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Review of Literature Addressing Effects of Pedestrian Safety-Related Test Requirements on Vehicle Design, Fleet Composition, and Pedestrian Injury

Task 2

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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 and vehicle size and weight published over the past 10 years on whether larger vans, pickups, and SUVs may be more dangerous to pedestrians than smaller vehicles. The review found 79 scholarly sources published from 2011 to 2022 that are relevant to whether larger light vehicles are more injurious to pedestrians than smaller passenger cars. These include 52 peer-reviewed articles; 7 university- or government-sponsored reports; and 20 conference proceedings papers. Overall, the review team found that many U.S. scholarly sources supported that LTVs cause higher levels of injury severity to pedestrians than smaller passenger cars in collisions. However, international English language-sources reported more results that are mixed, potentially due at least in part to vehicle markets trends that skew into favor of more SUVs that are compact, and fewer pickups. The review organized the literature review in five 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.

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List of Abbreviations

ACL	anterior cruciate ligament
AEB	automatic emergency braking
AIS	Abbreviated Injury Scale
ANOVA	analysis of variance
EPP	expanded polypropylene foam
Euro NCAP	European New Car Assessment Programme
FARS	Fatality Analysis Reporting System
FE	finite element
Flex-PLI	flexible pedestrian leg impactor
FRD	Federal Research Division
GIDAS	German In-Depth Accident Study
GMT	glass mat thermoplastic
HIC	head injury criterion
ITARDA	Institute for Traffic Accident Research and Data Analysis
Japan NCAP	Japan New Car Assessment Program
LTV	light trucks and vans
MADYMO	mathematical dynamic models
MAIS	Maximum Abbreviated Injury Scale
MCL	medial collateral ligament
MPV	multipurpose vehicle
NCAC	National Crash Analysis Center
NDTB	National Data Trauma Bank
PCDS	Pedestrian Crash Data Study
PCL	posterior cruciate ligament
PMHS	postmortem human subjects
STRADA	Swedish Traffic Accident Data Acquisition
THUMS	Total Human Model for Safety
TRL	Transportation Research Laboratory
VIPA	Vulnerable Road User Injury Prevention Alliance

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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 on pedestrian injuries and fatalities. NHTSA is interested in research that (1) identifies key vehicle crash data sources; (2) supports its policy decisions; and (3) identifies market trends in changes to vehicle design that affect pedestrian safety in the United States and internationally. NHTSA contracted the Federal Research Division at the Library of Congress to conduct this literature review on pedestrian safety.

In support of the second literature review, the review team examined domestic 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. The review team 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 and the Japan New Car Assessment Program.

This Task 2 report details the review team's findings in literature about the effects of vehicle design and pedestrian test requirements, test protocols, and regulations on pedestrian injury outcomes. Overall, the review team found a body of academic literature broadly discussing the effects of vehicle size and specific components, on pedestrian injuries, including head, chest, and lower-extremity injuries. However, the review team found 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.

Additionally, the review team found U.S. vehicle sales statistics to see whether the growing proportion of light trucks were exclusively sold in North America or also sold in Europe and Japan. Just one scholarly source compared U.S. variants with global variants of the same vehicle models, but this study found that most of the U.S. models tested were more dangerous to pedestrians than their European counterparts, particularly U.S.-exclusive pickups.

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.

Key findings from the literature review:

- Some studies suggest that higher-hood leading edges and low-hood angles result in head injuries that are more severe in pedestrian–vehicle collisions (Anderson & Doecke, 2011; Hu et al., 2023; Gunasekaran, 2021).
- Some studies suggest that vehicles with higher front ends are more likely to result in severe head injuries from ground contact mechanisms, particularly for child pedestrians (Crocetta et al., 2015; Simms et al., 2011; Hamacher et al., 2012).

- Simulation studies suggested that high-ground-clearance vehicles are more likely than lower ground clearance vehicles to result in knee ligament injuries, as well as fractures to sections of the femur and tibia closest to the knee (Sáez et al., 2011/2012; Mo et al., 2015; Wang et al., 2016; Matsui, Han, & Mizuno, 2011).
- Research on head impact locations for adult pedestrians suggested that collisions with sedans most often result in the head striking the windshield, while crashes with SUVs most often result in hood impacts (Wang et al., 2020; Kerrigan et al., 2012; Han et al., 2013).
- Although relatively few scholarly sources were found to have discussed the real-world effects of Euro NCAP and Japan NCAP testing protocols, several sources reported correlations between vehicles that had high ratings in Euro NCAP pedestrian crashworthiness testing and reductions of severe injury and fatality levels to pedestrians in collisions (Strandroth et al., 2011, 2014; Pastor, 2013).
- A study was found that analyzed real-world data from 1999 to 2009 in Japan and found that Japan's 2005 regulation requiring head-to-hood testing mitigated pedestrian injuries for some vehicle body types, including minivans and light cargo vans (Oikawa & Matsui, 2016/2017).
- Among the 40 best-selling vehicle models in the United States in 2022, sales of U.S.-exclusive light truck models exceeded global light truck model sales. The top three best-selling U.S. models were pickups not tested in Euro NCAP or Japan NCAP protocols (Wards Intelligence, 2023).
- A study found that some vehicle platforms designed to comply with European safety standards were found to have been carried over to variants sold in the United States; however, when they differ, some U.S. variants of global vehicle models were found to perform worse in tested pedestrian headform and legform tests than the European variants of the same vehicles (Suntay et al., 2019).

