crash database inputs when VINs were slightly misreported. Among consumer vehicles, passenger cars were the most prevalent, followed by SUVs and pickups. The table also shows that many crashes occurred during daylight, with dark conditions being the next most common. Low-speed maneuvers, such as turning, backing, slowing down, and other slow movements at intersections or parking lots, were almost equally distributed between crashes involving such maneuvers and those that did not. The table includes pedestrian age groups, with most pedestrians between 16 and 34 years old, and driver age groups, with most drivers between 25 and 54 years old. It also outlines the presence of alcohol and drugs in both pedestrians and drivers, indicating that only a small fraction was under the influence at the time of the crash. Pedestrian and driver race/ethnicity categories are detailed, where White pedestrians and drivers were the most common for both groups, respectively. Last, the table presents pedestrian injury outcomes, indicating that non-severe crash outcomes, such as 'No injury,' 'Possible,' and 'Minor,' were the most common. In contrast, severe injuries accounted for just over 21 percent of the total injury outcomes.

Table 2. Descriptive statistics for categorical variables: Frequency table for pedestrian crashes involving pickups, SUVs, minivans, and passenger cars

Variable	Frequency	%	Variable	Frequency	%
Lighting Condition			**Pedestrian Race/ Ethnicity**		
Dark-Lighted	2,930	28.08	*Hispanic*	315	3.02
Dark-Not Lighted	844	8.09	*Black*	2,982	28.57
Dawn/Dusk	355	3.40	*White*	4,969	47.61
Daylight	6,307	60.44	*Other*	2,170	20.79
Vehicle Type from VIN			**Pedestrian Alcohol Presence**		
Pickups	1,741	16.68	*No or Unknown*	9,819	94.09
Passenger cars	5,599	53.65	*Yes*	617	5.91
SUVs	2,669	25.57	**Pedestrian Drug Presence**		
Minivans	427	4.09	*No or Unknown*	10,353	99.20
Low-speed Maneuvers			*Yes*	83	0.80
No	5,274	50.54	**Driver Age**		
Yes	5,162	49.46	*15-24*	1,958	18.76
Crash Year			*25-54*	5,285	50.64
2009	732	7.01	*55 and above*	2,798	26.81
2010	798	7.65	*Unknown*	395	3.78
2011	895	8.58	**Driver Race/ Ethnicity**		
2012	958	9.18	*Hispanic*	334	3.20
2013	891	8.54	*Black*	3,348	32.08
2014	955	9.15	*White*	6,053	58.00
2015	1,080	10.35	*Other*	701	6.72
2016	1,117	10.70	**Driver Alcohol Presence**		
2017	1,121	10.74	*No or Unknown*	10,192	97.66
2018	1,072	10.27	*Yes*	244	2.34
2019	817	7.83	**Driver Drug Presence**		
Pedestrian Age			*No or Unknown*	10,319	98.88
15 and younger	1,769	16.95	*Yes*	117	1.12
16-34	3,171	30.39	**Pedestrian Injury Outcome**		
35-49	2,063	19.77	*No*	792	7.59
50-64	2,197	21.05	*Possible*	4,005	38.38
65 and above	1,225	11.74	*2Minor*	3,372	32.31
unknown	11	0.11	*3Serious*	1,786	17.11
Total	**10,436**	**100**	*4Fatal*	481	4.61

Figure 4 charts the relationship between fatal and severe injury outcomes with various posted speed limits and vehicle body types, excluding minivans due to their low representation. The figure reveals that fatal and severe injury rates increase non-linearly as the posted speed limit rises, with minimal rates at lower speed limits and significantly higher rates at higher speed limits. The variation across vehicle body types is less clear than for speed limits, though fatality rates appear slightly higher in pickups and SUVs compared to passenger cars. We do not observe a distinct variation in severe injury rates across different vehicle body types.

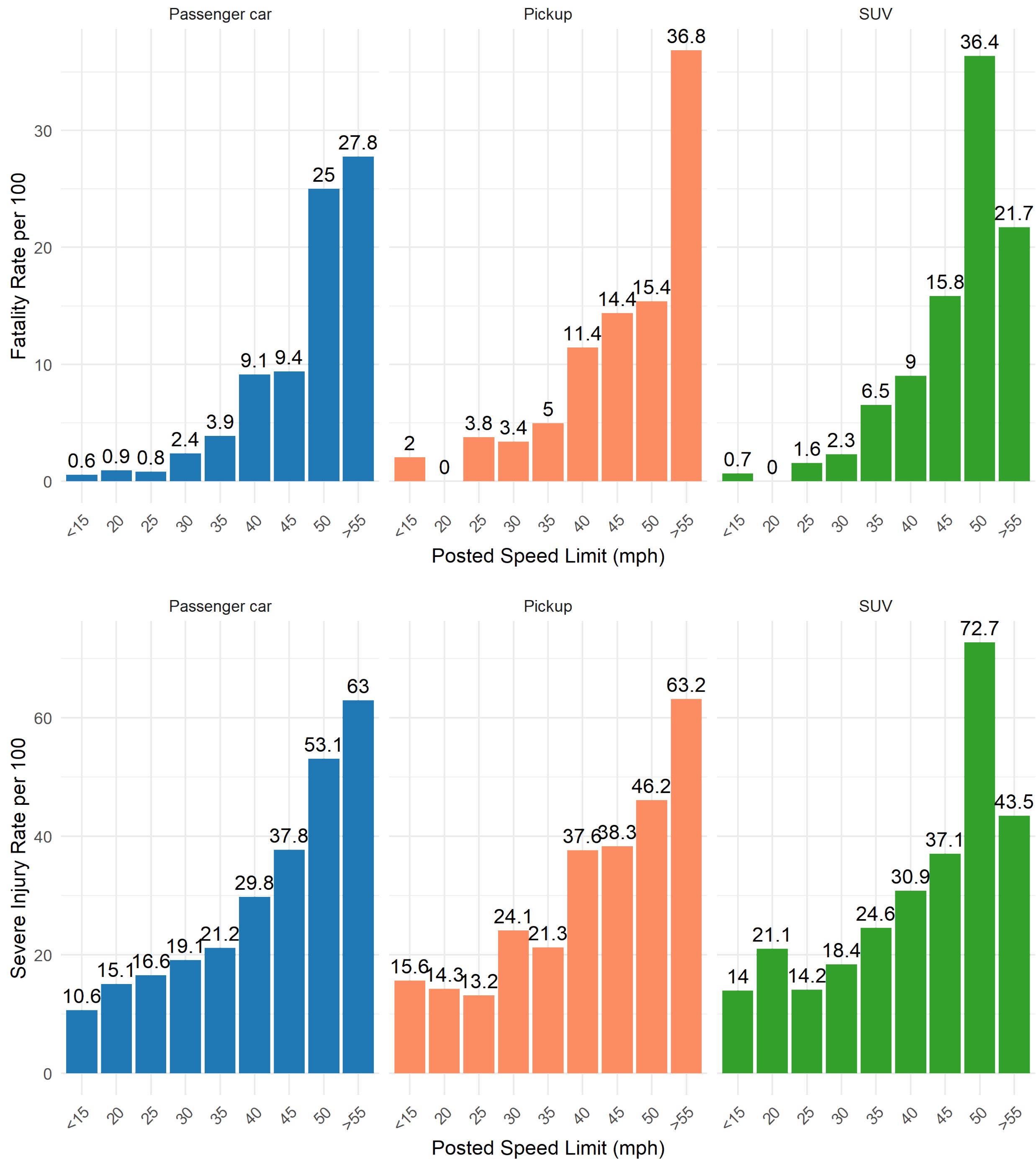

Figure 4. Fatal [top] and severe [bottom] injuries per 100 involved, distributed across various speed limits and vehicle types, including passenger cars, pickup trucks, and SUVs

Continuous Variables

Table 3 provides a summary of key vehicle-related variables involved in the study. The speed limit ranges from 5 mph (adjusted as the nominal speed limit) to 70 mph, with a median of 30 mph. Significant diversity is observed in vehicle characteristics, with curb weights ranging from 1,867 lbs. to 8,100 lbs., indicating a wide range of vehicles. The median age of cars at the time of the crash is 9 years, and the median vehicle model year is 2005 for pedestrian crashes from 2009 to 2019. Despite the relatively narrow span, Vehicle heights vary from 3.9 ft to 6.7 ft.

