U.S. Department
of Transportation
**National Highway
Traffic Safety
Administration**

NHTSA

DOT HS 813 676a

March 2025 (Revised)

Review of Literature Addressing Pedestrian Injury Risk and Motor Vehicle Characteristics

Task 1

DISCLAIMER

NOTE: This report is published in the interest of advancing motor vehicle safety research. While the report may provide results from research or tests using specifically identified motor vehicle models, it is not intended to make conclusions about the safety performance or safety compliance of those motor vehicles, and no such conclusions should be drawn.

Suggested APA Format Citation:

Frazier, H., Roulett, M., & McQuistion, I. (2025, March, Revised). *Review of literature addressing pedestrian injury risk and motor vehicle characteristics* (Task 1. Report No. DOT HS 813 676a). National Highway Traffic Safety Administration.

Two additional reports in this series are:

Frazier, H., & Flanders, I. (2025, March, Revised). *Review of literature addressing effects of pedestrian safety-related test requirements on vehicle design, fleet composition, and pedestrian injury* (Task 2. Report No. DOT HS 813 676b). National Highway Traffic Safety Administration.

McQuistion, I., & Flanders, I. (2025, March, Revised). *Review of literature addressing pedestrian injury risk and motor vehicle characteristics* (Task 3. Report No. DOT HS 813 676c). National Highway Traffic Safety Administration.

Technical Report Documentation Page

1. Report No.
DOT HS 813 676a

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Review of Literature Addressing Pedestrian Injury Risk and Motor Vehicle Characteristics

5. Report Date
March 2025 (Revised)

6. Performing Organization Code

7. Authors
Heather Frazier, Margaret Roulett, Ian McQuistion

8. Performing Organization Report No.

9. Performing Organization Name and Address
Federal Research Division
Library of Congress
101 Independence Ave SE
John Adams Building, LA 5281
Washington, DC 20540-4840

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Highway Traffic Safety Administration
1200 New Jersey Avenue SE
Washington, DC 20590

13. Type of Report and Period Covered
Task 1

14. Sponsoring Agency Code

15. Supplementary Notes
This report was prepared by the Federal Research Division, Library of Congress, under an Interagency Agreement with NHTSA. Whitney Tatem was the contracting officer representative on this project.

16. Abstract

NHTSA seeks to understand relationships between vehicle size and weight on pedestrian injuries and fatalities. To do so NHTSA engaged the Library of Congress' Federal Research Division to identify and evaluate literature on pedestrian injury in relation to vehicle size and weight. In Task 2, the review team examined domestical and international English-language studies from 2011 to the present [date of submission] that address the effects of national- and regional-level requirements for pedestrian safety features on passenger vehicle design, fleet composition, and pedestrian injury. It focused on sources discussing the effects of vehicle design, particularly hood design, on pedestrian injury outcomes; and test requirements and regulations affecting vehicle design, fleet composition, and pedestrian safety. The review team focused on studies that discussed the real-world effects of pedestrian safety-related regulations, and other consumer vehicle test protocols, such as those outlined in the European New Car Assessment Programme (Euro NCAP) and the Japan New Car Assessment Program (Japan NCAP). The review team located a body of academic literature that broadly discussed the effects of vehicle size, as well as specific vehicle components, on pedestrian injuries, including sources on head, chest, and lower extremity injuries. However, the review team located fewer scholarly sources discussing the real-world impacts of pedestrian testing protocols, including those outlined in Euro NCAP and Japan NCAP. The few academic sources on this subject nonetheless largely agreed that pedestrian safety outcomes improved following the implementation of vehicle testing protocols. The review team divided results from the literature review into five main sections: (1) vehicle size and related design changes; (2) thoracic injuries and testing requirements; (3) lower leg injuries and high ground clearance vehicles; (4) hood design and pedestrian kinematics; and (5) testing requirements, injury patterns, and fleet composition.

17. Key Words
LTV, SUV, pickup, pedestrian fatalities, vehicle size, vehicle weight

18. Distribution Statement
Document is available to the public from the DOT, BTS, National Transportation Library, Repository & Open Science Access Portal, https://rosap.ntl.bts.gov.

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
55

22. Price

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

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List of Abbreviations

AEB	automatic emergency braking
AIS	Abbreviated Injury Scale
ANOVA	analysis of variance
CAR	crash analysis reporting
CDMBS	collision damage mitigation braking systems
CIREN	Crash Injury Research and Engineering Network
COG	center of gravity
CRIS	Crash Records Information System
CRSS	Crash Report Sampling System
DAI	diffuse axonal injury
Euro NCAP	European New Car Assessment Programme
FARS	Fatality Analysis Reporting System
FDOT	Florida Department of Transportation
FE	finite element
F/I	fatal or incapacitating
FRD	Federal Research Division
GES	General Estimates System
GHSA	Governors Highway Safety Administration
GIDAS	German In-Depth Accident Study
GIS	geographic information ystem
GTR	Global Technical Regulation
GVWR	Gross vehicle weight rating
HALL	human active lower limb
HIC	head injury criterion
HOP	heteroskedastic ordered probit
HSIS	Highway Safety Information System
ITARDA	(Japanese) Institute for Traffic Accident Research and Data Analysis
JARI	Japan Automobile Research Institute
KSI	silled or seriously injured
LC	Library of Congress
LR	likelihood ratio
LTV	light trucks and vans
ML	mixed logit

MNL	multinomial logit
MPV	multi-purpose vehicle
NB	negative binomial
NCAC	National Crash Analysis Center
NCDOT	North Carolina Department of Transportation
PCDS	Pedestrian Crash Data Study
PMHS	post-mortem human subjects
PDO	property-damage-only
PPO	partial proportional odds
RCI	road characteristics inventory
RITIS	Regional Integrated Transportation Information System
SWITRS	Statewide Integrated Traffic Records System
TAZ	trraffic analysis zone
THUMS	total human model for safety
TxDOT	Texas Department of Transportation
VOIESUR	Vehicle Occupant Infrastructure Road User Safety Study
VRU	vulnerable road user
WIC	weighted injury cost
WUV	work utility vehicle

Executive Summary

As part of its mission to promote pedestrian safety, the National Highway Traffic Safety Administration seeks to understand relationships between vehicle size and weight and pedestrian injuries and fatalities. NHTSA is interested in research that (1) identifies key vehicle crash data sources; (2) supports the agency's policy decisions; and (3) identifies market trends in changes to vehicle design that may impact pedestrian safety, including market trends in the United States and internationally.

NHTSA contracted with the Library of Congress Federal Research Division to identify and evaluate literature on pedestrian injury and vehicle size and weight published over the past 10 years. This report details the review team's findings in literature on whether larger light vehicles, such as vans, pickups, and SUVs, which NHTSA often labels as light trucks and vans, may be more dangerous to pedestrians on impact than smaller vehicles, which are typically represented by smaller passenger cars. The review team located 79 scholarly sources published from 2011 to 2022 relevant to whether larger light vehicles are more injurious to pedestrians than smaller passenger cars. The sources include 52 peer-reviewed articles; 7 nonprofit-, university-, or government-sponsored technical reports; and 20 conference proceedings papers.

This report details the review team's synthesis of numerous domestic and international English-language sources. Overall, the review team found that many U.S. scholarly sources supported the hypothesis that LTVs cause higher levels of injury severity to pedestrians than smaller passenger cars in collisions. However, international English language-sources reported more mixed results, potentially due at least in part to vehicle markets trends that skew in favor of more SUVs that are compact, and fewer pickup trucks.

The review team organized the literature review into five primary study areas: (1) general pedestrian collision research methodology; (2) pedestrian collision research methodology with a medical focus; (3) vehicle size/weight/body type studies; (4) vehicle hood/front end profile studies; and (5) pedestrian collision avoidance/mitigation systems.

The review team examined all 79 studies. A full annotated bibliography is attached that synthesizes sources according to geographical region, data sources, methodologies, and study results. There were several findings in the literature (footnotes pointing to representative studies).

- Studies based on U.S. national data suggest that while passenger cars incur the greatest percentage of pedestrian fatalities, percentages of SUV–pedestrian fatalities were increasing at a faster rate (Retting, 2019, 2020, 2021; Macek & Petraglia, 2022; Schneider, 2020; Hu & Cicchino, 2018). However, since 2012, SUV production has been increasing, and passenger car production has been decreasing as percentages of all vehicles produced (U.S. Environmental Protection Agency, 2023).
- A study based on U.S. national data suggests that SUVs' greater power-to-weight ratios relative to small passenger cars might render them more injurious to pedestrians in collisions (Hu & Cicchino, 2018).
- A recent study on U.S. national data on pedestrian fatalities and North Carolina State-level data suggests that the dimensions of LTVs are more dangerous to pedestrians than the dimensions of passenger cars, due in part to poor visibility (Harmon et al., 2021).

- One study suggests that children and older pedestrians suffer more severe outcomes when struck by an LTV versus other smaller vehicle classes (Edwards & Leonard, 2022).
- Findings in another study suggest that vehicles with frontal guards are more injurious than vehicles without frontal guards in collisions with child pedestrians (Moradi & Lankarani, 2011).
- Results from some studies suggest that vehicle front end design, including dimensions such as hood leading edge height and hood length, are influential to pedestrian injury outcomes in the event of a collision (Li et al., 2017).

This report details the key research questions and themes the review team considered while evaluating the literature, as well as the search methodologies used, including search terms employed, and search results. Finally, sections 4 to 8 synthesize the sources according to study area and, where relevant, include sub-sections dividing sources by geographical region.

Overview

While pedestrian fatality rates declined steadily from 1977 to 2009, they increased from 2009 to 2020 (Schneider, 2020; Retting, 2019, 2020, 2021). NHTSA reported that in 2021 there were 7,388 pedestrians killed in traffic crashes, a 12.5 percent increase from pedestrian fatalities in 2020. This was the highest year-over-year increase since 1981, and initial NHTSA projections for the first 9 months of 2022 have estimated that pedestrian fatalities continue to increase by approximately 2 percent. The Governors Highway Safety Administration analyzes data from State Highway Safety Offices in all 50 States and the District of Columbia. The organization ascribed this increase in pedestrian deaths to infrastructure-related factors and driver behavior, such as speeding. In addition to infrastructure and driver behavior, GHSA also noted changes in the types of vehicles killing pedestrians, observing that although drivers of passenger cars have consistently accounted for the greatest number of pedestrian fatalities, over the decade 2010 to 2020, the percentage of SUVs involved in fatal pedestrian–vehicle collisions was increasing at a faster rate (GHSA, 2022; NHTSA, 2023). According to 2020 Fatality Analysis Reporting System data, light trucks and cars caused a nearly equal number of pedestrian fatalities (NCSA, 2022).

In response to increases in pedestrian injury and fatality, NHTSA is interested in research on whether larger light vehicles, such as SUVs, vans, and pickup trucks, are more injurious to pedestrians in collisions than smaller light vehicles, such as passenger cars. While scanning the available research, the research team also considered the following related research questions.

- How do pedestrian injury and fatality trends related to vehicle design differ in U.S. vehicle markets versus international vehicle markets?
- How does vehicle design interact with geographical and roadway features in pedestrian–vehicle collisions (e.g., urban versus rural, non-intersection versus intersection collisions)?
- What other structural features might render light truck vehicles more dangerous than passenger cars?
- What existing literature suggests that the front-end designs of SUVs, pickup trucks, and vans render those vehicles more dangerous than passenger cars?
- Are large light vehicles more dangerous for some pedestrian demographics than others (e.g., more dangerous for older pedestrians or child pedestrians)?

The review team located seventy-nine sources with information pertinent to one or more of the above questions, including simulation studies examining the impacts of vehicle front-end design on pedestrian injury severity and studies using real-life collision data to analyze the effects of vehicle characteristics on pedestrian safety.

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Methodology

The review team compiled the following literature review as both a report and an annotated bibliography spreadsheet. The spreadsheet complimentary to this report is provided as Attachment A. The review organized this report according to the study areas identified in the spreadsheet, and synthesized sources according to geographical region, study results, methodologies, data sources, and other relevant categories outlined in the annotated bibliography.