The next two sections outline the research topics that guided the literature review, as well as the review team's search methodologies. Sections 4 to 8 describe the team's observations on vehicle size, injurious vehicle components, the effects of pedestrian testing protocols on pedestrian safety, and U.S. fleet composition relative to Europe and Japan. The final section describes gaps in the current literature on vehicle design, testing requirements, and fleet composition.

Overview

This report addresses the effects of vehicle size and specific vehicle components on pedestrian injuries, as well as the effects of testing requirements on vehicle design and pedestrian safety. There is special focus on hood design that could influence head injuries, as well as front-end design components that influence leg injuries, as these are related to current pedestrian headform and legform test protocols in Europe and Japan. Particular attention is also paid to the influence of vehicle design on thorax injuries, an element not included in Euro NCAP and Japan NCAP testing protocols.

In addition to focusing on how vehicle design affects pedestrian injury outcomes in the United States, Europe, Japan, and Australia, the review team explored how NCAP testing protocols have influenced changes in vehicle designs and how widescale design changes have, in turn, influenced pedestrian safety, especially in Europe and Japan.

The 12 specific research topics explored by the project team:

1. Studies on pedestrian injury related to vehicle size, particularly any source that describes a vehicle's injurious component.
2. Studies on the injurious vehicle component, especially serious injuries, by vehicle size and injury type, including body regions such as the thorax that are not addressed by current test procedures.
3. Studies showing whether relatively fewer collisions with large light vehicles result in the pedestrian's propulsion over the vehicle hood versus collisions with small light vehicles. These studies may include kinematics in which the pedestrian strikes the windshield or other vehicle components rearward of the hood, or kinematics in which the pedestrian vaults over the vehicle.
4. Research addressing the premise that since larger vehicles have hoods that cover more physical area, the injurious component tends to be the hood (i.e., the regulated component) versus a rearward component (e.g., the A-pillar, roof, or ground impact).
5. Studies that address whether high-ground-clearance vehicles tend to produce lower-leg injuries, even at lower speeds. This includes real-world studies of ligament versus tibia injuries by vehicle size.
6. Research showing whether and how a high-ground-clearance pickup may be designed so that the flexible pedestrian leg impactor (Flex-PLI)* "bounces off" the front end before it gets a chance to wrap around (and thus does not produce high tibia bending or ligament elongation).
7. Research demonstrating whether or how larger vehicles have changed vehicle designs in response to pedestrian impact requirements.
8. Studies that describe how injury patterns may have changed following the implementation of pedestrian testing requirements and protocols.
9. Studies that show how designing according to a hood-only requirement may have the unintended effect of vehicle designs that are more injurious for smaller pedestrians.

* The Flex-PLI is used in pedestrian–vehicle collision tests to evaluate pedestrian lower limb injuries.

10. Studies that show how designing according to a head-to-hood impact requirement or an upper-leg-to-hood-leading-edge requirement could affect injury risk to the thorax in pedestrian–vehicle collisions.
11. Fleet studies and manufacturer sales information that can confirm whether the increasing proportion of pickups and SUVs in the U.S. fleet are "North American only" and are not offered for sale in Europe or Japan (where hood impact protocols apply).
12. Studies that show whether smaller vehicles have changed designs outside the United States and Canada to conform to international pedestrian protocols (i.e., "flatter" and higher front ends).

Methodology

The review team drafted the literature review based on searches related to the 12 research topics on vehicle design, testing requirements, and pedestrian safety outcomes. The review team scanned available literature for relevant peer-reviewed journal articles; monographs; book chapters; reports from government and regulatory bodies, university research centers, and relevant transportation nonprofit organizations; academic theses and dissertations; technical papers; trade journals; popular online automotive sources; and U.S. and international patents.

The team first found peer-reviewed articles in Library of Congress-hosted databases such as Academic Search Complete (EBSCO), Compendex (Engineering Village), JSTOR, Taylor & Francis, and Science Database (ProQuest). The review team also searched for other relevant sources through the Library's "Selected E-Journals in Engineering & Applied Sciences" using the sub-category "Automotive Engineering." Besides library-hosted resources, the review team searched Google Scholar and the open web for publicly available resources. The review team constructed Boolean search strings incorporating variations of the following phrases.