Table 3. Descriptive Statistics for Continuous Variables

Variable	Mean	SD	Min	Max	Median	Freq.
Speed Limit (mph)	26.31	14.59	5	70	30	10,436
Curb Weights (lbs.)	3,736	832	1,867	8,100	3,532	10,435
Vehicle Age at Crash	9.1	5.7	0	33	9	10,436
Vehicle Model Year	2,005.2	6.3	1,981	2,019	2,005	10,436
Vehicle Height (ft)	5.27	0.64	3.90	6.69	4.92	10,436

Figure 5 and Figure 6 visualizes the distribution of vehicle curb weights and vehicle height across different vehicle body types using kernel density estimates and histograms, respectively. Figure 5 shows that the curb weights are relatively consolidated with a slight separation of peaks among different body types. There is a visual separation between the curb weights of passenger cars and pickups, with SUVs encompassing a wider range. Minivans' curb weights are distributed almost in the middle of the distribution for passenger cars and pickups.

On the other hand, the distributions for vehicle heights, as shown in Figure 6 are more distinct, with narrower tails and steeper peaks for all vehicle body types, particularly for passenger cars with peaks at 4.8 feet and minivans at 5.8 feet. The peak vehicle heights of SUVs and pickups are also more distinct, with pickups peaking at around 6.2 feet and SUVs at around 5.6 feet. SUVs have wider tails on the right side, potentially representing larger SUVs, while pickups have wider tails on the left side, potentially representing smaller pickup trucks.

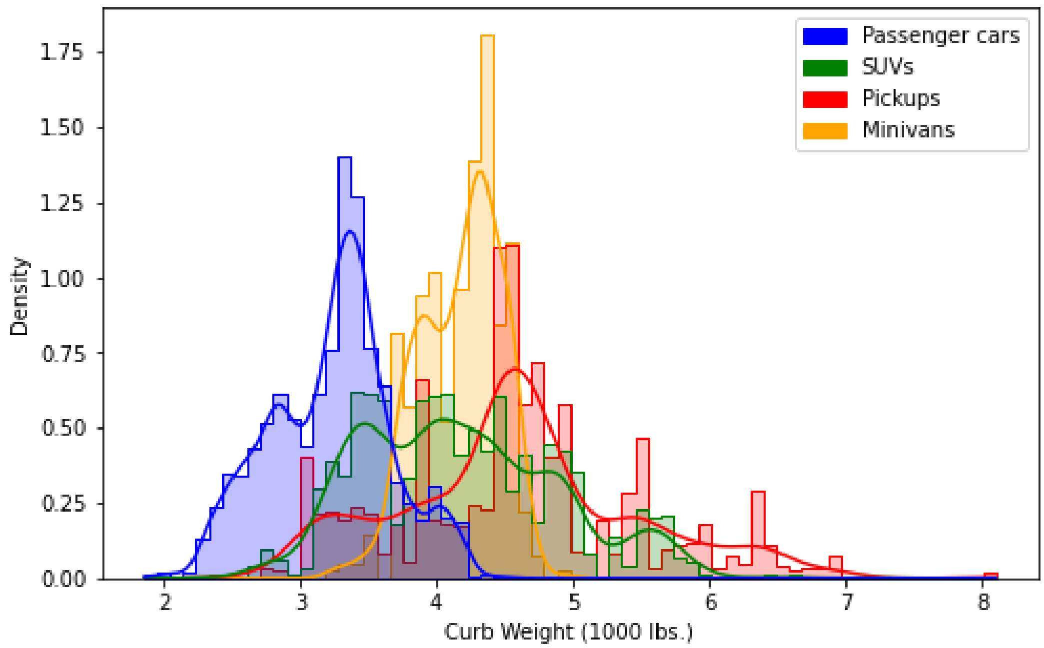

Figure 5. Distribution of vehicle curb weights (in 1,000 lbs.) among different vehicle types involved in pedestrian crashes

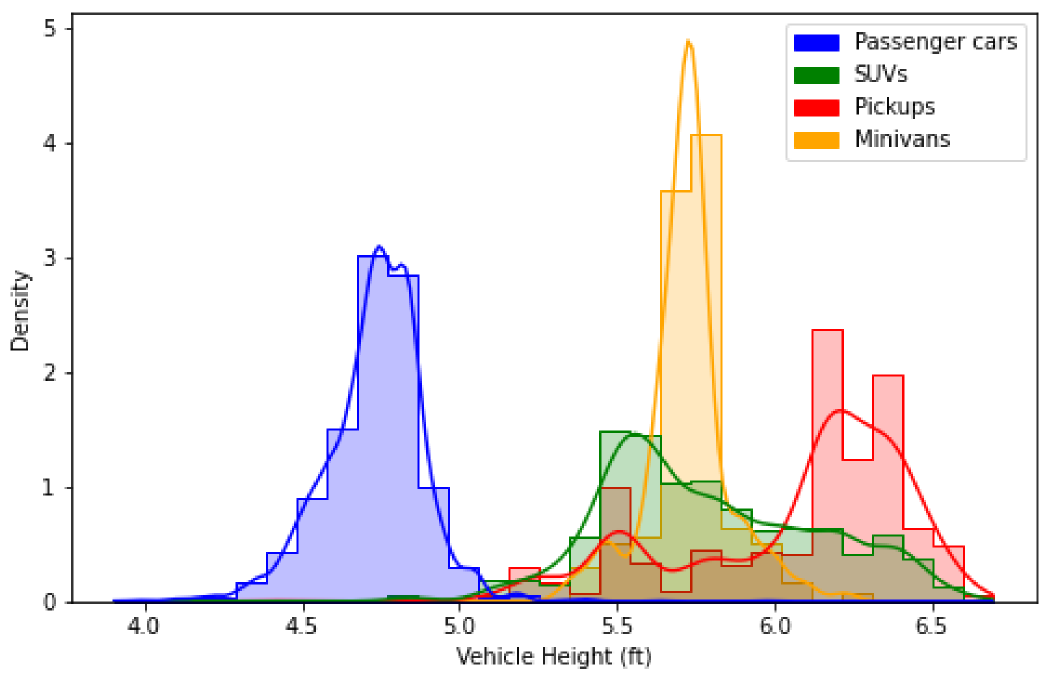

Figure 6. Distribution of vehicle heights (ft) among different vehicle types involved in pedestrian crashes

Binary logit results

Table 4 presents the results for the logit regression modeling the fatal vs. non-fatal outcomes. The speed limit variable is highly significant (<0.001) and positive across all the models, with a slightly accentuated effect in models containing the interaction term. This indicates that an increase in speed limit corresponds to an increase in the log odds of the fatal outcome, given a pedestrian crash. In contrast, the vehicle curb weight variable is significant only in Models 1A (coef. = 0.276, $p < 0.001$) and 1B (coef. = 0.589, $p < 0.01$) and not in other models that include vehicle design features like categorical body type or vehicle height. Furthermore, the AIC values for Models 2A, 2B, 3A, and 3B are slightly lower, indicating a better fit when vehicle design controls are included rather than just vehicle curb weights. This could be explained by Figure 5Figure 6, as curb weights are visibly consolidated while vehicle heights clearly separate vehicle body types. The low-speed maneuver indicator variable is consistent and negative with 99.9 percent confidence, indicating a decrease in the chances of fatal outcomes if a pedestrian crashes when the hitting vehicle is turning at an intersection, backing, slowing down, and performing other low-speed maneuvers.

In Models 2A and 2B, only pickup trucks showed a significant difference from the reference category of passenger cars, with 64 percent higher odds of a fatal outcome at the 0.01 significance level. Although SUVs and vans also posed greater risks, their differences from passenger cars were only weakly significant. Models 3A and 3B provided a better fit by including vehicle height as a design feature control, evidenced by the lowest AIC values. In these models, vehicle height is a significant predictor (p-value < 0.01), with the log odds of fatal outcomes increasing as vehicle height increases. Vehicle age and interaction terms for speed limit and vehicle curb weights did not significantly correlate with the odds of fatal outcomes in all six models.

We present the results of binary logit regression models for severe vs. non-severe outcomes in Table 5. The results of these models are, for the most part, slightly smaller magnitudes for some of the highly significant variables like speed limit, low-speed maneuvers, and other controls, similar to the Table 4 results. A major difference from the previous results is that vehicle age at the crash and the interaction term of the speed limit and vehicle weight are significantly associated with severe injuries across all models and interaction models, respectively. With a year increase in vehicle age, the odds of severe outcome increase by 1.2 percent, statistically significant at 0.01. Additionally, not considering the individual effects, collective unit increases in vehicle weights and speed limit are associated with diminishing log odds of the severe outcome, also statistically significant at 0.05 level.