In compiling sources as part of the literature scan, the review team first searched Library of Congress-hosted electronic databases, including Academic Search Complete (EBSCO), ABI, Business Source Complete, Emerald (Insight), Compendex (Engineering Village), JSTOR, and Science Database (ProQuest) for peer-reviewed articles and academic journals published during the period 2011–23. This year range is congruent with the present-day model year make-up of light vehicles in the U.S. fleet. It also reflects the most current research in the field while covering a long enough time period to capure a reasonable number of studies. It is notable that some vehicle technologies discussed, especially crash mitigation/avoidance systems, have advanced significantly since the 2010's, so those results should be considered accordingly.

The review team concurrently searched the LC online catalog for relevant sources. Boolean search criteria included variations of the following terms.

- Pedestrian
- Pedestrian accidents
- Pedestrian crash
- Injury
- Trauma
- LTV
- SUV
- Pickup
- Safety
- Fatality
- Vehicle
- Vehicle type
- Vehicle size
- Vehicle body type
- Vehicle class
- Vehicle weight
- Vehicle curb weight
- Vehicle GVWR

The peer-reviewed academic journals found to be relevant to this research effort included these:

- Accident Analysis and Prevention
- Annals of Advances in Automotive Medicine
- Archives of Civil and Mechanical Engineering
- European Transport Research Review
- International Journal of Automotive Technology
- International Journal of Crashworthiness
- International Journal of Injury Control and Safety Promotion

- International Journal of Sustainable Transportation
- International Journal of Vehicle Safety
- Journal of Automobile Engineering, Journal of Safety Research
- Journal of Transportation Safety & Security
- SAE International Journal of Transportation Safety
- Stapp Car Crash Journal
- Traffic Injury Prevention
- Transportation Research Record

In addition to searching LC-hosted databases, the review team also searched the U.S. Department of Transportation website and several State-level Department of Transportation websites to locate government-sponsored reports. University-sponsored studies and nonprofit reports were located mainly by searching the institutions' websites.

The team's searches yielded 79 sources relevant to researching whether larger passenger vehicles are more dangerous to pedestrians than smaller passenger vehicles. The review team then divided these sources into five main categories based on key study areas emerging from the literature: (1) general pedestrian collision research methodology; (2) pedestrian research methodology with a medical focus; (3) vehicle size/weight/body type studies; (4) vehicle hood/front end profile studies; and (5) pedestrian collision avoidance/mitigation system studies. As showed in the literature review below, one study by Cai, Xia, and Huang (Cai et al., 2020) falls into two categories, and the review team has therefore incorporated a hybrid subcategory, medical/vehicle hood/front-end studies, for this source.

The largest portion of the studies incorporated a general pedestrian collision research methodology that considered factors besides vehicle design or vehicle body type while evaluating trends in pedestrian injury incidence and severity. The review team further divided this category into "All-factors studies," which took a comprehensive approach to examining the pedestrian demographics, environmental characteristics, and vehicle characteristics influencing injury severity. Other subcategories incorporated vehicle body type as a variable, but included other factors as main emphases, including "Roadway/geographical/environmental focus studies," "Time focus studies," and "Pedestrian focus studies." The category with the second highest number of studies included international and domestic English-language studies on vehicle hoods and front-end profiles, sub-divided into "General front-end focus studies," "Front-end studies examining frontal guards," "Front-end studies examining ground impact effects," and "Front-end studies examining pedestrian gait/stance effects."

Finally, most sources used either one of two overarching research approaches – either analysis based on real-world data or analysis based on computational simulations. A handful of studies used a combination of both methods. The larger cross-section of scientific methods that appear in this report provide a robust view of the collective results where any limitations associated with a particular research method do not govern overall findings.

General Pedestrian Collision Research Methodology

The review team located 38 studies taking comprehensive approaches to pedestrian safety research. The following section is divided into four research themes; (1) all-factors studies; (2) roadway/geographical/environmental focus studies; (3) time-of-day focus studies; and (4) pedestrian focus studies. The largest subcategory, all-factors studies, includes studies that use real-world collision data to examine the effects of vehicle characteristics, pedestrian demographics, and environmental characteristics on pedestrian injury. The second largest subcategory, roadway/geographical/environmental focus studies, are studies on the effects of roadway, geographical, or other environmental features on pedestrian injury, as well as their relationships with other significant factors, including vehicle characteristics. Due to the large number of sources in these subcategories, both subcategories are further divided according to geographical region.

The fourth subcategory, pedestrian focus studies, considers pedestrian characteristics and kinematics during collision in relation to other characteristics, including vehicle body type, and unlike other subcategories in this section, incorporates simulation data. Within the pedestrian focus subcategory, there was one study that was time-focused, analyzing crash/pedestrian characteristics significant to nighttime collisions.

All-Factors Studies

In total, researchers identified 22 sources examining a comprehensive range of factors affecting pedestrian injury severity levels, such as vehicle characteristics, roadway characteristics, pedestrian characteristics, and driver characteristics. While some authors used U.S. national data, including FARS, to examine pedestrian injury trends, many U.S. studies applied State-level data to study trends in pedestrian injury incidence and severity. Additionally, the review team located 7 international English-language sources discussing the pedestrian, vehicle, and environmental variables affecting pedestrian safety.

U.S. national studies focused on how changes in vehicle fleet composition influenced rising pedestrian fatality rates. The U.S. State studies focused on pedestrian injuries, crashes, anon-roadway crashes, and crashes with children. International English-language sources reported results that were more mixed regarding vehicle body types and weight, potentially due in part to differences in vehicle classifications between U.S. and international vehicle markets.

U.S. National Studies

In the United States the passenger vehicle market has shifted towards larger vehicles over the past couple of decades, especially large SUVs and pickup trucks. This trend can clearly be seen when looking at both production share of new vehicles and vehicle registration data (Tyndall, 2021). Studies incorporating U.S. national data on pedestrian crashes generally placed emphasis on how changes in vehicle fleet composition influenced rising fatality rates, though this was not always analytically accounted for. Many U.S. national studies taking a comprehensive approach to studying characteristics associated with pedestrian fatality or injury risk were sponsored by government agencies, with four studies sponsored by the GHSA.

Since 2014 the GHSA has released annual reports on pedestrian fatality trends in U.S. States, including trends in location, light condition, and driver’s alcohol and drug impairment. In 2019

GHSA also began examining the significance of vehicle type for pedestrian fatality, with a specific focus on the increased sales of SUVs, as well as their increased influence on pedestrian fatality trends. GHSA's *Pedestrian Traffic Fatalities by State, 2023 Preliminary Data* report examined the most recent national pedestrian fatality data available from FARS (calendar year 2022) in addition to preliminary State data. The national analysis of FARS found that the highest percentage of fatalities of all singular vehicle categories involved passenger cars (~40%) in 2022. When collectively considering "light trucks," these vehicles were involved in more than half (51.9%) of all pedestrian fatalities in 2022 – 29.3 percent SUVs, 18.2 percent pickup trucks, and 4.4 percent vans. Further, pedestrian–light truck collision fatalities increased at a faster rate from 2012 to 2022 than pedestrian–passenger car fatalities. The number of pedestrian fatalities involving light trucks increased by 76.7 percent since 2012, while those involving passenger cars increased by 24.9 percent. Vehicle sales and lease data provided in the report show that the integration of light trucks into the U.S. vehicle fleet continues to outpace that of passenger cars, which may contribute to the observed difference in elevating fatality rates.

Similarly, Schneider (2020) used FARS data to analyze long-term trends in U.S. pedestrian fatalities from 1977 to 2016, finding that fatality rates decreased until 2009, and increased from 2009 to 2016. Between the 5-year increments 1982–to-86 and 2012–to-16, the percentage of pedestrian fatalities involving SUVs, vans, and trucks increased from 22 percent to 44 percent. While this finding was statistically significant, it is discussed that this trend coincides with growth in the overall vehicle fleet, especially within the SUV, pickup truck, and van categories (Schneider, 2020; McGuckin & Fucci, 2018).

Hu and Cicchino (2018) also examined changes in U.S. pedestrian fatality trends considering associated environmental, pedestrian, and vehicle characteristics. They used 2009–to-16 FARS data and 2009–to-15 GES data to obtain crash statistics on vehicle classification, model, and weight. Additionally, they collected 2009–to-2016 data from the U.S. Census Bureau to obtain population data for age and sex to estimate per capita death rates. The review team found that the most significant increases in pedestrian fatality rates during the study period "occurred in urban areas (54% increase from 2009–2016), on arterials (67% increase), at nonintersections (50% increase), and in dark conditions (56% increase)." Study results also showed significant changes in fatality trends according to vehicle body type, finding that SUV-pedestrian fatalities increased at a higher rate than increases for other vehicle types examined. Hu and Cicchino noted that this trend is also likely associated with shifts in the U.S. passenger vehicle market toward vehicles with greater power-to weight ratios, which allows the drivers of such vehicles to drive at higher speeds.

State-Level Studies

Most detailed pedestrian safety research studies produced in the Unites States from 2011 to 2022 focused on State-level data. However, State-level studies from this period were not distributed evenly across different regions of the country, as authors examining this topic from 2011 to 2022 used data from North Carolina, Illinois, Colorado, and Indiana. North Carolina was overrepresented in the studies under this category, with Li and Fan (2018, 2020a, 2018/2020b) producing three of the four studies covering the State. Despite the overrepresentation of North Carolina data, overall, the State-level studies echoed the results of the national studies, as several studies in this category found that SUVs and other light truck vehicles have been involved in increased rates of severe pedestrian injuries and fatalities relative to smaller passenger vehicles.

For example, Harmon et al. (2021) used linked North Carolina hospital and crash data in 2010 to 15 to examine factors influencing roadway and non-roadway pedestrian collisions, with dual focus on both crash frequency and pedestrian injury severity levels on impact. The study found that while passenger cars were involved in pedestrian roadway crashes at higher rates than SUVs and pickup trucks, SUVs and pickup trucks were slightly more likely to cause severe injury or fatality to the pedestrain. SUVs caused serious injuries or fatalities in 41 percent of cases and pickup trucks caused serious injuries or fatalities in 43 percent of cases, as opposed to passenger cars, which caused serious injuries or fatalities in 37 percent of cases. Passenger cars were significantly more likely than SUVs and pickup trucks to cause lower extremity injuries (50% versus 43% and 41%), while SUVs and pickup trucks were significantly more likely to cause torso injuries than passenger cars (22% and 25%, versus 19%). In this study, all vehicle types were equally likely to yield pedestrian head injury.

In addition to roadway crashes, the study also examined factors associated with pedestrian injury severity in non-roadway (parking lot, private driveway, etc.) collisions. In non-roadway crashes, SUVs were 41 percent more likely and pickup trucks were 97 percent more likely to cause serious pedestrian injury than passenger cars.

Li and Fan (2018, 2020a, 2018/2020b) also analyzed North Carolina State-level data to identify variables associated with injury severity levels in pedestrian-vehicle collisions. In 2020 they used a mixed logit (ML) model and direct pseudo-elasticity calculations to identify relevant collision characteristics, as well as heterogeneities across specific factors associated with pedestrian injury. The study found that from 2007 to 2014, larger and heavier vehicle types compared to smaller and lighter vehicle types increased the risk of pedestrian fatality in pedestrian–vehicle collisions, with vans increasing the likelihood of pedestrian fatalities by 75.3 percent, pickup trucks by 80.7 percent, and SUVs by 22.1 percent. Li and Fan (2020b) examined factors associated with pedestrian injury severity in North Carolina vehicle–pedestrian crashes from the same years, 2007 to 2014. The study used three models, a multinomial logit model, mixed logit model, and partial proportional odds model, to identify variables associated with pedestrian injury. Results from the PPO model also showed that SUVs and pickup trucks from the same dataset carried greater likelihood of pedestrian fatality compared to smaller and lighter vehicle types. Li and Fan's 2018 study used latent class clustering and a PPO model to examine the same 2007–14 dataset to find that heavy commercial vehicles had higher likelihood of a pedestrian incurring an incapacitating injury or fatality than other vehicle classifications in most latent classes.