Logit regression models for both outcome variables indicate that vehicle weight alone does not adequately capture the design differences among various vehicle types. Incorporating the categorical body type variable slightly improved the model's fit and interpretability. However, Model 3, which included the vehicle height variable, significantly enhanced the model fit while maintaining lower complexity. Subsequent modeling efforts will, therefore, use the combination of independent variables from Model 3 for both interaction and non-interaction models.

Table 4. Logistic regression models comparing fatal outcome vs. non-fatal

Variables	(1A)	(1B)	(2A)	(2B)	(3A)	(3B)
Speed Limit (mph)	0.066***	0.099***	0.066***	0.102***	0.066***	0.101***
	(0.006)	(0.024)	(0.006)	(0.024)	(0.006)	(0.025)
Curb Weight (in 1000 lbs.)	0.276***	0.589**	0.119	0.452˙	0.024	0.349
	(0.061)	(0.223)	(0.084)	(0.233)	(0.104)	(0.243)
Low-speed maneuver	-1.087***	-1.088***	-1.095***	-1.096***	-1.093***	-1.094***
	(0.136)	(0.136)	(0.136)	(0.136)	(0.136)	(0.136)
Lighting Conditions (Base: Daylight)						
Dark Lighted	1.423***	1.423***	1.433***	1.434***	1.431***	1.431***
	(0.135)	(0.135)	(0.135)	(0.135)	(0.135)	(0.135)
Dark Not-lighted	1.302***	1.309***	1.301***	1.309***	1.303***	1.309***
	(0.174)	(0.174)	(0.174)	(0.174)	(0.174)	(0.174)
Dawn/Dusk	0.501	0.505	0.498	0.503	0.502	0.507
	(0.329)	(0.330)	(0.330)	(0.330)	(0.330)	(0.330)
Vehicle age at crash	0.012	0.012	0.007	0.007	0.011	0.011
	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)
Vehicle Body Types (Base: Passenger cars)						
Pickup			0.496**	0.502**		
			(0.186)	(0.186)		
SUV			0.270˙	0.273˙		
			(0.150)	(0.150)		
Van			0.527˙	0.533˙		
			(0.274)	(0.274)		
Vehicle Height					0.412**	0.413**
					(0.137)	(0.137)
Speed Limit × Curb Weight		-0.008		-0.009		-0.009
		(0.006)		(0.006)		(0.006)
Year F.E.	Y	Y	Y	Y	Y	Y
Pedestrian Features	Controlled					
Driver Features	Controlled					
(Intercept)	-6.793***	-8.020***	-6.382***	-7.689***	-8.042***	-9.322***
	(0.446)	(0.966)	(0.470)	(0.990)	(0.614)	(1.081)
R. deviance	2,840.5	2,838.5	2,832.2	2,830	2,831.5	2,829.4
AIC	2,912.5	2,912.5	2,910.2	2,910	2,905.5	2,905.4

Notes: *** p-value < 0.001, ** p-value < 0.01, * p-value < 0.05, ˙ p-value < 0.1
Standard errors are shown in parenthesis

Table 5. Logistic regression models comparing severe outcomes (K, A) to non-severe outcomes

Variables	(1A)	(1B)	(2A)	(2B)	(3A)	(3B)
Speed Limit (mph)	0.027*** (0.002)	0.045*** (0.009)	0.027*** (0.002)	0.045*** (0.009)	0.027*** (0.002)	0.045*** (0.009)
Curb Weight (in 1000 lbs.)	0.091** (0.031)	0.231** (0.073)	0.033 (0.042)	0.172* (0.079)	-0.003 (0.052)	0.136 (0.084)
Low-speed maneuver	-0.705*** (0.056)	-0.704*** (0.056)	-0.707*** (0.056)	-0.706*** (0.056)	-0.707*** (0.056)	-0.706*** (0.056)
Lighting Conditions (Base: Daylight)						
Dark Lighted	0.483*** (0.060)	0.481*** (0.060)	0.484*** (0.060)	0.482*** (0.060)	0.483*** (0.060)	0.480*** (0.060)
Dark Not-lighted	0.590*** (0.089)	0.592*** (0.089)	0.588*** (0.089)	0.591*** (0.089)	0.589*** (0.089)	0.591*** (0.089)
Dawn/Dusk	0.045 (0.144)	0.045 (0.144)	0.040 (0.144)	0.040 (0.144)	0.043 (0.144)	0.043 (0.144)
Vehicle age at crash	0.012** (0.005)	0.012** (0.005)	0.010* (0.005)	0.010* (0.005)	0.012** (0.005)	0.012** (0.005)
Vehicle Body Types (Base: Passenger cars)						
Pickup			0.192* (0.092)	0.190* (0.092)		
SUV			0.085 (0.073)	0.087 (0.073)		
Van			0.192 (0.136)	0.191 (0.135)		
Vehicle Height					0.154* (0.068)	0.153* (0.068)
Speed Limit × Curb Weight		-0.005* (0.002)		-0.005* (0.002)		-0.005* (0.002)
Year F.E.	Y	Y	Y	Y	Y	Y
Pedestrian Features	Controlled					
Driver Features	Controlled					
(Intercept)	-1.899*** (0.191)	-2.435*** (0.321)	-1.736*** (0.207)	-2.270*** (0.331)	-2.355*** (0.277)	-2.885*** (0.378)
R. deviance	9,738.1	9,733.7	9,733	9,728.8	9,732.8	9,728.6
AIC	9,810.1	9,807.7	9,811	9,808.8	9,806.8	9,804.6

Notes: *** p-value < 0.001, ** p-value < 0.01, * p-value < 0.05, ˙ p-value < 0.1
Standard errors are shown in parenthesis

Partial Proportional Odds Model Results

Due to the significant discrepancies among the coefficients of some variables in the binary logit results for fatal and severe outcomes as seen in Table 4 Table 5, some of these variables may violate the parallel lines assumptions for ordinal logit regression, requiring more advanced modeling alternatives. Consequently, we opted to use the partial proportional odds model, with the results presented in Table 6: Model A for the non-interaction term model and Model B for the interaction model. As we speculated, variables such as speed limit, vehicle height, dark lighting conditions, and pedestrians over 50 violated the parallel lines assumption in both models at the 0.001 significance level. This violation mandated using separate coefficients when comparing the categories of the ordinal dependent variable, which are categorized as non-severe, serious, and fatal outcomes.

Speed Limit and Vehicle Weight

According to Model A results (Table 6), a 1 mph increase in speed limit increases the log odds of a pedestrian crash, resulting in severe versus non-severe injury by 0.027 (p-value < 0.001), and increases the log odds of the crash, resulting in fatal versus non-fatal injury by 0.061 (p-value < 0.001). Regarding odds, a 1 mph increase corresponds to a 2.7 percent increase in serious injuries compared to non-severe injuries and a 6.3 percent increase in fatal versus non-fatal injuries. The log odds of increasing injury severity to vehicle curb weight are not statistically significant for Model A.

Adding an interaction term between the speed limit and vehicle curb weight, as shown in Model B (Table 6), slightly alters the results. For the main effect of the speed limit, a 1 mph increase raises the log odds of a pedestrian crash resulting in a severe versus non-severe outcome by 0.044 and a fatal versus non-fatal outcome by 0.078, with a significance level of 0.001. Unlike in Model A, a weaker positive relationship is associated with the vehicle curb weight variable (coef. = 0.141, p-value < 0.1) and increasing injury severity. However, the interaction of speed limit and curb weight presents a significant negative relationship with the increasing injury severity (coef. = -0.004, p-value < 0.05). This means that the combined increase in speed limit and vehicle weight have diminishing returns in injury severity. To put this in perspective, consider two identical cars with the same features, except one is heavier and the other lighter. The negative interaction term indicates that on high-speed roads, although the main effects of the speed limit and vehicle weight increase the likelihood of a severe crash, the negative coefficient for heavier cars moderates this likelihood. In contrast, with higher speeds and less weight, the lighter car experiences less moderation from the interaction term, suggesting that vehicle weight may have less influence on high-speed roads. On lower-speed roads, where the interaction term is inherently weaker, heavier cars might still experience a slight effect from weight. At the same time, lighter vehicles will have minimal impact from speed and weight.