Edwards and Leonard (2022) analyzed the influence of factors including roadway characteristics, pedestrian and pedalcyclist age and race, and vehicle type on crash frequency and pedestrian and pedalcycylist injury severity levels in collisions. The study used linked Illinois hospital and crash data from 2016 to 2018 to show that SUVs and pickup trucks were overrepresented in fatalities relative to the proportion of their involvement in all crashes. SUVs were involved in 14.7 percent of the pedestrian and pedal-cyclist cases included in the study, while pickup trucks were involved in 5.6 percent. When narrowing to fatalities, SUVs were involved in 25.4 percent of cases and pickup trucks were involved in 12.6 percent of cases. When considering pedestrians and pedalcyclists under age 18, together, SUVs, pickup trucks, and vans/minivans were involved in 28.9 percent of cases (with most remaining cases attributable to passenger cars), but the SUVs, pickup trucks, and vans/minivans are again largely overrepresented in fatality outcome for this young age group, accounting for almost two-thirds (65.6%) of fatalities. While these findings provided Illinois State-level information on what environmental, pedestrian, and vehicle characteristics influenced pedestrian and pedalcyclist injury, the source did not divide findings according to vulnerable road user type. Therefore, although the above figures provide useful context for vulnerable-road-user injury in Illinois, they cannot substitute for dedicated data on pedestrian injury.

Pour-Rouholamin and Zhou (2016), on the other hand, studied factors associated exclusively with pedestrian injury severity levels in Illinois collisions during earlier years, 2010 to 2013. They used ordered-response models to determine that compared to passenger cars, pickups, SUVs, and buses increased likelihood of severe pedestrian injury by 12.3 percent, 8.6 percent, and 22.9 percent, in that order.

Batouli et al. (2020) examined Colorado crash data from 2006 to 2016 to find that overall, pickup trucks, utility vans, and SUVs are more strongly associated with pedestrian fatalities than passenger cars and vans. The study examined both crash frequency and fatality levels in collisions. From 2006 to 2016 the percentages of SUV-pedestrian collisions increased from 10.6 percent to 25.2 percent, and the percentage of SUV involvement in fatal collisions increased from 8.7 percent to 32.2 percent. Additionally, the study segmented the data into two periods from 2006 to 2010 and 2011 to 2016, finding that SUV-pedestrian fatalities increased from 15.9 percent in the 2006 to 2010 period to 25.5 percent in the 2011 to 201616 period. When compared to passenger cars and vans, fatalities involving SUVs had higher odds ratios for the 2011-to-2016 timeframe (1.78) than the entire period of study from 2006 to 2016 (1.59).

Tarko and Azam (2011) used 9,453 Indiana crash records, and 4,822 linked crash and hospital records from 2003 to 2008 to analyze variables associated with pedestrian injury severity levels in collisions. They applied a bivariate ordered probit model to the unlinked and linked data to examine factors associated with injury severity and help eliminate selection bias. The bivariate model showed that heavy vehicles, such as trucks and buses, were more likely to cause severe pedestrian injury than medium vehicles and passenger cars. Large light vehicles, such as vans, pickups, and SUVs, were in turn more likely to cause severe injury than smaller passenger vehicles.

International Studies

Seven international peer-reviewed articles from 2011 to 2022 addressed a range of factors associated with pedestrian injury, including vehicle characteristics, such as vehicle size, weight, and body type, pedestrian demographics, and environmental characteristics. Although many of these studies have limited applicability to the specific issue of vehicle size, as they included different vehicle classifications than U.S. market vehicle classifications, they nonetheless provide a global context for research on the effects of vehicle size and weight on pedestrian safety during collisions. The seven studies analyzed data from Australia, Canada, France, Germany, Japan, and South Korea.

For example, Nasri et al.'s (2022) recent peer-reviewed study on pedestrian safety in Victoria, Australia, illustrates the difficulties of extrapolating results from international studies addressing vehicle design to pedestrian safety in the Unites States. They used an unordered multinomial logit model and an ordered logit model to analyze characteristics associated with pedestrian injury severity levels in collisions from 2010 to 2019. The study examined the effects of both vehicle type and age on injury severity. The ordinal logistic regression model showed that, compared to cars, pedestrian collisions with heavy vehicles, light commercial vehicles, trams, and buses/minibuses/coaches increased the probability of more severe injuries to the pedestrian. The multinomial logit model also found that those same vehicle categories carried greater likelihood of severe pedestrian injury and fatality. Both the ordinal logistic regression model and the multinomial logit model showed that passenger cars were more likely to result in greater injury severity than station wagons and SUVs. However, this finding does not directly correlate with U.S. vehicle classifications, as the Australian vehicle market categorizes station wagons and SUVs as belonging in the same vehicle class (Federal Chamber of Automotive Industries, 2023). In addition to vehicle size, the Nasri et al. 2022 study also considered vehicle age, finding that likelihood of severe injury was lower in collisions with vehicles less than twenty years old than in collisions with vehicles twenty years and older.

Plonka et al.'s (2021) study on pedestrian fatalities in Ontario, Canada, found that pedestrian collisions with light trucks, including SUVs and pickup trucks, but excluding passenger vans, were more likely to result in fatal injuries than passenger cars. Based on Ontario aggregate data from 2012 to 2016, about 3.3 percent of all pedestrian injury collisions involving light trucks resulted in a fatality, whereas for pedestrian injury collisions involving a passenger car, 2.1 percent resulted in fatalities. They examined pedestrian fatality considering both crash frequency and fatality rates on impact. They ascribed the discrepancy in fatality rates to differences in vehicle front-end shape, which resulted in greater impact force for SUVs, as well as greater vehicle height, which resulted in greater risk of thoracic injury. The study used Ontario crash data from 2002 to 2016 to develop a Poisson regression model identifying changes in pedestrian fatality rates during the study period, as well as a Bayes theorem and joint logistic regression to analyze the likelihood of fatalities for pedestrians 75 and older continuing to increase in the future. Additionally, they used joint logistic regression to examine whether the increased proportion of pedestrian fatalities caused by light trucks was primarily a result of more light trucks being on the road. They concluded that increases in the number of registered light trucks account for increases in the rates of pedestrians killed in collisions with light trucks.

Martin et al. (2011) also identified characteristics associated with pedestrian injury severity in collisions, particularly factors related to vehicle front-end geometry and injured body region. They estimated pedestrian fatality rates using French national police reports from 1996 to 2007, and linked fatality rates with pedestrian injury data from the Rhône Road Trauma Registry to identify the front-end profiles of involved vehicles. The study used statistical tables and logistic regression to identify relevant characteristics related to pedestrian age, gender, and vehicle type. Study results showed that pedestrians struck by multipurpose vehicles with sloped hoods were more likely to suffer fatalities than pedestrians struck by other vehicle types. By injured body region, MPVs were also significantly more likely to incur moderate or more severe (AIS 2+) thoracic injuries than cars with "medium-length" hoods or small family cars. Analysis of medical data from the Rhône Road Trauma Registry showed that lower extremity injuries constituted the most common injury type, but head and thoracic injuries had the highest rates of severe injury values (AIS 4+).

Similarly, Saadé et al. examined injured body type, as well as other factors, in a 2020 conference paper[*] about pedestrian injury severity levels and injured body regions in French pedestrian–

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[*] The International Research Council on the Biomechanics of Injury planned to hold its annual conference in Munich, Germany, but postponed it to 2021 due to the COVID-19 pandemic.

vehicle collisions. Saadé et al. used the Vehicle Occupant Infrastructure Road User Safety Study (VOIESUR), which includes more than 8,500 crash reports from 2011, weighted to be representative of all 2011 reported vehicle crashes causing injuries. They limited their data selection to crashes between pedestrians and the front ends of passenger vehicles. The study examined seven injured body regions—the pelvis, femur, knee, tibia, fibula, ankle/foot, and "other" body region—and set an additional criterion for lower extremity injuries as exclusively including at least moderate (AIS 2+) and serious (AIS 3+) injuries. Saadé et al. then used multivariate logistic regression to examine injured body region in relation to vehicle speed, first impact location on the vehicle, vehicle model year, hood leading edge height, pedestrian direction prior to collision, and pedestrian age. Study results showed that most AIS 2+ and AIS 3+ injuries were lower extremity injuries. The head received the second highest number of AIS 2+ and AIS 3+ injuries. Pedestrians had a higher risk of fatality if they struck the outside of the vehicle front-end, rather than the center. Although vehicle model year was not associated with injury severity, higher hood leading edges (here defined as a hood leading edge height greater than or equal to 835 mm) were associated with a "significantly higher risk" of pedestrian fatality, but not a significantly higher risk of a "[hospitalization] or death" (KSI) outcome.

Staack and Labenski (2022) focused specifically on thoracic injuries in VRU collisions in Germany. The study examined June 2021 data from the German In-Depth Accident Study. They found that overall, thoracic injuries were most often associated with collision velocities greater than 45 kph (approximately 28 mph). In terms of vehicle design, three of the four front ends studied—passenger cars, SUVs/pickups, and MPVs—demonstrated similar numbers of moderate (AIS 2+) and serious (AIS 3+) injuries. However, vans demonstrated significantly higher rates of such injuries, although study authors noted that overall van sample numbers were low.

Only two articles from the study period took comprehensive approaches to identifying factors associated with pedestrian injury severity levels in East Asia. Oikawa and Matsui (2016/2017) examined factors influencing pedestrian injury in Japan in 1999 and 2009, with a special focus on injured body regions, vehicle type, crash year, gender, and age. The study used statistical comparisons to identify the effects of vehicle type on body region injured, finding that crashes in both 1999 and 2009 "passenger car types," including sedans, mini vans, and light passenger cars, were more likely to injure pedestrians' legs, while "van types," including box vans and light cargo vans, were more likely to injure pedestrians' heads. They concluded that this difference in injured body region is due to differences in vehicle geometry, as the front panels and bumpers of box vans and light cargo vans struck both the head and legs at the same time, with lower loading forces affecting pedestrians' legs in van collisions than in passenger car collisions. The study also considered the effects of pedestrian gender and age on the body region injured and injury severity, finding that women were more likely than men to be seriously injured for all vehicle types studied.

Tay et al. (2011) examined Korean National Police Agency data from 2006 to identify the vehicle characteristics, pedestrian and driver characteristics, and environmental characteristics associated with serious and fatal pedestrian injury in collisions. The study used a multinomial logit model to estimate the effects of each variable on pedestrian injury severity, finding that vehicles such as vans, trucks, and special vehicles were more likely to be involved in crashes with serious and fatal pedestrian injuries. However, the study did not specify whether the truck cases fell into light or heavy vehicle classifications.

Roadway/Geographical/Environmental Focus Studies

The review team located several domestic and international English-language studies on roadway, geographical, and other environmental characteristics relevant to whether larger light passenger vehicles cause higher levels of pedestrian injury severity than lighter passenger cars during pedestrian–vehicle collisions. Several studies analyzed the mediation of crash location, such as roadway features and land use, on other factors affecting pedestrian injury, including vehicle body type.

U.S. National Studies

Although several studies using real-world crash data focused on roadway, geographical, and other environmental characteristics, only one study in this category used U.S. national crash data to examine pedestrian injury. Ammar et al. (2022) used 2013–to-2015 General Estimates System data and 2016–to-2018 Crash Report Sampling System data to analyze pedestrian injury characteristics at intersection collisions. Ammar et al. developed two logistic regression models to identify factors associated with injury severity, constructing one model for serious and fatal injury and one model for not serious or fatal injury. The study found that both light trucks and buses carried higher risk of causing pedestrian fatality than passenger cars. Results differed for light trucks and bus vehicle types between the GES and CRSS models. The 2013–to-2015 GES data showed that light trucks, rather than buses, were significant for pedestrian fatality at intersections, while the 2016–to-2018 CRSS data showed that buses, rather than light trucks, were significant for pedestrian fatality.

State- and City-Level Studies

Eight U.S. studies used State- or city-level data to examine the roadway, geographical, and other environmental characteristics influencing pedestrian injury in pedestrian–vehicle collisions. Like the detailed State-level pedestrian safety studies outlined above, the State-level studies with environmental emphases included several studies making use of North Carolina data. Most recently, Qiu and Fan (2022) examined North Carolina police crash data from 2007 to 2016 to analyze variables influencing pedestrian injury severity levels in non-intersection and intersectioe crashes. They first compared an MNL model to an ML model with a likelihood ratio test to determine best model fit. After determining that the ML model performed better, Qiu and Fan applied the ML model to identify factors associated with pedestrian injury, as well as direct pseudo-elasticity analysis to examine how the identified factors affect injury outcome probabilities. Results showed that SUVs were more likely than passenger cars to cause pedestrian fatality in both intersection and non-intersection crashes, at 68 percent and 55 percent. Pickups were 194 percent more likely than passenger cars to cause pedestrian fatality in intersection crashes. Vans were 60 percent more likely than passenger cars to cause fatality in non-intersection crashes.

Two additional North Carolina studies examined pedestrian injury in relation to specific geographical regions as well as related vehicle characteristics. Song et al. (2020/2021) identified crash “hot spots” associated with greater crash frequency in North Carolina, as well as other factors influencing pedestrian injury severity levels in collisions, such as pedestrian and vehicle characteristics. Study data included North Carolina Department of Transportation information on 33,707 pedestrian–vehicle collisions from 2007 to 2018. The study used the Getis-Ord Gi index, the Mann-Kendall test, average nearest neighbor tests, and a spatial autocorrelation test to examine spatiotemporal trends for "hot" and "cold spots" in pedestrian injury. Additionally, they divided the datasets into four latent classes representing different combinations of land use and roadway characteristics to observe heterogeneities within the datasets. The authors then developed four random parameter logit models to correspond to the latent classes. Results showed that large light vehicles and heavy vehicles have greater probability of fatal or incapacitating pedestrian injury than small vehicles.

Liu et al. (2019) developed a geographically and temporally weighted ordinal logistic regression (GTWOLR) model to examine factors influencing pedestrian injury severity levels according to specific times and locations in North Carolina collisions. They used data from an NCDOT database documenting pedestrian–vehicle collisions in 2007 to 2014. Results demonstrated that some factors were associated with higher pedestrian injury severity regardless of space and time-related factors, including involvement of SUVs, heavy vehicles, pedestrian impairment, and nighttime collisions without streetlighting. Model results also suggested some vehicle body types had greater effects on injury severity levels in certain geographical regions and found that the effects of pickup trucks on more severe injuries were especially pronounced between the Triangle Area, Fayetteville, and Wilmington.

Haleem et al.'s (2015) study on crashes in intersections with and without traffic signals also examined variables influencing pedestrian injury severity levels in intersection collisions. They used Florida Department of Transportation Crash Analysis Reporting data from 2008 to 2010, as well as environmental characteristics from FDOT's Roadway Characteristics Inventory, to develop two separate mixed logit models for collisions at intersections with and without signals. The mixed logit model for intersections without signals showed that vans were "associated with 0.38 [percent] increase in the probability of severe injuries compared to other vehicle types." However, the authors did not specify how other heavy passenger vehicles, such as SUVs and pickups, compared to passenger cars in terms of injury severity.

Additionally, two Texas studies focused on environmental characteristics associated with pedestrian injury trends at the State level. Rahman et al. (2022) used Texas Department of Transportation Crash Records Information System data from 2010 to 2019, along with roadway characteristics data from the TxDOT Roadway Inventory database together with the horizontal curves (GEO-HINI) database to determine road geometry. The study identified the roadway characteristics most associated with greater crash frequency, as well as factors influencing pedestrian injury severity in collisions. They also collected population data from the 2014 to 2018 American Community Survey and job data from the Longitudinal Employer-Household Dynamics (Rahman et al., 2022). The study mapped all the datasets onto 708,738 road segments and developed two negative binomial models to determine pedestrian crash frequency. One NB model was used for all the pedestrian–vehicle collisions, while the other was used for only fatal collisions. Rahman's group also used a heteroskedastic ordered probit model to identify factors influencing pedestrian injury severity. The HOP model showed that compared with passenger cars, collisions with pickups, SUVs, and vans "result in a 1 percentage point increase in the possibility of being killed or seriously injured." Furthermore, analysis of CRIS data showed that between 2010 and 2018 both SUV and pickup truck involvement in fatal collisions increased at higher rates than passenger car involvement. While passenger car involvement in fatal pedestrian crashes increased by 64.7 percent, SUV involvement in fatal pedestrian crashes increased by 98.6 percent and pickup involvement increased by 92.9 percent. Newer vehicle model years, which are often cited as incorporating safer designs, did not "show significant impact" on the severity of pedestrian injuries.

However, another recent source evaluating the environmental and vehicle characteristics associated with pedestrian safety in North Texas suggested different results. Vavrova et al. (2021) conducted a State-government-sponsored study evaluating pedestrian and bicyclist collisions in North Central Texas, focusing on collision frequency and pedestrian injury severity in pedestrian–vehicle crashes. They developed a database using police crash reports, CRIS Automated Crash Data Public Extract, and secondary GIS data. Additionally, the study performed descriptive trend analysis on factors affecting pedestrian injury severity in collisions. While Vavrova et al. showed freight truck involvement as a significant factor influencing pedestrian injury severity, they did not indicate that SUVs, vans, and pickups were significant factors. Equal percentages (31 percent) of pedestrian–passenger car and pedestrian–SUV/van/pickup collisions resulted in serious injuries and fatalities.

Besides State-level studies, two studies from 2011 to 2022 have analyzed city-level trends in pedestrian injury outcomes, environmental characteristics, and vehicle characteristics. For example, Hamilton et al. (2022) used North Carolina data to identify characteristics associated with VRU injury severity in collisions, with a focus on Charlotte, Mecklenburg County. They collected 2014–to-2018 collision data from the NCDOT, Highway Safety Information System data, U.S. Census Bureau data, and Regional Integrated Transportation Information System data. The study included data from arterial and collector roadways and did not include collisions on interstates and local roadways. Hamilton et al. segmented the datasets according to the five study years, 2014 to 2018. They then developed three models to analyze pedestrian volume, crash severity, and crash probability. The pedestrian crash severity model showed higher likelihood of serious injury or fatality if it was a large vehicle that struck the pedestrian (light truck, commercial bus, SUV, van, pickup truck, single-unit truck, other bus, or tractor/trailer/truck) compared to a passenger car (odds ratio = 1.6), but this finding was not statistically significant, partially due to the small study sample size ($N = 590$).

In another city-focused study, Jang et al. (2013) identified "pedestrian crash hot spots" in San Francisco, as well as relevant characteristics associated with pedestrian injury severity levels in pedestrian–vehicle crashes. The study used 2002–to-2007 Statewide Integrated Traffic Records System (SWITRS) crash data for public roads in San Francisco. They mapped the five levels of injury severity studied, including property-damage-only, slight injury, visible injury, severe injury, and fatal injury, and performed spatial kernel density analysis for each injury severity, with injuries concentrated around commercial business development areas, and fatalities more dispersed across areas. They then aggregated pedestrian crashes by traffic analysis zone and mapped them according to injury severity levels, with results like the spatial kernel density analysis. The study used an ordered probit model to identify variables influencing pedestrian injury severity. Like the Charlotte study, Jang et al. (2013) found that large vehicle involvement, including involvement of pickups, trucks, and buses, was statistically more likely to result in severe injury than passenger car involvement.

International Studies

Although many studies in this category originate from the United States, a few peer-reviewed international studies emphasize the influence of environmental characteristics on pedestrian injury. For example, Prato et al. (2017/2018) examined the influence of built environment, as well as other characteristics, on pedestrian injury severity in Denmark. The study used 2006–to-2015 crash data from the Danish Road Directorate, as well as road and other built environment characteristics from GIS data. They developed a linearized spatial logit model to examine the effect of relevant characteristics on pedestrian injury severity levels in collisions, including built environment characteristics, as well pedestrian and vehicle characteristics. Prato et al. found that residential areas, shopping areas, industrial areas, and areas with low speed limits were associated with lower likelihood of severe injuries and fatalities. In terms of vehicle characteristics, the study showed that although heavy vehicles were related to higher pedestrian injury severity overall, vans and pickup trucks did not have a significantly different effect from passenger vehicles.

Khan and Habib’s study (2021/2022) on collision attributes, among other variables, and pedestrian safety in Nova Scotia, Canada, yielded different results for the impact of larger vehicle types on pedestrian safety, finding that passenger trucks increased risk of serious injury and fatality in pedestrian–vehicle collisions.

Pedestrian Focus Studies

Several studies on pedestrian safety focused on pedestrian characteristics, particularly pedestrian motion before collisions, as well as pedestrian kinematics during collisions. Just one study by a Chinese research team on vulnerable road users’ behavior at mid-block, used U.S. national data to examine injury patterns in relation to pedestrian behavioral factors. Dong et al. (2018) used 2002–to-2009 GES data to analyze the effects of pedestrian behavior at mid-block collisions, as well as various contributing factors, including vehicle type, on injury severity. The mixed logit model results showedshowed that light truck vehicle types result in higher probability of fatality, with a pseudo-elasticity of 122.8 percent. However, the study results for vehicle type have an important limitation, as the authors used vehicle factors as control variables, rather than the analysis’ focus.

Another study used GES data to examine the impact of pedestrian age on injury severity in pedestrian–vehicle collisions in relation to other factors, such as vehicle body type. Kim and Ulfarsson (2018/2019) analyzed 2012 and 2013 GES data with a random-effects logistic regression model to identify vehicle, environmental, and other factors influencing injury outcomes in pedestrians over age sixty-five compared to pedestrians 18 to 59 years old. Results showed that SUVs and minivans were especially injurious to older pedestrians compared to other light vehicle types.

Four additional international studies either evaluated existing methods or developed new methods for analyzing pedestrian-related factors, such as pedestrian size, in relation to other variables associated with pedestrian injury severity in collisions, including vehicle body type. In a recent peer-reviewed study, Wang et al. (2022) evaluated whether the current standard adult multibody models used in computer simulations, which are based on Western European anthropometry, can accurately represent the effects of pedestrian–vehicle collisions for the Chinese population. They used a standard multibody model representing a Western European

50th percentile male pedestrian (EU-50) to develop two additional models more representative of Chinese anthropometry, a “preliminary” model representing a 50th percentile Chinese male (EU-CN-50), and a “comprehensive” Chinese 50th percentile male model (CN-50). The authors then conducted 290 simulations with the three pedestrian models in six different pre-collision stances with three models representing a sedan, an SUV, and a minivan typical of the Chinese vehicle fleet travelling at five different speeds. Study results showed that changes in anthropometry were significant for injury severity. For example, for head injury measures at secondary ground impact, the Western European model exhibited higher head center of gravity (COG) maximum linear acceleration and higher head injury criterion (HIC) values for simulations with the SUV and minivan than with the sedan. Although these simulation results have limited applicability, particularly because they use Chinese vehicle models, they nonetheless provide context for how variability in pedestrian height influences simulation outcomes.

A conference paper by a team of researchers at the Toyota Motor Corporation in Japan discussed another study that examined how variability in pedestrian size affected simulation outcomes on pedestrian injury severity levels. Ito et al. (2017) used the Toyota-developed total human model for safety (THUMS) in simulations of pedestrian–vehicle collisions. They created and validated child finite element human body models representing 3-year-old, 6-year-old, and 10-year-old pedestrians. After validating the models with 11 load application cases representing different loading conditions and body region locations, the study then ran 48 simulations with the three child models, an adult 50th percentile male model, and three different vehicle types, including a sedan, an SUV, and a minivan. Simulations with the 3-year-old child model and SUV and minivan showed that in some collision scenarios, the vehicle hood leading edge struck the child’s head directly, leading to greater skull strain than for the adult model. Analysis of pedestrian kinematics for the SUV-6-year-old child collisions also revealed that the pedestrian model’s shoulder impacting the hood leading edge caused high angular acceleration of the head and greater brain strain than similar collisions with the 50th percentile male model. While the study did not specify the weights or models of any of the vehicle body types studied, the results suggested that injury types and kinematics may be different between small children and adults.