Vehicle Design

This research uses vehicle height to indicate the effects related to the vehicle's design. Model A's coefficient for vehicle height is 0.152 for severe versus non-severe outcomes, significant at the 0.05 level, and 0.403 for fatal versus non-fatal outcomes, significant at the 0.001 level. Similar estimates are found in Model B. These coefficients suggest that each 1-foot increase in vehicle height corresponds to a 16 percent increase in severe versus non-severe injuries and a 49 percent increase in the odds of fatal versus non-fatal injuries.

Vehicle Age

The partial proportional odds model (Table 6) report that the variable "Vehicle Age at Crash" has a coefficient of 0.012 ($p < 0.01$) in both models. This positive coefficient shows that for each additional year of a vehicle's age, there is a 0.012 increase in the log odds and a 1.2 percent increase in the odds of higher injury severity in a pedestrian crash. In practical terms, older vehicles have higher odds of injury severity (fatal or severe injuries) than new ones.

Low-speed Maneuver

Regarding speeds, the variable "Low-speed Maneuver" has coefficients of -0.726 in Model A and -0.724 in Model B, both significant at 0.001 significance level. These negative coefficients indicate that low-speed maneuvers are associated with decreased log odds of higher injury severity. In other words, when a crash involves a vehicle performing a low-speed maneuver, such as turning at an intersection, slowing down, or backing up, the likelihood of resulting in more severe injuries (serious or fatal) is 51.6 percent lower compared to situations where such maneuvers are not involved.

Other variables and controls

Pedestrian crashes at nighttime are linked to increased log odds of severe injuries and even higher odds of fatal injuries compared to crashes that occur during the daytime. Similarly, pedestrians over 50 years old have higher odds of experiencing severe injuries and even greater odds of fatal injuries compared to those aged 16-34. Both intoxicated pedestrians and drivers are more likely to be involved in crashes resulting in higher injury severity. Lastly, White pedestrians have a higher likelihood of being involved in severe and fatal crashes compared to pedestrians of other races or ethnicities. These variables will not be discussed in the following sections as it does not lie within the scope of our study.

Table 6. Partial proportional odds models for injury outcomes in pedestrian crashes, with dependent variable outcomes categorized as non-severe (BCO), serious (A), and fatal (K)

Variables	(A)			(B)		
	Coef.	SE	z	Coef.	SE	z
Severe (K, A) vs non-severe (B, C, O)						
Speed Limit (mph) [1]	0.027***	0.002	13.35	0.044***	0.009	5.07
Vehicle Height (ft) [1]	0.152*	0.067	2.27	0.150*	0.067	2.24
Curb weight (in 1,000 lbs.)	0.005	0.051	0.1	0.141·	0.084	1.68
Speed limit × Curb Weight	-	-	-	-0.004*	0.002	-2.02
Low-speed maneuver	-0.726***	0.056	-13.02	-0.724***	0.056	-12.99
Vehicle age at crash	0.012**	0.004	2.78	0.012**	0.004	2.8
Lighting Condition (Base: Daytime)						
Dark-Lighted [1]	0.487***	0.059	8.19	0.485***	0.059	8.15
Dark-Not Lighted [1]	0.592***	0.089	6.68	0.593***	0.089	6.69
Dawn/Dusk	0.073	0.143	0.51	0.073	0.143	0.51
Pedestrian Age (Base: 16-34)						
15 and below	0.038	0.083	0.46	0.037	0.083	0.45
35-49	0.280***	0.073	3.85	0.280***	0.073	3.84
50-64 [1]	0.485***	0.072	6.76	0.484***	0.072	6.74
65 and above [1]	0.824***	0.088	9.4	0.820***	0.088	9.36
Pedestrian Alcohol Use	0.266**	0.092	2.89	0.263**	0.092	2.85
Pedestrian Drug Use	1.572***	0.231	6.8	1.575***	0.231	6.82
Driver Alcohol Use	0.592***	0.147	4.03	0.600***	0.147	4.08
Driver Drug Use	1.435***	0.203	7.06	1.434***	0.203	7.06
Driver Age (Base: 25-54)						
15-24	-0.039	0.068	-0.57	-0.038	0.068	-0.56
55 and above	-0.114·	0.061	-1.88	-0.112·	0.061	-1.85
Unknown	0.141	0.182	0.77	0.147	0.182	0.81
Pedestrian Race/Ethnicity (Base: White)						
Hispanic	0.023	0.142	0.16	0.021	0.142	0.15
Black	-0.407***	0.064	-6.36	-0.408***	0.064	-6.36
Other	-0.871***	0.088	-9.9	-0.872***	0.088	-9.9
Driver Race/ Ethnicity (Base: White)						
Hispanic	0.141	0.141	1.0	0.137	0.141	0.97
Black	0.030	0.060	0.5	0.030	0.060	0.49
Other	-0.163	0.143	-1.13	-0.166	0.143	-1.16
(Intercept-1)	-2.368***	0.275	-8.6	-2.879***	0.375	-7.67
Fatal (K) vs. non-fatal (A, B, C, O)						
Speed Limit (mph) [1]	0.061***	0.005	12.35	0.078***	0.010	7.93
Vehicle Height (ft) [1]	0.403***	0.091	4.44	0.414***	0.091	4.56
Curb weight (in 1,000 lbs.)	0.005	0.051	0.1	0.141·	0.084	1.68

Variables	(A)			(B)		
	Coef.	SE	z	Coef.	SE	z
Speed limit × Curb Weight	-	-	-	-0.004*	0.002	-2.02
Low-speed maneuver	-0.726***	0.056	-13.02	-0.724***	0.056	-12.99
Vehicle age at crash	0.012**	0.004	2.78	0.012**	0.004	2.8
Lighting Condition (Base: Daytime)						
Dark-Lighted [1]	1.357***	0.123	11.05	1.355***	0.123	11.03
Dark-Not Lighted [1]	1.258***	0.160	7.86	1.260***	0.160	7.89
Dawn/Dusk	0.073	0.143	0.51	0.073	0.143	0.51
Pedestrian Age (Base: 16-34)						
15 and below	0.038	0.083	0.46	0.037	0.083	0.45
35-49	0.280***	0.073	3.85	0.280***	0.073	3.84
50-64 [1]	1.130***	0.115	9.83	1.129***	0.115	9.82
65 and above [1]	1.612***	0.140	11.54	1.607***	0.140	11.51
Pedestrian Alcohol Use	0.266**	0.092	2.89	0.263**	0.092	2.85
Pedestrian Drug Use	1.572***	0.231	6.8	1.575***	0.231	6.82
Driver Alcohol Use	0.592***	0.147	4.03	0.600***	0.147	4.08
Driver Drug Use	1.435***	0.203	7.06	1.434***	0.203	7.06
Driver Age (Base: 25-54)						
15-24	-0.039	0.068	-0.57	-0.038	0.068	-0.56
55 and above	-0.114˙	0.061	-1.88	-0.112˙	0.061	-1.85
Unknown	0.141	0.182	0.77	0.147	0.182	0.81
Pedestrian Race/Ethnicity (Base: White)						
Hispanic	0.023	0.142	0.16	0.021	0.142	0.15
Black	-0.407***	0.064	-6.36	-0.408***	0.064	-6.36
Other	-0.871***	0.088	-9.9	-0.872***	0.088	-9.9
Driver Race/ Ethnicity (Base: White)						
Hispanic	0.141	0.141	1	0.137	0.141	0.97
Black	0.030	0.060	0.5	0.030	0.060	0.49
Other	-0.163	0.143	-1.13	-0.166	0.143	-1.16
(Intercept-2)	-7.676***	0.474	-16.19	-8.263***	0.557	-14.84
Year Fixed Effects	Y			Y		
Number of Observations	10,435			10,435		
Log-likelihood (LR)	-5827.627			-5825.611		
Degree of Freedom (DoF)	42			43		
LR Chi^2 (DoF)	1608.44			1612.47		
Prob. > Chi^2	0.000			0.000		
Pseudo R^2	0.1213			0.1216		

*** p-value < 0.001, ** p-value < 0.01, * p-value < 0.05, ˙ p-value < 0.1

[1] variables that violate the parallel lines assumption at the 0.01 significance level

Note: The log-likelihood ratio tests and pseudo-R^2 values suggest that Model B fits the data slightly better. However, we will use the simpler Model A results unless discussing the interaction terms specifically.