Two additional conference papers produced by research teams at Toyota -- Iwamoto and Nakahira (2014) and Watanabe et al. (2011) -- described pedestrian kinematics during impact with SUV models. Although neither study used other vehicle types for comparison purposes, both studies provided data on pedestrian kinematics and associated injury severity outcomes for SUV collisions. Iwamoto and Nakahira (2014) studied the effects of muscle activation on pedestrian kinematics by developing an “active THUMS model” with the baseline THUMS FE model and 282 muscles created in LS-DYNA. The study demonstrated different effects for the inactivated and activated models in computer simulations with an SUV FE model developed by the National Crash Analysis Center under NHTSA sponsorship. Regarding whole-body kinematics, muscle activation decreased likelihood of injury relative to no activation. Simulations suggested that muscle activation in the model’s trunk and lower extremities slowed the moment of head impact, and muscle activation in the neck decreased neck elongation. However, all simulation cases of tense and untensed muscles demonstrated the possibility of mild traumatic brain injury (greater than 50% probability of concussion in all cases). Overall findings showed that muscle activation decreased the likelihood of knee ligament ruptures, as well as the likelihood of neck injuries. They found that the results “partially correspond to differences” between results for PMHS tests and real-world crash incidents recorded in the NHTSA-sponsored data-collection program, Crash Injury Research and Engineering Network.

Watanabe et al. (2011) conducted a simulation study using the Toyota-developed THUMS FE model and an SUV model to investigate head and chest injuries, as well as whole-body kinematics in pedestrian–SUV collisions. Although the study did not specify vehicle weight or model year, it nonetheless provided general information on pedestrian impact with a large passenger vehicle at different speeds. The study ran collision simulations at 30, 40, and 50 kph (approximately 19, 25, and 31 mph) to determine the relationship between collision speed and head and chest injuries, as well as the relationship between collision speed and pedestrian fatality. In each simulation, the center of the vehicle's front-end first struck the pedestrian from the side. At collision speeds of 30 kph, the vehicle bumper first struck the pedestrian's knee, before the hood struck the hip, side of the stomach, and chest and shoulder, and last, the windshield struck the head. Simulations at speeds of 40 kph and greater entailed the same kinematics, but the cowl part of the vehicle hood also struck the chest and shoulder before the windshield collided with the head. Simulation results showed high risk of diffuse axonal injury at collision speeds 40 kph and higher. Overall, findings showed that collision speeds of 40 kph and higher result in brain strain and higher risks of severe brain injuries, and speeds of 50 kph and higher result in heart damage. The study showed that impact speeds of 40 kph and more resulted in higher risk of pedestrian fatality.

Time-of-Day Focus Studies

One recent peer-reviewed domestic study discussed the effect of crash time-of-day on other factors influencing pedestrian injury severity levels in collisions. Ferenchak and Abadi (2021) noted that pedestrian fatalities increased in 2009 to 2017 by 1,868 fatalities, and 1,594 of the fatalities, or 85 percent of the increase in fatalities, happened at night. They therefore analyzed FARS data from 2009 to 2017 to examine factors associated with pedestrian fatality in nighttime collisions, including vehicle type, environmental characteristics, and pedestrian characteristics. They divided FARS variables into the four separate categories of infrastructure, users, vehicles, and situation, then analyzed relationships between nighttime collision frequency and functional classification categories using one-way ANOVA tests and two-sample *t*-tests. The authors then analyzed trends for the individual variables with scatterplots for 2002 to 2017 and used two-sample *t*-tests to identify differences in crash frequency between the variable categories for 2002 to 2009 and 2010 to 2017. The study further employed linear regressions to analyze "changes in the proportions of the categories" for the variables during 2002 to 2009 and 2010 to 2017. Results showed that although the heavy vehicle, sedan/coupe, and SUV vehicle types all had statistically significant increases in pedestrian fatalities over the study period, only SUVs had a statistically significant increase "in terms of proportions" from 2010 to 2017. They noted that although SUVs represented one of the driving factors in the increase in pedestrian fatalities since 2009, the results did not determine the degree to which SUVs caused the rise in fatalities. In fact, the proportion of SUV-pedestrian fatalities had an even greater increase from 2002 to 2009 than from 2010 to 2017, the period that saw an overall increase in pedestrian fatalities.

Pedestrian Collision Research Methodology With Medical Focus

The review team located 4 domestic and international English-language studies incorporating medical or clinical applications relevant to whether larger light vehicles are more dangerous to pedestrians than smaller light vehicles. One domestic study published in the *Western Journal of Emergency Medicine* used real-world collision data and interview information collected through trauma centers to examine child pedestrian–vehicle collisions on non-roadways, while the other domestic and international English-language studies conducted experiments with PMHS and ran computer simulations to examine the effects of vehicle classifications on pedestrian injuries (Rice et al., 2012).

Medical Focus Studies

One U.S. study relied primarily on information collected in a clinical setting to analyze child-pedestrian collisions in non-roadway settings. The study completed by Rice et al. (2012) collected information about risk factors from children that were injured in driveways or parking lots by passenger vehicles. By focusing their efforts on studying eight trauma centers in California, researchers gathered nuanced information on non-traffic pedestrian collision injuries for children 14 or younger. The study examined crash frequency by vehicle type, as well as injured body region, and information on fatalities. From January 2005 to July 2007 researchers conducted follow-up interviews with the family members of 21 children involved in non-roadway collisions. In these interviews, researchers found that of the 21 children, 17 were male and 13 were 2 or younger. Additionally, in 13 of the cases the vehicle backed over the child, and in 11 of those cases, a parent backed over the child. Most significantly, 15 of the cases involved SUVs, pickups, or vans. Other significant factors included driveway or parking lot location, vehicle in reverse, and child pedestrian without supervision. Despite limited case numbers, the study suggested that pickup trucks, vans, and SUVs were more frequently involved in non-traffic collisions with child pedestrians, particularly back-over collisions, likely due in part to poorer visibility relative to passenger cars. Although this study predates NHTSA's 2014 final rule requiring that new vehicles have backup cameras (where full compliance was due in 2018), it nonetheless provides useful information on how vehicle size and body type influences pedestrian injury outcomes.

Another U.S. study in this category conducted by Kerrigan et al. (2012) compared tests with PMHS with real-world collision data to examine injury severity levels in pedestrian–vehicle crashes. The study ran impact experiments with 17 PMHS and five vehicle models representing various vehicle body types, including a compact car, small sedan, mid-sized sedan, minivan, and large SUV. Researchers then compared their results with CIREN program data. The PMHS experiments produced similar kinds of injuries to the injuries captured in real-world injury data. Researchers found that for the PMHS experiments, SUVs were the attributed cause of most major pelvic injuries. However, this finding has an important limitation, as the PMHS experiments generally produced "more frequent and more severe injuries" than the CIREN cases, likely due at least in part to the higher average age of the post-mortem human subjects (63 years for the PMHS versus 38 years for the CIREN data), as well as the PMHS' lack of active musculature that might mitigate the impacts of collision.

In Japan, a group of researchers from Honda's Research & Development Center analyzed differences in pelvic injury severity levels between various vehicle models in pedestrian–vehicle collision simulations. Using a human FE model for simulation, they experimented on four distinct vehicle types (two different sedans, a minivan, and a SUV) to represent different impacts of the hood leading edge. Simulation results showed that the SUV resulted in a pelvic deflection of 860 mm, and the minivan resulted in a pelvic deflection of 962 mm, values exceeding the Sedan-1 (666 mm) and Sedan-2 (742 m) values. Furthermore, the likelihood of pelvic fracture resulting from the SUV and minivan models was over 90 percent, while the Sedan-2 model had a value of 40 percent, and the Sedan-1 had a value of under 5 percent. Although study authors specified the use of sedan, minivan, and SUV body types, they did not provide information on vehicle model that might indicate whether these classifications align with U.S. vehicle classifications.

Medical/Vehicle Hood/Front-End Studies

Additionally, the review team located one international English-language study published in *The Journal of Mechanics in Medicine and Biology* (Cai et al., 2020) that examined vehicle front-end design considering head injury outcomes in pedestrian–vehicle collisions. Researchers focused on head injuries caused by impact with vehicle windshields, as vehicle windshields frequently cause pedestrian head injuries. After developing a head finite element model, researchers simulated different velocities of impact as well as different angles of contact between the head and windshield. They matched three vehicle body types to vehicle windshield angles: a sedan with an angle of 35°, an SUV with an angle of 40°, and another type of multipurpose vehicle with an angle of 45°. The results showed that the extent of damage to the skull increased as both the velocity of the impact and the angles of contact increased, with the most detrimental angle of contact coming from the MPV.

Vehicle Size/Weight/Body Type Studies

The review team located 6 studies from a range of domestic and international English-language sources that focused primarily on the effects of vehicle size, weight, and body types on pedestrian injury and fatality. Several studies in this section, including Monfort and Mueller (2020) and Hu and Cicchino (2022), suggested that SUVs and LTVs were more injurious than passenger cars to pedestrians during collisions.

Just two U.S. studies focused exclusively on the effects of vehicle size, weight, and body type on pedestrian injury outcomes in collisions. Monfort and Mueller (2020) used data from real-world pedestrian crashes occurring from 2015 to 2021 and involving passenger cars and SUVs, including police reports, pedestrian medical records, and reconstructions of the crashes, and matched injuries to specific parts of the SUV or car. Monfort and Mueller found that SUVs caused more severe pedestrian injuries than passenger cars, with even more risk of higher injury severity at higher impact speeds. Their study also found that SUVs might be especially injurious to pedestrians when struck by the leading edge of the vehicle.

Hu and Cicchino (2022) analyzed North Carolina State-level data to identify relationships between vehicle body type and crash frequency, as well as pedestrian injury severity in collisions. They collected State police-reported crash data from 2010 to 2018, as well as data from FARS, to develop multinomial logistic regression models analyzing the vehicle characteristics associated with pedestrian injury. Hu and Cicchino also examined the impact of intersection versus non-intersection location in relation to vehicle body type on pedestrian injury outcomes. Overall, they found that LTVs are more injurious to pedestrians in collisions than passenger cars. Study results suggested that LTVs had greater likelihood than cars of involvement in pedestrian crashes due to poor visibility at the front corners of the vehicles. Additionally, LTVs were more likely than cars to have crashes when turning left or right, and LTVs were more likely to be involved in pedestrian crashes at non-intersections.

In addition to Monfort and Mueller (2020) and Hu and Cicchino (2022), several international studies focused on how vehicle size, weight, and body type affected the severity of pedestrian injuries in collisions. Carollo et al. (2018/2019) examined how vehicle weight affects head, chest, and femur injuries resulting from collisions between a teenage pedestrian model and an SUV model with a weight of 2,270 kilograms (approximately 5,004 pounds). They developed vehicle and pedestrian models with SimWise software and used SIMPACK and MADYMO software to conduct simulations at vehicle speeds of 20, 30, 40, and 50 kph (approximately 12, 19, 25, and 31 mph). Carollo et al. then validated the simulation results with real-world crash data from Palermo, Italy, and its associated province. Their research concluded that the frontal shape of the SUV renders the SUV less injurious to a teenage pedestrian than the sedan studied in previous research. Additionally, pedestrian stance prior to impact was a significant factor determining injury severity, as pedestrians facing directly towards the vehicle were in more danger than pedestrians in lateral positions in terms of head and chest injuries. However, pedestrian position did not affect femur injury outcomes.

D’elia and Newstead’s (2015) study from Victoria, Australia, analyzed the death and injury risk of pedestrians in collisions with 10 vehicle types. They gathered data using police crash reports linked to insurance injury compensation claims. To analyze the data, researchers used logistic regression models to study the relationship between vehicle type and injury outcome, with particular emphasis on the head, face, neck, thorax, and lower extremities. Researchers found that LTVs had a higher risk of injury to pedestrians than cars. Through an analysis of all body regions, researchers also found risk of severe pedestrian injury or fatality to be 28.5 percent statistically significantly higher for utility vehicles, such as LTVs, relative to large cars. When compared to large cars, the risk of head, face, or neck injury or fatality was 27.1 percent statistically significantly higher for small cars, 53.9 percent higher for people movers (cars with higher capacity, which typically can carry eight or nine passengers), 44.5 percent higher for large SUVs, 65.1 percent higher for vans, and 53.6 percent higher for utility vehicles. Risk of thoracic injury or fatality was found to be 74.4 percent higher for large SUVs and 52.7 percent higher for vans than large cars. Risk of lower extremity injury or fatality did not differ significantly from large cars. Generally, the results suggested that large SUVs were found to show higher pedestrian thoracic injury and fatality risk compared to large passenger cars, whereas people movers, vans, and utility vehicles were found to show higher pedestrian head, face, or neck injury and fatality risk than large cars.