Discussion

We employed binary logit and partial proportional odds models to investigate the influence of factors such as speed limit, vehicle weights, vehicle design aspects, vehicle age, and other relevant variables on the severity of injury outcomes in pedestrian crashes, focusing particularly on severe and fatal injuries. To determine the most critical variables, we will translate the model results into practical terms and discuss the overall effects of these variables. Additionally, we will suggest appropriate countermeasures based on our study findings and existing literature.

Speed Limits

Suburban roads prioritize accessibility and mobility, often featuring long, straight stretches (*Ewing et al., 2016*). This pattern is also evident in urban areas of Tennessee, where cities are spread out with numerous suburbs surrounding the core. These suburban roads typically fall under the arterial classification and have higher speed limits, generally starting at 40 mph, with 45 and 50 mph limits also common. They often lack infrastructure for pedestrian separation, whether for those walking alongside the road or crossing at midblock locations. According to Model A (Table 6), a 15 mph increase in the speed limit correlates with a 50 percent increase in the odds of a severe injury compared to a non-severe one and a 150 percent increase in the odds of a fatal outcome compared to a non-fatal one, without considering the interaction with curb weight. This finding conforms with other studies that have found that higher speed limits are associated with more fatal and severe injuries in pedestrian crashes (*Islam, 2023; Wang et al., 2022*). Not considering the effect of weights, a 5 mph reduction in the speed limit, assuming a perfect correlation between the speed limit and vehicle impact speed, would reduce severe injuries by 12.6 percent and fatal by 26.6 percent, respectively.

Studies on impact speed have shown that the risk of severe and fatal injuries to pedestrians is greatly reduced when vehicles travel at impact speeds of 30 km/h (~20 mph) (*Hussain et al., 2019*). Setting speed limits at 30 mph and maintaining this speed could improve drivers' peripheral vision, allowing them to react to pedestrians and brakes and potentially reduce the impact speed to below 20 mph, thereby avoiding severe or fatal injuries (*NACTO, 2013*). However, we must acknowledge that driving speeds are not perfectly correlated with speed limits. Drivers may still be tempted to exceed them due to permissive road designs prioritizing mobility. Therefore, lowering speed limits alone is insufficient. Road design should also incorporate traffic calming and other safety strategies to enforce passive speed limits, ensuring that drivers find it challenging to exceed the target speed limit of 30 mph for roads with the highest pedestrian traffic.

Vehicle weights

We investigated the relationship between vehicle curb weights, estimated using VIN data and the CVS dataset, and injury severity outcomes. Our findings indicate that vehicle weights are weakly related to injury severity after accounting for vehicle design, aligning with the conclusions of Tyndall (*2024*). While vehicle weight contributes to the kinetic energy transfer during a crash, the variations in curb weight among different vehicles may not be substantial enough to have a significant impact compared to impact speed (*Simms & Wood, 2006*). That said, the effects of vehicle weight could still be crucial on roads with lower speed limits and during low-speed maneuvers, as indicated by the statistically significant interaction between vehicle weight and speed in Model B (Table 6).

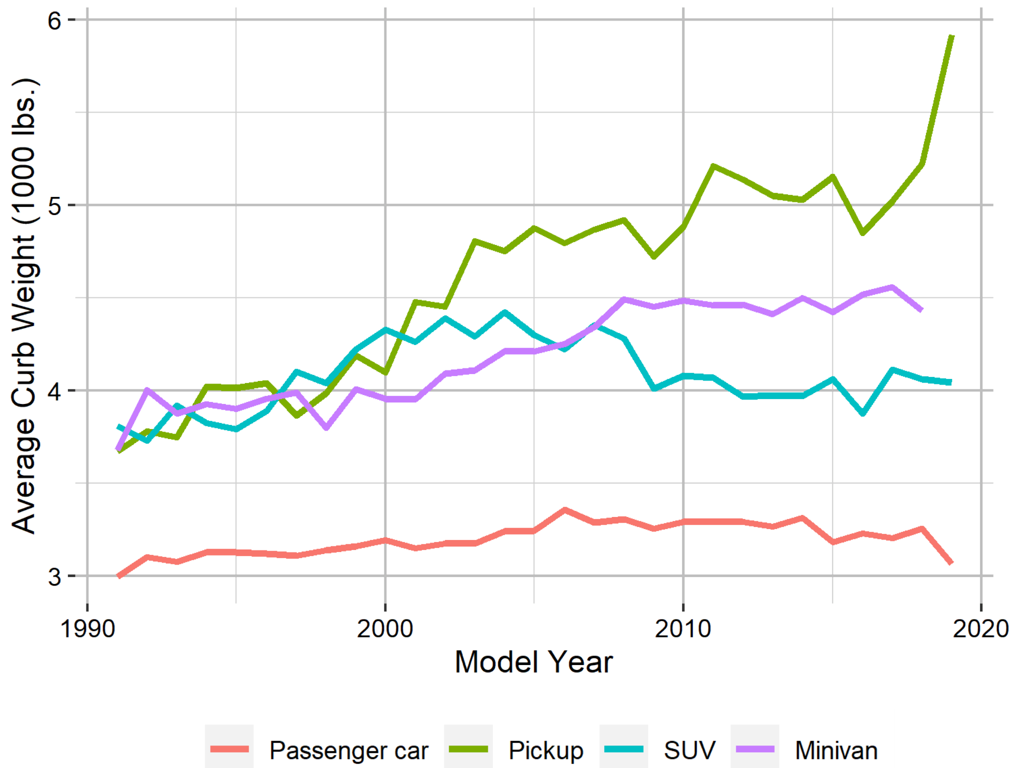

Figure 7. Pedestrian crashes in Tennessee (2009-2019): Average curb weights of vehicles involved by model year

Over the past two decades, vehicle weights have been steadily increasing, as illustrated in Figure 7 based on the Tennessee pedestrian crash data. The weight disparity between different vehicle body types, particularly pickup trucks and passenger cars, has recently widened. With the rising popularity of heavier electric vehicles in the U.S. and the general trend of increasing vehicle weights, pedestrians are at greater risk, especially on low-speed roads and during maneuvers involving low-speed movements. To understand the impact of growing vehicle weights, let's consider a hypothetical scenario where the average curb weight of the vehicle fleet rises from the current 3,800 lbs. (based on pedestrian crash data in Tennessee) to 4,800 lbs. Based on Model B results, this increase will lead to an 8.4 percent rise in total fatalities and severe injuries on roads with a speed limit of 15 mph and a 2.1 percent increase on roads with a speed limit of 30 mph. While these results should be interpreted with caution due to the weaker statistical significance of the effect of vehicle weight, they illustrate how growing vehicle weight puts a disproportionate injury burden on pedestrians at lower speeds. Furthermore, increasing vehicle weight has little impact on the efficacy of speed limit reductions. Assuming a perfect correlation between speed limit and vehicle impact speed, a 5 mph reduction in speed limit would result in a 13.4 percent reduction in severe injuries and a 27 percent reduction in fatal injuries for the current vehicle fleet, with an average curb weight of around 3,800 lbs. If the average vehicle weight increases to 4,800 lbs., the same 5 mph reduction would lead to an 11.7 percent reduction in severe injuries and a 25.5 percent reduction in fatal injuries, indicating that speed limits are relatively resilient to changes in vehicle weight.

We recommend that regulatory bodies closely monitor and manage the trend of increasing vehicle weights to enhance pedestrian safety on U.S. roads. Implementing infrastructure improvements that include adequate pedestrian facilities to separate pedestrian traffic from vehicle traffic can significantly improve safety, especially on low-speed roads and during low-speed maneuvers. As discussed, benefits of speed limit reduction trump the adverse effects of vehicle weight increases, provided that these reductions lead to corresponding changes in driving behavior.

Vehicle Design

Model 3A (Table 6) findings reveal that with every 1-foot increase in vehicle height, there is a 0.152 increase in the log odds of severe injuries versus non-severe injuries and a 0.403 percent increase in the log odds of fatal injuries versus non-fatal injuries. Before discussing the implications of these results for vehicle body types and injury outcomes, let us examine the trends in vehicle height over the years, as shown in Figure 8. The figure illustrates a steady increase in the average height of vehicles involved in pedestrian crashes, particularly for pickups, minivans, and passenger cars. However, the average height of SUVs appears to have declined since 2004. This trend is attributed to the increasing market share of compact crossover SUVs, which began rising in popularity around 2004 (*Consumer Reports, 2019*). This shift is also evident in our data, as shown by the distorted trends in the average vehicle height of SUVs in Figure 8. Before the popularity of compact SUVs, pickup trucks and SUVs exhibited similar rising trends in vehicle height until 2004, after which the trends diverged, with pickups continuing to increase in height while SUVs appeared to decrease. Considering the proportion of compact crossover SUVs, large SUVs closely follow the height trend of pickup trucks, with associated risks similar to pickups. Conversely, the height of compact crossover SUVs is typically between larger SUVs and pickup trucks and smaller vehicles like passenger cars, providing a unique perspective on the impacts of vehicle design.

Upon analyzing the peak height distributions of different vehicle types in Figure 6, we found that minivans are generally about 1 foot taller, and pickup trucks are about 1.4 feet taller than passenger cars. These height differences suggest that minivans are approximately 16.4 percent more likely to be involved in severe and 49.6 percent more likely to be involved in fatal pedestrian crashes than passenger cars. In comparison, there is a 23.7 percent higher odds of being involved in severe and 75.8 percent higher odds of being involved in fatal pedestrian crashes compared to the passenger cars. Larger SUVs, which tend to have greater overall height, likely align with the estimates for pickup trucks. For compact SUVs, which are roughly 0.6 feet taller than passenger cars (based on the height differences between the 2015 Toyota RAV4 and the 2015 Toyota Camry), there is a 9.6 percent higher odds of being involved in severe pedestrian crash and 27.3 percent higher odds for fatal pedestrian crashes than passenger cars.

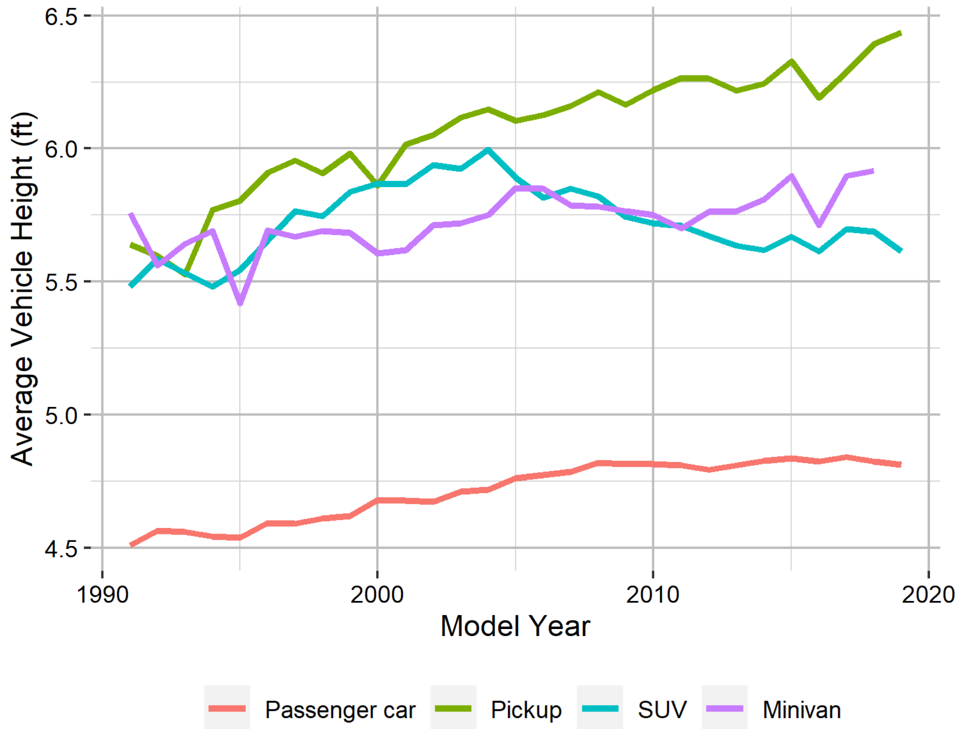

Figure 8. Pedestrian crashes in Tennessee (2009-2019): Average heights of vehicles involved by model year

The differences in injury outcomes across the vehicle types could possibly be due to the relationship between injury mechanisms and the front design of vehicles. For example, when a pedestrian is struck by a passenger car with a lower height and hood, the primary impact is generally on the limbs, followed by secondary impacts and ground contact (*Hamacher et al., 2012; Simms et al., 2011*). In contrast, if a pedestrian is hit by a taller pickup truck with a higher hood, the initial impact is likely to occur below the chest or lower abdomen, exposing a larger area of the body to blunt trauma (*Simms & Wood, 2006*), as well as increasing the risk of being run over. These findings conform with the past pedestrian safety literature that has controlled vehicle body types instead of vehicle height (*Desapriya et al., 2010; Edwards & Leonard, 2022*). Tyndall (*2024*) reported a 22 percent increase in fatality risk for every 10 cm (0.33 ft) increase in front-end height. We assume that a similar increase in fatality risk would occur if this difference were applied to the vehicle height increase in this study. Besides pedestrian injury impacts, the vehicle height could also act as a control visibility issue due to front-hood height and thicker A-pillars in taller vehicles (*Hu & Cicchino, 2022*). Overall, the modeling results demonstrated that vehicle height is an appropriate control for vehicle design, as it fits better than the categorical vehicle body types or vehicle weight parameters.

Figure 6 highlights a concerning trend of increasing vehicle heights across all types, with particularly notable increases in pickup trucks, heightening pedestrian risks. In addition to increasing average vehicle heights, SUVs have increasingly become overrepresented in Tennessee pedestrian crashes in recent years, as shown in Figure 9, corroborating the boom of compact SUVs. Regulatory agencies like NHTSA should prioritize monitoring and regulating these vehicles' heights and front hood levels, including excessive customizations that increase overall vehicle heights.

Figure 9. Pedestrian crashes in Tennessee (2009-2019): Area charts displaying the counts [top] and proportions [bottom] of vehicle body types by vehicle age at the time of crash [left] and vehicle model year [right]

Vehicle Age at Crash

Figure 9 illustrates that pedestrian crash involvement peaked for vehicles aged 11 years and then declined sharply. Additionally, the data shows that the vehicle model year peaked around 2007 for crashes occurring between 2009 and 2019. The model results indicated that older vehicles are associated with higher injury severity. For instance, 11-year-old vehicles, which are the most involved in pedestrian crashes in Tennessee, have nearly 14 percent higher odds of causing severe or fatal injuries compared to new vehicles. Among these older vehicles, pickup trucks are notably overrepresented, underscoring their utility but also revealing a safety concern, as vehicles up to 25 years old were 35 percent more likely to be associated with higher injury severity.

Figure 9 indicates a strong correlation between vehicle model year and vehicle age, attributable to the study's limited timeframe from 2009 to 2019. This positive correlation between vehicle age and increased injury severity in pedestrian crashes can be attributed to two primary factors: first, the degradation of vehicle safety due to wear and tear, which makes older vehicles less safe, potentially due to declining performance, worn-out brakes, and other safety-compromising issues. Second, the advancements in safety technologies in newer model-year cars enhance their safety compared to older models. These advancements include features like pedestrian detection, automatic braking, and the use of shock-absorbent materials in newer vehicles. There is also a possibility that older vehicles are driven by drivers that exhibit less-safe behaviors.

While we have established that older vehicles pose more dangers to pedestrians, newer vehicles also present risks due to their increased size and height, as shown in Figure 8. It is crucial to assess whether the safety enhancements and the benefits of less wear and tear in newer vehicles outweigh the negative impacts of the design changes adopted by manufacturers over the years. Using the CVS data, we extracted the overall heights of base models of the most common vehicle models for pickup truck and passenger cars category – Ford F-150 and Toyota Camry from different years: 2019, the latest base model within the study period; 2008, which is notably common vehicle model for the study period; and 1994, representing an older model.

Based solely on vehicle height for the Ford F-150, the 2019 model (vehicle height = 75.6 in) is 9.9 percent more likely to be associated with fatal injuries than the 2008 model (vehicle height = 72.8 in) and 20.4 percent more than the 1994 model (vehicle height = 70.1 in). Similarly, the 2019 Toyota Camry (vehicle height = 58.27 in) is 2.8 percent more likely than the 2008 model (vehicle height = 57.48 in) and 11.5 percent more likely to be associated with fatal injuries than the 1994 Toyota Camry (vehicle height = 55.12 in) in terms of design-related risks. Conversely, considering vehicle age effects alone for both models, the 2008 models are 14 percent more dangerous, and the 1994 models are 35 percent more dangerous than the 2019 models.