A study completed by Høye (2018/2019) in Norway investigated the relationship between vehicle weight, vehicle age, and the number of pedestrians that were killed or seriously injured in pedestrian–vehicle crashes using Poisson regression models. Regression models focused on the following variables: vehicle age and weight, crash year, the age and gender of the driver, and car-to-car collisions with cars that were of the same weight or year. The study found that heavy cars incurred a higher risk of killed or seriously injured pedestrians in collisions.

Li et al. (2016) discussed how vehicle design has changed because of voluntary Euro NCAP testing. Many countries have reported a reduction in the number of KSI pedestrians, but the researchers wanted to discover the cause of this reduction. Researchers compared two databases, the Pedestrian Crash Data Study with information collected from U.S. cities in the 1990s, and more current data from the German In-Depth Accident Study database after 2000. They compared distributions of vehicle body types across the two databases for different injured body regions and injury severities. The study found that SUVs and pickups in the PCDS dataset incurred higher rates of severe injuries than cars and vans in pedestrian–vehicle crashes. The GIDAS dataset did not exhibit this same statistic, possibly due to the comparatively small sample of SUVs in its dataset. For both PCDS and GIDAS, vans incurred fewer severe injuries for mid-body and lower limb regions, but more severe head and face injuries than cars. Overall, cars and SUVs incurred more severe lower limb injuries than vans, but PCDS reported more severe injuries for each vehicle body type. Additionally, it is worth noting that the data used in this study was collected from two different continents during two different eras, which might lead to possible inconsistences between the two datasets. Furthermore, Li et al. did not specify whether vehicle size and body type definitions were consistent between the PCDS and GIDAS datasets.

Vehicle Hood/Front-End Profile Studies

The review team has identified 26 studies focusing on the front-end design of vehicles when assessing pedestrian injury risk in a pedestrian–vehicle collision. While only 3 of these studies were based in the Unites States and, as such, focus on the North American fleet, several international studies considered vehicles in the North American market alongside other vehicles. The review team has noted the region of a vehicle model under study when this information is available. The review team discusses U.S. studies first in each of the sections, as their findings are likely more applicable to the U.S. market.

This section divides studies into four groups. The first is "General Front-End Focus Studies," which examines the role common front-end design plays in a collision with a pedestrian. This is followed by "Front-End Studies Examining Frontal Guards," which assesses the effects that front ends modified with frontal guards (also known as bull bars or frontal protection systems) have when striking a pedestrian. The third group surveys "Front-End Studies Examining Ground Impact Effects," as a pedestrian's secondary impact with the ground after a collision is not often considered in the literature, though it can have a significant effect on injury outcomes. Last, this section covers "Front-End Studies Examining Pedestrian Gait/Stance Effects," as the stance of a pedestrian introduces variability in the kinematics of a collision.

General Front-End Focus Studies

The review team has identified one U.S.-based paper and eleven international studies that focused on the effect of vehicle front-end design in vehicle–pedestrian collisions in general. Specifically, these papers focused on the injury sustained by the non-modified front end of a vehicle striking a pedestrian. None of these studies explicitly examined vehicle weight as a factor in pedestrian collisions, focusing instead on front-end characteristics of various body types of vehicles, including sedans, SUVs, and one-box vehicles. Most studies did not examine pickup trucks, likely because pickup trucks are less common in international vehicle fleets than in the U.S. vehicle fleet.

The U.S.-based study was the only report that included pickup trucks as well as other vehicle types in its examination of general front-end geometry. Mueller et al.'s (2012) conference paper assessed the usefulness of tests employed by Global Technical Regulation No. 9 on Pedestrian Protection (United Nations Global Registry, 2009) by comparing GTR 9 methods with real-world pedestrian injuries documented in the CIREN dataset. The authors found that while vehicle hoods are subject to GTR 9 impactor tests, relatively few of the cases resulting in pedestrian head injuries involved a pedestrian's head striking a vehicle's hood. Instead, the impact to the pedestrian was more often from the cowl, A-pillar, or windshield, none of which are addressed by GTR 9 testing methods. The authors recommended extending the wraparound distance that the GTR 9 methods cover to 2,100 mm, including the cowl, A-pillar, and windshield, so that it includes the head impact locations in more scenarios. Currently, the GTR 9 wraparound distance does extend to 2,100 mm except for when this would cause the adult head form to contact the rear of the hood, A-pillar, or windshield before impacting the top of the hood. The International Harmonized Research Activities Pedestrian Safety informal working group tasked with drafting the GTR 9 had considered including testing head form impacts to the windshield, windshield frame, and A-pillars in the GTR, but decided not to include these tests because these areas must be very stiff to meet regulatory requirements and no countermeasures were available to provide sufficient protection to pedestrians. However, countermeasures such as inflatable windshields and A-pillar air bags have become available since the GTR 9 was drafted, as Mueller et al. noted.

The authors also found that the GTR 9 leg impactor often failed to capture a significant source of damage because the impactor did not include instrumentation below where a vehicle's bumper typically strikes. The authors found that this was where leg fractures were likely to occur. Lastly, the study noted that a hood leading edge test should be included when an impactor with sufficient biofidelity to test pelvis and thigh injures becomes available.

The following investigations are non-U.S.-based studies, and the findings should be interpreted with caution because the vehicle models under review are often European or Asian, and as such, have a different front-end design than North American models. Even so, several studies used FE models developed by the National Crash Analysis Center, based at George Washington University, in their simulations, suggesting that the authors examined some North American models. The general findings regarding non-North American models are also relevant because they provide evidence for general mechanisms of pedestrian injury in collisions and sometimes suggest safer front-end designs.

These studies primarily used simulations to examine the effects of different front-end designs on pedestrian injury. Chen et al. (2021) used data from two real-world crashes to simulate those circumstances when evaluating a FE human body lower limb mode known as a HALL (Human Active Lower Limb) model. The two vehicle–pedestrian crashes that Chen et al. reconstructed involved a Dongfeng MPV 2008 minivan[*] with a frontal guard and a Citroen Elysee 2015 sedan. The authors found support for the HALL model as it functioned similarly to a pedestrian's legs in the two actual collisions, with a tibia fracture occurring in the minivan collision and a femur fracture in the sedan collision. The authors claimed these crashes are representative for vehicle-to-pedestrian collisions; however, selecting a minivan with a frontal guard and a sedan without a guard makes it difficult to compare the vehicle types.

In fact, the findings of other studies suggest that these are not typical injury patterns of similar-sized vehicles. In a study by Han et al. (2011/2012b), the authors developed FE models of a passenger car, a one-box vehicle, and an SUV, and simulated pedestrian kinematics when struck laterally by each of these vehicles. The authors based models of the passenger car and SUV on NCAC FE models of the Honda Accord and Toyota RAV4, while the one-box FE model was developed for the study and was based on the Honda Acty. The authors did not state the model years. The researchers found that the injury pattern varied widely based on the front-end shape of a vehicle but made no statement as to which designs are safer overall. They found that head injury risk was high in the SUV and passenger car collisions due to the relatively high head injury criterion values and high acceleration of the head into the vehicle's hood. The HIC was especially high in the case of the passenger car impact, in which the head contacted the relatively stiff rear part of the hood, while the head contacted the less stiff hood top in the SUV impact, resulting in a lower HIC number. Head injury risk was lowest in the one-box vehicle collision because the windshield was less stiff than the hood. Chest injury risk, however, was found to be much greater in the one-box vehicle collision than the other types of collisions because of the high stiffness of the lower windshield frame, which applied local loading on the ribcage with large deformation. The authors found that hip fracture risk was low in the passenger car collision

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[*] Based on the EQ6362PF chassis.

and high in the other two types. Lastly, the passenger car caused the highest bending moment on the knee joint, and tibia compared to the other vehicle types, which agreed with the authors' analysis of crash data. The SUV caused the highest bending moment on the femur, and the one-box vehicle caused the lowest bending moments on all three of these areas of the lower extremity.

A second article in which Yong Han (Han et al., 2012a) is the lead author examined injury parameters to the head, chest, rib cage, pelvis, and lower extremities among several vehicle types and collision speeds. In this study, the authors used FE models of a medium-size sedan (2000 Honda Accord, developed by NCAC), SUV (1997 Toyota RAV4, developed by NCAC), minicar (2006 Suzuki Alto, developed by the authors), and one-box vehicle (2006 Honda Acty, developed by the authors). The findings in this article were like the findings in the study by Han et al., although this research examined a minicar alongside the three vehicle types discussed previously. Head injury risk was highest in collisions with the sedan and SUV; chest and pelvic injury risk were highest with the one-box vehicle; and the lower extremity injury risk was highest with the sedan and SUV. Notably, the short hood length and flat and smooth shape of the front bumper of the minicar resulted in relatively low injury risk to all parts of a pedestrian's body. Increasing vehicle speed at the time of impact resulted in higher injury risk for the pedestrian. The head injury risk caused by the sedan and SUV in both studies led by Han is particularly notable because, as the authors noted, head injuries were the dominant cause of fatal injuries in Japan in vehicle–pedestrian collisions in 2010. Chest injuries were the second-most-common cause of death.

Mo et al. (2015) also examined lower limb injuries in FE simulations of pedestrian collisions with various vehicle types—super mini, small family car, executive car, and multipurpose vehicle. They found that the MPV differed from the other vehicles because its bumper beam center height was above the knee joint center of their pedestrian models, while all other vehicles had it below the knee joint center. This higher bumper beam resulted in larger valgus bending values and greater ligament injury risk caused by the MPV compared to the other passenger vehicles. The authors found that, in general, "low bumper beam height can limit joint kinematics and reduce knee ligament injuries." In addition, the authors found that a vertically wider bumper beam and larger deformable space between the bumper beam and bumper fascia also reduced injury risk.

In a study by Anderson and Doecke (2011) examining head kinematics in simulated collisions between pedestrians and common Australian SUVs and work utility vehicles, study authors found that the SUVs and WUVs caused greater injury risk to a pedestrian model's head than the sedan model with which they compared those vehicles. The SUV/WUV models included the following vehicle models (with their hood leading edge heights in parentheses): Toyota Land Cruiser (1.01 meters), Nissan Patrol (1.03 meters), Ford Courier (0.99 meters), GM Holden Rodeo (0.95 meters), and Toyota Hilux (1.07 meters). The sedan included in the study was a model of a 2006 GM Holden Commodore with a leading-edge height of 0.7 meters. The SUV and WUV models caused greater injury risk to the pedestrian model's head even though the head impact speed was higher in the crash simulation with the sedan model. However, the pedestrian model's neck force was higher in SUV/WUV crash simulations, increasing HIC values. The authors attributed this primarily to the higher hood leading edge height and cautioned against relying on subsystem impact tests, which have difficulty accounting for neck force because the free-flight head forms used in these tests are separated from the kinematics of the rest of the body. While this study was not conducted using North American vehicle models, its findings suggested that vehicles with a hood leading edge height of 0.95 to 1.07 meters might have a higher risk of head injury than vehicles with lower hood leading edge heights.

A study by Nie and Zhou (2016) assessed changes to vehicle front-end design of "representative passenger car models" in Europe, Asia, and the United States by comparing FE models of sedans and SUVs produced before 2003 with those produced from 2008 to 2011. The authors chose this time period to examine changes that European regulations enacted during that time may have had on front-end design of new vehicle models. Even though many of the models appear to be based on non-North American vehicles, because of global integration in the design and marketing of vehicles, the authors claimed that the "regulatory efforts led to geometrical changes in new car models sold in multiple end markets." Nie and Zhou found that the depth between the main bumper and secondary, lower bumper had decreased in the newer vehicles. The same was true for the depth between the main bumper and the hood leading edge, resulting in "flatter" front ends, which tended to reduce knee ligament rupture when simulated. However, the bottom height increased in newer vehicles, which increased tibia fracture risk while decreasing femur fracture risk in the simulations. The authors defined "bottom height" as the lowest "contact points between the secondary bumper (also known as the lower bumper) and a straight reference inclined by 65° to the vertical line." The authors did not discuss the relative dangers of these injuries to pedestrians, instead suggested that more research considering multiple injury patterns is necessary. The authors noted that the higher hood leading edge height in the newer vehicles likely increased force on the pelvis, though this was not directly tested. A further limitation is that the study did not examine vehicle structural stiffness, which has likely changed over time.