This analysis reveals that newer vehicles are still safer than older vehicles across all body types, though the margin is narrower for pickup trucks. However, if the increasing vehicle size trend continues, older vehicles could become safer for pedestrians than newer models.

Conclusions and Recommendations

Using the partial proportional odds model to study the relationship between severe and fatal injury outcomes, we found that the speed limit is the most influential factor, consistently highly significant in all modeling efforts and for both fatal and severe injury outcomes. The speed limit is associated with the vehicle impact speed, and a higher speed limit means higher vehicle impact speeds.

Similarly, vehicle design, as represented by the vehicle height parameter in our study, plays a crucial role in determining pedestrian fatalities. Taller vehicles typically have higher front hoods, larger sizes, and vicinity visibility issues, leading to more severe and fatal crashes when they strike pedestrians. Consequently, pickup trucks and large SUVs generally have higher vehicle heights and are more dangerous than passenger cars. Although minivans and compact SUVs are less hazardous than pickup trucks and large SUVs, they still pose a significantly higher risk than passenger cars. In comparing vehicle design and weight, vehicle weight was not significantly associated with pedestrian crash outcomes, possibly due to the minimal weight variations within consumer vehicles.

We also examined the detailed effects of vehicle trends concerning size/height, weight, age and model year, yielding some noteworthy findings. Our study revealed that older vehicles are more dangerous than newer ones for pedestrian safety. While this may seem intuitive, as newer vehicles generally feature more advanced technologies and less wear and tear, they are also associated with larger sizes and designs that can harm pedestrians. Additionally, we investigated the trend of increasing vehicle weights. Although the main effect of vehicle weight was only weakly significant, its interaction with the speed limit variable was statistically significant. This suggests that increasing vehicle weights could pose a substantial risk to pedestrians in low-speed areas and zones with frequent low-speed maneuvers.

Countermeasures should prioritize speed management since speed limits have the greatest impact on determining injury severity. Reducing speed limits to a safer 30 mph on roads with high pedestrian traffic is crucial, but it's also essential to ensure drivers do not unintentionally exceed this limit. To achieve this, we recommend implementing complex road designs with traffic calming devices that make it difficult to surpass the target speed limit of 30 mph. Design-related interventions to control vehicle impact speed are effective and immediate, unlike waiting for newer technology to become widespread in the vehicle fleet, which can take 5-10 years. Additionally, reducing speed limits can help mitigate some of the effects of the trend toward heavier vehicles. Manufacturers should also be encouraged to include pedestrian safety technologies in their cars and adopt pedestrian-friendly designs of vehicle bodies in all models and trims, which will benefit in the long run. Regulatory bodies should monitor vehicle size and weight trends and discourage excessive customizations that lead to higher hood and vehicle heights.

Study Limitations and Future Research

This study addresses several important questions regarding vehicle features and their relationship with speed limits, but certain limitations exist. Firstly, the study relies on police crash data, which may be subject to subjective bias from the police officers. Although we mitigated this bias by linking the data with standardized datasets like VIN information and the CVS dataset—resulting in some data loss—our control variables might still be susceptible to this bias. Additionally, we used curb weights for vehicle weight estimations and speed limits as proxies for vehicle impact speeds, similar to other pedestrian crash studies based on police crash data. Future research should focus on using actual speeds and weights to understand the dynamics of kinetic energy transfer and determine if weight variations significantly impact pedestrian harm. Another limitation is that the study did not consider the differences in the manner of impact (*Jurewicz et al., 2016*), as we used vehicle height to encompass all design aspects. Further investigation into pedestrian hit angles, impact locations, and design differences, such as front hood height and slope (*Hu et al., 2024*), is necessary to understand these factors in detail. Lastly, we did not explore whether EVs and HEVs, which generally maintain consistent designs in terms of body types, are useful in estimating the impacts of vehicle weights. Future research should also consider vehicle power sources to assess how trends in electrification specifically affect pedestrian safety.

References

AASHTO. Highway Safety Manual. In: American Association of State Highway and Transportation Officials (AASHTO).

Anderson, M. L., & Auffhammer, M. (2014). Pounds that kill: The external costs of vehicle weight. *Review of Economic Studies*, *81*(2), 535-571.

Ballesteros, M. F., Dischinger, P. C., & Langenberg, P. (2004). Pedestrian injuries and vehicle type in Maryland, 1995–1999. *Accident Analysis & Prevention*, *36*(1), 73-81.

Bureau of Transportation Statistics. *New and Used Passenger Car and Light Truck Sales and Leases*. https://www.bts.gov/content/new-and-used-passenger-car-sales-and-leases-thousands-vehicles

Calhoun, V. D., Altschul, D., McGinty, V., Shih, R., Scott, D., Sears, E., & Pearlson, G. D. (2004). Alcohol intoxication effects on visual perception: an fMRI study. *Human brain mapping*, *21*(1), 15-26.

Canadian Vehicle Specifications (CVS) ((2024). https://carsp.ca/download/38208

Cicchino, J. B. (2022). Effects of automatic emergency braking systems on pedestrian crash risk. *Accident Analysis & Prevention*, *172*, 106686.

Consumer Reports. (2019). *The Rise of the Crossover: The segment that's really driving the auto industry's sales*. https://advocacy.consumerreports.org/research/the-rise-of-the-crossover-the-segment-thats-really-driving-the-auto-industrys-sales/

Daviaux, Y., Mignardot, J.-B., Cornu, C., & Deschamps, T. (2014). Effects of total sleep deprivation on the perception of action capabilities. *Experimental brain research*, *232*, 2243-2253.

Davis, G. A. (2001). Relating severity of pedestrian injury to impact speed in vehicle-pedestrian crashes: Simple threshold model. *Transportation Research Record*, *1773*(1), 108-113.

Desapriya, E., Subzwari, S., Sasges, D., Basic, A., Alidina, A., Turcotte, K., & Pike, I. (2010). Do light truck vehicles (LTV) impose greater risk of pedestrian injury than passenger cars? A meta-analysis and systematic review. *Traffic injury prevention*, *11*(1), 48-56.

Doecke, S. D., Kloeden, C. N., Dutschke, J. K., & Baldock, M. R. (2018). Safe speed limits for a safe system: The relationship between speed limit and fatal crash rate for different crash types. *Traffic injury prevention*, *19*(4), 404-408.

Edwards, M., & Leonard, D. (2022). Effects of large vehicles on pedestrian and pedalcyclist injury severity. *Journal of Safety Research*, *82*, 275-282. https://doi.org/https://doi.org/10.1016/j.jsr.2022.06.005

El-Shawarby, I., Abdel-Salam, A.-S. G., & Rakha, H. (2013). Evaluation of driver perception–reaction time under rainy or wet roadway conditions at onset of yellow indication. *Transportation Research Record*, *2384*(1), 18-24.

Elvik, R., Christensen, P., & Amundsen, A. H. (2004). *Speed and road accidents: an evaluation of the Power Model*. Transportøkonomisk Institutt.

European Commission. (2024). *Annual statistical report on road safety in the EU, 2024. European Road Safety Observatory*.

Ewing, R., Hamidi, S., & Grace, J. B. (2016). Urban sprawl as a risk factor in motor vehicle crashes. *Urban Studies*, *53*(2), 247-266.

Federal Highway Administration. KABCO Injury Classification Scale and Definitions. In.

Feng, Z.-x., Liu, J., & Zhang, W.-h. (2012). Efficiency of Driver Identification of Pedestrians in Low Illumination. In *CICTP 2012: Multimodal Transportation Systems—Convenient, Safe, Cost-Effective, Efficient* (pp. 2665-2672).

FHWA. (2009). *Manual on Uniform Traffic Control Devices for Streets and Highways*. https://mutcd.fhwa.dot.gov/pdfs/2009r1r2/pdf_index.htm

FHWA. (2023). *Manual on Uniform Traffic Control Devices for Streets and Highways*. https://mutcd.fhwa.dot.gov/kno_11th_Edition.htm

Gibbs, N. (2024). SUVs reach new high, accounting for more than half of all sales. https://europe.autonews.com/automakers/suvs-surge-new-milestone-helped-evs

Hamacher, M., Eckstein, L., & Paas, R. (2012). Vehicle related influence of post-car impact pedestrian kinematics on secondary impact. Proceedings of the International Research Council on the Biomechanics of Injury conference,

Han, Y., Yang, J., Mizuno, K., & Matsui, Y. (2012). Effects of vehicle impact velocity, vehicle front-end shapes on pedestrian injury risk. *Traffic injury prevention*, *13*(5), 507-518.

Hu, W., & Cicchino, J. B. (2022). Relationship of pedestrian crash types and passenger vehicle types. *Journal of Safety Research*, *82*, 392-401. https://doi.org/https://doi.org/10.1016/j.jsr.2022.07.006

Hu, W., Monfort, S. S., & Cicchino, J. B. (2024). The association between passenger-vehicle front-end profiles and pedestrian injury severity in motor vehicle crashes. *Journal of Safety Research*, *90*, 115-127. https://doi.org/https://doi.org/10.1016/j.jsr.2024.06.007

Hussain, Q., Feng, H., Grzebieta, R., Brijs, T., & Olivier, J. (2019). The relationship between impact speed and the probability of pedestrian fatality during a vehicle-pedestrian crash: A systematic review and meta-analysis. *Accident Analysis & Prevention*, *129*, 241-249. https://doi.org/https://doi.org/10.1016/j.aap.2019.05.033

IIHS-HLDI. (2022). *Fatality facts 2022: Pedestrians*. https://www.iihs.org/topics/fatality-statistics/detail/pedestrians

International Energy Agency. (2024). *Global EV Outlook 2024: Moving towards increased affordability*. https://www.iea.org/reports/global-ev-outlook-2024/trends-in-electric-cars

Islam, M. (2023). An exploratory analysis of the effects of speed limits on pedestrian injury severities in vehicle-pedestrian crashes. *Journal of Transport & Health*, *28*, 101561. https://doi.org/https://doi.org/10.1016/j.jth.2022.101561

Jurewicz, C., Sobhani, A., Woolley, J., Dutschke, J., & Corben, B. (2016). Exploration of Vehicle Impact Speed – Injury Severity Relationships for Application in Safer Road Design. *Transportation Research Procedia*, *14*, 4247-4256. https://doi.org/https://doi.org/10.1016/j.trpro.2016.05.396

Lerner, N. D. (1993). Brake perception-reaction times of older and younger drivers. Proceedings of the human factors and ergonomics society annual meeting,

Liu, J., Hainen, A., Li, X., Nie, Q., & Nambisan, S. (2019). Pedestrian injury severity in motor vehicle crashes: an integrated spatio-temporal modeling approach. *Accident Analysis & Prevention*, *132*, 105272.

NACTO. (2013). *Urban street design guide*. Island Press. https://nacto.org/publication/urban-street-design-guide/

NHTSA. *VIN Decoder*. NHTSA,. https://www.nhtsa.gov/vin-decoder
Event data recorders, (2006). https://www.govinfo.gov/content/pkg/CFR-2023-title49-vol6/pdf/CFR-2023-title49-vol6-part563.pdf

NHTSA. (2017). MMUCC Guideline: Model Minimum Uniform Crash Criteria. In: National Highway Traffic Safety Administration, US Department of Transportation.

Parajuli, S., Cherry, C. R., Zavisca, E., & Rogers III, W. (2023). Are Pedestrian Crashes Becoming More Severe? A Breakdown of Pedestrian Crashes in Urban Tennessee. *Transportation Research Record*, 03611981231198475.

Plainis, S., & Murray, I. (2002). Reaction times as an index of visual conspicuity when driving at night. *Ophthalmic and physiological optics*, *22*(5), 409-415.

Robertson, L. S. (2022). Vehicle safety tests, rankings, curb weight, and fatal crash rates: automatic emergency brakes associated with increased death rates. *medRxiv*, 2022.2012. 2008.22283253.

Rosén, E., & Sander, U. (2009). Pedestrian fatality risk as a function of car impact speed. *Accident Analysis & Prevention*, *41*(3), 536-542. https://doi.org/https://doi.org/10.1016/j.aap.2009.02.002

Ryb, G. E., Dischinger, P. C., & Ho, S. (2009). Vehicle model year and crash outcomes: a CIREN study. *Traffic injury prevention*, *10*(6), 560-566.

Saadé, J., Cuny, S., Labrousse, M., Song, E., Chauvel, C., & Chrétien, P. (2020). Pedestrian injuries and vehicles-related risk factors in car-to-pedestrian frontal collisions. 2020 IRCOBI conference proceedings,

Schmitt, A. (2020). *Right of Way: Race, Class, and the Silent Epidemic of Pedestrian Deaths in America*. Island Press.

Schubert, A., Babisch, S., Scanlon, J. M., Campolettano, E. T., Roessler, R., Unger, T., & McMurry, T. L. (2023). Passenger and heavy vehicle collisions with pedestrians: Assessment of injury mechanisms and risk. *Accident Analysis & Prevention*, *190*, 107139. https://doi.org/https://doi.org/10.1016/j.aap.2023.107139

Simms, C. K., Ormond, T., & Wood, D. P. (2011). The influence of vehicle shape on pedestrian ground contact mechanisms. Proceedings of IRCOBI Conference. Poland,

Simms, C. K., & Wood, D. P. (2006). Pedestrian risk from cars and sport utility vehicles-a comparative analytical study. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of automobile engineering*, *220*(8), 1085-1100.

Sobhani, A., Young, W., Logan, D., & Bahrololoom, S. (2011). A kinetic energy model of two-vehicle crash injury severity. *Accident Analysis & Prevention*, *43*(3), 741-754. https://doi.org/https://doi.org/10.1016/j.aap.2010.10.021

Strandroth, J., Sternlund, S., Lie, A., Tingvall, C., Rizzi, M., Kullgren, A., Ohlin, M., & Fredriksson, R. (2014). Correlation between Euro NCAP pedestrian test results and injury severity in injury crashes with pedestrians and bicyclists in Sweden. *Stapp car crash journal*, *58*, 213.

Tefft, B. C. (2013). Impact speed and a pedestrian's risk of severe injury or death. *Accident Analysis & Prevention*, *50*, 871-878.

Tennessee Highway Safety Office. (2021). *Tennessee Integrated Traffic Analysis Network* (

Timmers, V. R. J. H., & Achten, P. A. J. (2016). Non-exhaust PM emissions from electric vehicles. *Atmospheric Environment*, *134*, 10-17. https://doi.org/https://doi.org/10.1016/j.atmosenv.2016.03.017

Tyndall, J. (2021). Pedestrian deaths and large vehicles. *Economics of Transportation*, *26-27*, 100219. https://doi.org/https://doi.org/10.1016/j.ecotra.2021.100219

Tyndall, J. (2024). The effect of front-end vehicle height on pedestrian death risk. *Economics of Transportation*, *37*, 100342. https://doi.org/https://doi.org/10.1016/j.ecotra.2024.100342

Van Den Berg, J., & Neely, G. (2006). Performance on a simple reaction time task while sleep deprived. *Perceptual and Motor Skills*, *102*(2), 589-599.

Vilchez, J. J. G., Pasqualino, R., & Hernandez, Y. (2023). The new electric SUV market under battery supply constraints: Might they increase CO2 emissions? *Journal of Cleaner Production*, *383*, 135294.

Wang, J., Parajuli, S., Cherry, C. R., McDonald, N. C., & Lyons, T. (2022). Vulnerable road user safety and freight vehicles: A case study in North Carolina and Tennessee. *Transportation Research Interdisciplinary Perspectives*, *15*, 100650. https://doi.org/https://doi.org/10.1016/j.trip.2022.100650

White, M. J. (2004). The "arms race" on American roads: the effect of sport utility vehicles and pickup trucks on traffic safety. *The Journal of Law and Economics*, *47*(2), 333-355.

Williams, R. (2006). Generalized ordered logit/partial proportional odds models for ordinal dependent variables. *The stata journal*, *6*(1), 58-82.

Xu, J., Li, Y., Lu, G., & Zhou, W. (2009). Reconstruction model of vehicle impact speed in pedestrian–vehicle accident. *International Journal of Impact Engineering*, *36*(6), 783-788. https://doi.org/https://doi.org/10.1016/j.ijimpeng.2008.11.008

Zahabi, S. A. H., Strauss, J., Manaugh, K., & Miranda-Moreno, L. F. (2011). Estimating potential effect of speed limits, built environment, and other factors on severity of pedestrian and cyclist injuries in crashes. *Transportation Research Record*, *2247*(1), 81-90.