Three articles seeking to identify a theoretically ideal front-end design that is not currently manufactured were identified.[*] A simulation study by Tolea et al. (2017) examined head injuries sustained by pedestrian models when a vehicle strikes them from behind traveling at 30 kph (approximately 19 mph).[†] The vehicle three-dimensional mesh simulation models under study were representative models of compact, sedan, SUV, sports, van, and one-box class vehicles, developed from the average measurements of each body type of vehicle. As the authors were affiliated with a Romanian institution, the models were likely European. The study compared the six vehicle models with models of the same vehicle body type, but with the geometry adjusted in various ways to lessen the injury of each vehicle to a pedestrian. No modifications to the compact body type decreased injury, while the sedan body type benefited by increasing the hood radius and hood length. The SUV and van body type models decreased injury with an increased hood length of 1,400 mm for the SUV and 800 mm for the van. Increasing hood leading edge height improved injury measures in the sport and one-box vehicle models.

Tolea et al. noted that this study is limited, in that the structure of the vehicle models were non-deformable—that is, stiffness was not considered—but found that this would have little effect on the ideal front-end designs proposed by the authors. While the authors considered relatively stiff parts of the hood, they did not consider the relative stiffness of the windshield compared to other vehicle components, such as the hood and windshield frame, which other studies have found to

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[*] The studies by Tolea et al., Li et al., and Sankarasubramanian et al. are distinct from studies developing pedestrian front-end models for testing purposes, such as Bengt Pipkorn et al. and Miwako Ikeda et al.

[†] This article by Tolea et al. was published in a peer-reviewed academic journal with a pay-to-publish model. Bogdan Tolea et al., "Influence of the Geometric Parameters of the Vehicle Frontal Profile on the Pedestrian's Head Accelerations in Case of Accidents." See References section for full citation.

be important. In addition, unlike other comparable studies, this study examined a pedestrian struck from the rear rather than laterally, which represents the more typical configuration. Tolea et al. seem to have selected this stance because it results in the highest HIC values, due to the pedestrian's arms not contacting the hood of the vehicle. Last, the text of the article at times conflicts with the data conveyed through images, suggesting that decreasing the hood length of the van and decreasing the hood leading edge height of the one-box vehicle may decrease pedestrian injury in the text, but demonstrating the opposite in accompanying figures.

A study by Li et al. (2017) partly contradicted Tolea et al.'s findings, instead calling for a relatively short hood in an SUV-body type front end. Using MADYMO simulations, the authors sought to create an ideal vehicle front-end shape for reducing pedestrian injury and developed a design that could accommodate an SUV-size engine. The authors found that "passenger cars should have a wide and flat bumper (covering pedestrians' legs from the lower leg up to the [thigh] with generally even contacts), a [hood] leading edge height of around 750 [mm], a short [hood] (less than 800 [mm]) with a relatively shallow or steep angle (greater than [17° or less than 12°), and a shallow windscreen (less than or equal to 30°])." A similar study by Sankarasubramanian et al. (2015/2016) generated an ideal vehicle for vehicle–pedestrian collisions with similar dimensions: a hood leading edge height of 740 mm and a hood length of 760 mm, approximating a crossover SUV shape with a hood leading edge height lower than the SUV category. Li et al. found that this shape, particularly the hood leading edge height, increases the risk of pelvis injury; however, the lesser head and leg injury risk offset the increased risk of pelvis injury.

Li et al. further validated these findings by comparing pedestrian injuries sustained in real-world crashes with vehicles like this ideal vehicle to pedestrians struck by vehicles that were very different, based on GIDAS data, and found support for their ideal vehicle shape. A reason these findings differed from those of Tolea et al., which recommended a longer hood for an SUV-body type vehicle, rather than a shorter one, could be because Li et al. and Sankarasubramanian et al. (2015/2016) considered stiffness in their simulations, where the windshield had a markedly lower stiffness than the seam between the windshield and the hood, as well as the hood itself. Li et al. and Sankarasubramanian et al. were limited by not considering variations in stiffness levels of the same front-end components across vehicle designs (e.g., a soft hood compared to a hard hood with all other characteristics remaining the same). In addition, neither study considered injuries caused by ground impact or any events other than the initial impact between a pedestrian and a vehicle.

Front-End Studies Examining Frontal Guards

In addition to these studies and experiments focusing on the front ends of common vehicles in pedestrian collisions, the review team identified a small number of projects that examined the effect frontal guards (also known as bull bars or frontal protection systems) had in vehicle–pedestrian crashes. In a U.S.-based experiment, Moradi and Lankarani (2011) investigated the pedestrian kinematics and injury risk in collisions involving a Chevrolet Silverado, with and without a frontal guard. The authors ran simulations in which MADYMO pedestrian models of a 6-year-old child, and 50th percentile and 95th percentile males were struck by a vehicle front-facet model at speeds of 25, 36, 40, and 54 kph (approximately 16, 22, 25, and 34 mph). The frontal guard essentially consisted of two vertical cantilever I-beams separated from the centerline by 700 mm and connected by four horizontal tubular beams. In general, the added stiff frontal guard altered the leading angle of the vehicle front profile, "resulting in forward projection of the pedestrian instead of rotation around the hood." Because of this, the authors found that pelvis acceleration and injury risk greatly increased for all pedestrian sizes, and head acceleration increased "catastrophically" for the small pedestrian in the scenario with a frontal guard compared with the absence of a guard. The authors found only slight differences in the head impact of the pedestrian with the vehicle in the two scenarios, in both cases observing greater head injury risk from the secondary impact with the ground after being struck by the vehicle. A limitation of this study is that it only considered head, thoracic, and pelvic injuries, but not leg or ankle injuries that could be caused by wrapping of the lower extremities. In addition, even though the vehicle model selected is among the best-selling light trucks in the Unites States, this study is limited in that it only examined the scenario of a single vehicle model with a single frontal guard shape. Despite this limitation, the article provided useful information about pedestrian kinematics resulting from collision with a light truck with a generic frontal guard.

Several international studies also examined the effect of frontal guards on vehicle–pedestrian collisions. A Chinese study by Li et al. (2019) sought to assess the THUMS pedestrian model by simulating a real-world collision involving a minivan (2008 Dongfeng MPV) with a frontal guard and a pedestrian. As such, the focus of this study was not to assess the impact of the vehicle size or the frontal guard on a pedestrian in a collision and it did not discuss in detail the role specific aspects of the vehicle, such as size or frontal guard, had on the pedestrian's injury patterns. The authors found that the lower bar of the frontal guard broke the tibia in the real-world collision and in the THUMS simulation, and no fracture occurred when the bar was removed in a subsequent simulation. The authors attributed no other injuries or lack of injuries to the frontal guard.

A pair of studies in which Mariusz Ptak of Wrocław University of Technology is the first author (Ptak et al., 2012, Ptak & Karlinski, 2013) similarly examined the efficacy of testing methods on vehicles with frontal guards, finding the testing methods mandated by European Regulation (EC) 78/2009 were insufficient to identify frontal guards that are potentially dangerous to pedestrians in a collision. Running an FE simulation as well as a MADYMO multibody simulation of a Nissan Navara with a frontal guard striking a pedestrian model laterally compared to a lower leg impactor, the authors found the kinematics to be substantially different. Unfortunately, the authors did not compare the injury pattern of a pedestrian collision with a vehicle equipped with a frontal guard versus a vehicle without a guard. Instead, it only noted the study's findings of much higher bending moments in the knee of the dummy model than the impactor. The study did not examine injuries above the leg. It is possible that the injury patterns in these international studies differed from the U.S. study by Moradi and Lankarani (2011), not only because the authors examined different injury locations, but also because the frontal guard appeared to be higher and covered more of the vehicle front end in Moradi and Lankarani's simulations than in the others.

Front-End Studies Examining Ground Impact Effects

In a vehicle–pedestrian collision, there are usually two impacts: a primary impact between the pedestrian and the vehicle and a secondary impact between the pedestrian and another surface, often the ground. As some studies note, the secondary impact can be more injurious to the pedestrian than the primary impact. Several studies showed that the front-end shape of a vehicle had a significant effect on the severity of the secondary impact of a pedestrian (Anata et al., 2011; Gupta & Yang, 2013; Moradi & Lankarani, 2011; Shang et al., 2018; Tian et al., 2020, Crocetta et al., 2015, Simms et al., 2011). This was true even when considering other variables, such as vehicle speed, pedestrian size, and pedestrian stance.

A U.S. study by Gupta and Yang (2013) examined MADYMO pedestrian models struck by FE vehicle models of a mid-sized sedan and an SUV. To examine the effects of vehicle front ends, the authors morphed the front-end shape of representative models of both vehicle types to simulate a high, medium, and low front-end scenario.[*] The authors investigated the impact on a 50th percentile male, 5th percentile female, and 6-year-old child being struck at a speeds of 30 and 40 kph (approximately nineteen and twenty-five miles per hour). The study found that the mid-sized sedan with the lowest profile eliminated head contact with the ground for the 5th percentile female and the 50th percentile male models. Even so, it appeared that this front-end shape caused relatively high HIC values at primary impact with the 5th percentile female, which the authors did not discuss. No SUV profile prevented head impact with the ground at 40 kph, but the profile with the higher front end was less injurious than the other profiles at 30 kph. Models of active hoods seemed to have reduced HIC values of primary impact but did not reduce HIC values of secondary impact with the ground.

These findings were like another study in Japan by Anata et al. (2011), which investigated the injury caused by pedestrian impact with the ground after collision with a vehicle, though the data used in this study was older, from 1993 to 2001. The authors found that impact with the ground was often more injurious than the initial impact with a vehicle when examining real-world collision data gathered from the Japanese Institute for Traffic Accident Research and Data Analysis. Similarly, HIC values from Japan Automobile Research Institute pedestrian models in collisions with MADYMO computer models of sedan, van, and SUVs showed higher head injury risk from secondary impact with the ground. The highest HIC values at any point in a collision, including primary and secondary impacts, were, on average, highest for the SUV models, followed by the van type model, with the sedan type model having the lowest values. In most cases among all vehicle types, and in all cases involving SUV models, secondary ground impact caused the highest HIC value in each simulation.

A further international study by Shang et al. (2018) used 1,221 pedestrian collision cases from GIDAS data occurring from 2000 to 2015 to reconstruct collisions via simulation in MADYMO to examine relationships between hood leading edge height and ground injury. In a logistic regression to assess the potential relationship between adult ground-related head injuries and normalized hood leading edge height, the authors found that higher normalized hood leading edge height led to higher head injury risk from the ground in the GIDAS data, though these differences were not statistically significant, partially due to a small sample size (*N*n = 41). The virtual test system that the authors created showed that there was relatively wide variability between SUV models with "good" front-end shapes versus "bad" shapes, compared to the relatively low variability between "good" and "bad" van and sedan model front-end shapes. In both the logistic regression examining normalized hood leading edge height using GIDAS data and the virtual test system, the authors of this study only examined injuries caused by contact with the ground and did not consider injuries sustained during the primary impact with the vehicle.

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[*] The authors did not state which sedan and SUV models they studied.

At least one article aimed to improve on the use of rigid multibody models representing pedestrians. Tian et al. (2020) sought to understand the specific mechanisms that cause head injuries when a pedestrian's head strikes the ground by reconstructing a collision between a pedestrian and a van, using an FE model of the skull and brain. By using this FE model of the head, the authors were able to examine intracranial pressure, von Mises stress, shear stress, and strain that occur in the head throughout the collision. While the authors suggested that this method would be useful in assessing and developing safer vehicle front ends, they did not compare the reconstructed collision to other collisions or provide any guidance on how to create safer vehicle front ends.

Three further studies investigated the effect of ground impact, while also examining the possible effects that a pedestrian's gait may have on their kinematics in a collision and injury risk. A paper by Simms et al. (2011) used MADYMO multibody models of vehicle–pedestrian collisions involving different vehicle shapes and speeds, and two pedestrian sizes and two stances to analyze the kinematics of pedestrian–ground contact, including the HIC score from ground contact. Simms et al. identified six mechanisms of ground contact that described the kinematics of how a pedestrian model strikes the ground in most scenarios. In their modeling, the authors also found a positive correlation between higher hood leading edge height and the occurrence of injury mechanisms that result in a higher HIC score from ground impact. The paper did not comment on the danger of primary impact.

Crocetta et al. (2015) and Hamacher et al. (2012) built on Simms et al.'s study (2011) by conducting similar research, but including more variables, such as more vehicle shapes and impact speeds in their modeling than Simms et al.'s research. Crocetta et al. found that, at 30 kph (the head–ground impact speed in the simulations increased along with increasing hood leading edge height. However, at 40 kph a low front end did not appear to make an appreciable difference in head–ground impact speed, given a collision. Similarly, Hamacher et al. found in their simulations that the higher hood leading edge heights of one-box vehicles, which Crocetta et al. did not study, were particularly likely to cause the head of the pedestrian model to strike the ground first following a simulated collision, though they did not discuss how often SUVs and vans caused head-first contact with the ground. The sports car model caused the pedestrian model to strike the ground head-first the fewest number of times because it rotated 240 to 420° on average before striking the ground in Hamacher et al.'s study. In the studies by Simms et al., Crocetta et al., and Hamacher et al., the authors noted that pedestrian model stance at the moment of impact introduced variability in the findings but did not alter the general trend that higher hood leading edge height tended to cause greater risk of head injury when striking the ground following a simulated collision.

Crocetta et al. (2015) included a 6-year-old child MADYMO model in their study and found that impact mechanisms in which the child model was thrown forward and sustained high head–ground impact speed were very common when struck by the big SUV and van models due to the child model's low center of gravity. Hamacher et al. (2012) also found the van body type resulted in particularly high impact measures for the child model. Furthermore, Hamacher et al. qualitatively described the secondary impacts caused by various vehicle model body types and found the one-box and SUV model body types were "very critical" for children and adults, while the van model body type was "very critical" to children and "critical" to adults.

It should be noted that the studies in this section all focused on HIC values or head injuries to the exclusion of other injuries that a pedestrian might sustain from secondary impact with the ground or other objects following a collision. Several studies justified this focus on head injury risk by noting that pedestrian fatalities were most commonly a result of head injuries. Even so, as the available studies exclusively focused on head injuries, they provided little information about other potential injuries because of secondary ground impact.

In addition, most studies that examined secondary ground impact did not also examine the primary vehicle impact. Because of this, it is difficult to know whether the front-end designs that resulted in less dangerous head–ground impact in these studies were safer for pedestrians overall. That is, front ends that caused less injury risk from head–ground impact might also increase injury risk from the primary collision between the vehicle and the pedestrian.

An exception to this lack of information on primary vehicle impact in studies that examine secondary impact was Anata et al.'s 2011 investigation of JARI pedestrian model HIC values caused by simulated collisions with Japanese vehicle models both at the time of primary impact and secondary ground impact. In these MADYMO computer simulations, a total of 45 conditions were considered with variations in vehicle model (sedan, SUV, and van), pedestrian model (five variations in age and sex), and collision velocity (20, 30, and 40 kmh). The authors found the HIC_{15} values from the pedestrian model were higher from secondary impact with the ground in a large majority (38 of 45, or 8%) of the impact simulated scenarios.

Front-End Studies Examining Pedestrian Gait/Stance Effects

As the simulation studies by Simms et al. (2011), Crocetta et al. (2015), and Hamacher et al. (2012) discussed in the previous section demonstrated, a pedestrian's gait at the time of impact may introduce a large amount of variability to the kinematics of a vehicle–pedestrian collision. None of these studies, however, provided an assessment of how the kinematics changed because of various gaits or stances when a pedestrian was struck. The modeling did suggest, though, that while pedestrian stance may affect injury patterns, the shape of the vehicle modeled may have a large effect too.

Similarly, a simulation study by Peng et al. (2011), with authors based in China, France, and Sweden, found that simulated pedestrian gait was a cause of variability in wrap around distance, head relative velocity, and impact angle with a vehicle model. A subsequent peer-reviewed journal article by many of the same authors reported similar findings (Peng et al., 2012). In MADYMO simulations, gait caused higher variability for the 50th percentile male adult model compared to the 6-year-old child model (Peng et al., 2011). Neither study discussed if a particular pedestrian gait was more injurious than another gait. Both papers found head impact speed higher for the small family car model striking the adult model, even exceeding the vehicle velocity, compared to the other vehicle models, though the authors did not discuss the exact mechanisms that caused this outcome. The authors also found that the wrap around distance could vary by as much as 150 mm from the average for the adult model, depending on its gait, while the child model had much less variance.* While the authors did not directly assess the effect this might have on head injury, the finding is important because it suggests that a range of possible head impact locations are possible. As other studies have shown, the location of head impact on a vehicle might have large effects on head injury risk, with a head-strike on the

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* The authors list 150 mm as the variance in wrap-around distance in Peng et al. (2011). The other study by four of the same authors (Peng et al., 2012) does not list a specific measurement of variance but does reference that there is significant variance in adult wraparound distance and relatively little variance for the child model.

windshield being softer than one on the cowl (Han et al., 2011/2012b; Li & Simms, 2015; Sankarasubramanian et al., 2015/2016).

A simulation study by Li et al. (2015) provided more detail about the specific kinematics of a collision according to the stage of the pedestrian's gait cycle at the moment of impact. Specifically, the study examined the stress caused by the simulated impact of an SUV or sedan on a pedestrian's lower limbs at various stages of the walking gait cycle, finding that, in general, the more flexed the struck knee, the less stress it sustains. The authors based the SUV FE model on a 1997 Toyota RAV4 model from the NCAC Vehicle Model Library, with implication that the model was on the U.S. market. The authors did not state the vehicle on which the sedan FE model was based. While vehicle models of sedans and SUVs caused different kinds of stress on different parts of the legs in a collision, SUV impacts generally resulted in higher knee bending angles than sedan impacts because of the lower leg wrapping under the SUV's bumper, which was relatively higher from the ground on the SUV model than the sedan model.

Pedestrian Collision Avoidance/Mitigation System Studies

Overall, the review team located four international studies discussing the impact of collision avoidance and mitigations systems on pedestrian injuries as a function of vehicle category. These studies reviewed both active safety systems and passive safety systems in different vehicle body types, with two studies discussing their effectiveness for preventing injuries in pedestrians of different ages and sizes (Leo et al., 2020). Three studies considered the effects of automatic emergency braking (AEB) on pedestrian safety.

One study completed by Hamacher et al. (2011) in Germany noted that vehicles are incorporating the latest technologies when it comes to pedestrian safety but acknowledged that more measures are necessary to ensure total pedestrian safety. Currently, vehicle markets include vehicles with active safety systems, such as automatic emergency braking, and passive safety systems, such as a windscreen air bag. Hamacher et al. compared the safety options offered by these two types of safety systems via both MADYMO simulations and Polar-II ATD tests. In simulation, characteristics of the vehicle's frontal design were compared with each safety system to determine its overall effectiveness at reducing pedestrian injury. This study used specific Euro NCAP headform test results to translate the HIC values to simulated pedestrian kinematics. The results of this comparison assessment matched the values for the pedestrian model's risk of serious (AIS 3+) head injury due to the primary impact at a simulated collision speed of 40 kmh (~25 mph). The results of this computational study showed that for secondary impact, SUVs and one-box vehicle models were particularly harmful in the context of simulated pedestrian head injuries. However, in general, study authors found automatic emergency braking systems were helpful for reducing injuries due to secondary impact. The safety measures studied had varying degrees of success for different sized pedestrian models, as simulated windscreen air bags were particularly helpful for adult pedestrian models and pedestrian automatic emergency braking was particularly helpful for child models The findings with regard to the adult pedestrian models were validated via four tests conducted with the Polar-II 50 th percentile male ATD (two tests at a collision speed of 40 kmh – one without advances safety systems and one with such systems, one test at 30 kmh, and one test at 20 kmh).

Similarly, in a simulation study completed in Austria by Leo et al. (2020), researchers found that automatic emergency braking benefited child models, as well as decreasing simulated collision velocities by one-third. Leo et al. found that in simulations with the 50th percentile adult male pedestrian model, the head impact velocity slightly exceeded the simulated collision velocity for both the sedan and SUV models, with higher average head impact velocity values for sedan collisions. Head impact angles reduced with reduced simulated collision velocity. Impact simulations with the 5th percentile female pedestrian model resulted in higher average head impact velocity and head impact angle values with the SUV. Simulations with the 6-year-old child pedestrian model resulted in lower head impact velocity values than collision velocity, with higher head impact velocity values for the sedan, and similar head impact angle values for both the sedan and the SUV. The simulation study suggested that incorporating both active and passive pedestrian protections provides more measures for protection from different impact conditions.

Moreover, a simulation study in Japan by Toshiyuki and Yukou (2017) estimated the reduction in pedestrian injuries and fatalities resulting from pedestrian AEB systems by applying the logic of a Japanese production system to national accident statistics. It was estimated that the production pedestrian AEB system studied could result in a 20 percent decrease in injured pedestrians, as well as a 5 percent decrease in fatalities and a 12 percent decrease in serious injuries. Specifically, factors associated with vehicle category, pedestrian age, and most severely injured body region demonstrated the greatest degree of "sensitivity" for this result.

Another Japanese study, by Matsui et al. (2011), modeled the impact of collision damage mitigation braking systems on pedestrian model injuries in simulated collisions and evaluated the success of CDMBS in lessening pedestrian model injury severity for a medium sedan, a mini car, and an SUV model at various speeds. They conducted impact experiments with a pedestrian surrogate and medium sedan, as well as collision simulations with the THUMS 50th percentile male pedestrian model, and three FE vehicle models. Matsui et al. used modified front ends from the NCAC's Honda Accord and Toyota RAV4 FE models to represent the medium sedan and SUV and developed a minicar FE front-end model based on the Suzuki Alto. Simulation results showed that a ten kilometer-per-hour decrease in impact velocity due to CDMBS helped prevent severe injury at impact speeds of 40 kph or more, particularly for the medium sedan and SUV models.

Summary

Current pedestrian safety research encompasses a range of factors influencing injury severity levels, including vehicle characteristics, pedestrian demographics, collision location, crash time-of-day, and other environmental factors. The review team performed a comprehensive scan of pedestrian safety literature addressing vehicle factors relevant to pedestrian safety outcomes and generally narrowed the literature review to studies addressing whether larger passenger vehicles, such as pickup trucks, SUVs, and vans, are more dangerous to pedestrians than smaller passenger vehicles. The review team divided results into five main categories according to study area: (1) general pedestrian collision research methodology, (2) pedestrian collision research methodology with a medical focus, (3) vehicle size/weight/body type studies, (4) vehicle hood/front-end profile studies, and (5) pedestrian collision avoidance/mitigation studies.

There were several findings in the literature.

- Studies based on U.S. national data suggest that while passenger cars incur the greatest percentage of pedestrian fatalities, percentages of SUV–pedestrian fatalities were increasing at a faster rate (Retting, 2019, 2020, 2021; Macek & Petraglia, 2022; Schneider, 2020; Hu & Cicchino, 2018); However, since 2012, SUV production has been increasing, and passenger car production has been decreasing as a percentage of all vehicles produced (U.S. Environmental Protection Agency, 2023).
- A study based on U.S. national data suggests that SUVs' greater power-to-weight ratios relative to small passenger cars might render them more injurious to pedestrians in collisions.
- A recent study on U.S. national data on pedestrian fatalities and North Carolina State-level data suggests that the dimensions of LTVs are more dangerous to pedestrians than the dimensions of passenger cars, due in part to poor visibility.
- One study suggests that children and older pedestrians suffer more severe outcomes when struck by an LTV versus other smaller vehicle classes.
- Findings in another study suggest that vehicles with frontal guards are more injurious than vehicles without frontal guards in collisions with child pedestrians.
- Results from some studies suggest that vehicle front end design, including dimensions such as hood leading edge height and hood length, are influential to pedestrian injury outcomes in the event of a collision.

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DOT HS 813 676a
March 2025 (Revised)

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