- Bonnet leading edge
- Bumper
- Chest
- Chest injury
- Child pedestrian
- Euro NCAP
- Femur
- Femur injury
- Flex-PLI
- Grille
- Hip
- Hip injury
- Hood
- Hood dimensions
- Hood length
- Hood size
- Japan NCAP
- JNCAP
- Knee
- Knee injury
- Legform impactor
- Ligament
- Ligament injury
- Lower extremity
- Lower leg
- NCAP
- New car assessment program
- New car assessment programme
- Pedestrian
- Pedestrian crash
- Pedestrian fatality
- Pedestrian injury
- Pedestrian leg injuries
- Pedestrian safety
- Pedestrian trauma
- Pelvis
- Pelvic injury
- Pickup
- Pickup
- Pickup bonnet leading edge
- Roof vault
- Sedan

- SUV
- Thoracic injury
- Thorax
- Thorax injury
- Tibia
- Tibia bending
- Tibia injury
- Vehicle
- Vehicle design
- Vehicle dimensions
- Vehicle fleet
- Vehicle sales
- Vehicle shape
- Vehicle size
- Vehicle type
- Windshield
- Wraparound

Relevant academic journals and conference proceedings found during the searches of Library resources included the following publications.

- *Accident Analysis & Prevention*
- *Acta of Bioengineering and Biomechanics*
- *Annals of Advances in Automotive Medicine*
- *Archives of Civil and Mechanical Engineering*
- *Chinese Journal of Traumatology*
- *International Conference on Measurement Technology and Mechatronics Automation*
- *International Journal of Automotive Technology*
- *International Journal of Crashworthiness*
- *International Journal of Injury Control and Safety Promotion*
- *International Journal of Vehicle Safety*
- *International Research Counsel on Biomechanics of Injury (IRCOBI) Conference*
- *International Technical Conference on the Enhanced Safety of Vehicles*
- *Journal of Automobile Engineering*
- *Journal of Biomedical Physics and Engineering*
- *Journal of Mechanical Science and Technology*
- *Journal of Safety Research*
- *SAE (Society of Automotive Engineers) International Journal of Transportation Safety*
- *Stapp Car Crash Journal*
- *Structural and Multidisciplinary Optimization*
- *Traffic Injury Prevention.*

Beside identifying the above resources, the review team consulted U.S. and European vehicle sales statistics to address Topic 11 on light trucks in the U.S. vehicle fleet, including 2018 to 2022 U.S. vehicle sales data from Wards Intelligence; these statistics were found by the review team addressing the third literature review—trends in vehicle markets and changes to vehicle design that affect pedestrian safety. The team focused its analysis on the 40 best-selling passenger vehicles in 2018, the most prolific year for U.S. vehicle sales in the past 5 years, and 2022, the most recent year with comprehensive sales data. The review team then searched the global websites of several top vehicle manufacturers and the Euro NCAP and Japan NCAP websites to determine whether best-selling U.S. pickup and SUV models are also sold in Europe and Japan.

The review team also searched the U.S. Department of Transportation's Repository & Open Science Access Portal (ROSAP) database for relevant sources on pedestrian leg and thoracic injuries in relation to vehicle types and injurious vehicle components. The review team examined the Euro NCAP site for reports showing whether pickups might be designed so that the Flex-PLI bounces off the vehicle's bumper rather than wrapping around the front end. The team did not find any detailed Euro NCAP reports that provided tibia bending or knee ligament elongation values for the tests.

As the review team found relatively few academic sources addressing discrete design changes in direct response to the implementation of pedestrian testing protocols, the team also searched for patents responding to NCAP programs. Although patents should not be interpreted as providing evidence of real-world design changes, they nonetheless provide insight into potential design changes that might successfully address testing requirements. In the process of reviewing design changes referencing NCAP protocols, the team found several patents that proposed designs for high-ground-clearance vehicles to mitigate leg bending in pedestrian–vehicle collisions.

The 12 research topics focused on here share extensive overlap with the first literature review's focus on vehicle size and weight, as well as whether light trucks and vans are more injurious to pedestrians than smaller passenger cars in collisions. Therefore, the review team's keyword searches yielded many of the sources previously identified during the first literature review. Besides identifying new sources through keyword searches, the review team consulted the first literature review and annotated bibliography for sources addressing vehicle size, injurious vehicle components, high-ground-clearance vehicles, lower-leg injuries, thoracic injuries, and pedestrian kinematics. The review team has listed duplicate sources by section in an appendix to this report.

As relatively few English-language scholarly sources identified design changes in direct response to NCAP testing protocol implementation or pedestrian protection regulations, the review team also used the Library of Congress's Primo search service to find foreign-language academic sources on design changes. The results yielded two Chinese-language sources from the China National Knowledge Infrastructure database referencing front-end design changes in response to NCAP testing protocols with respect to specific vehicle models. The research team then used translation applications to evaluate the sources.

In reporting the results of the literature review, the review team divided the 12 topics into five main sections:

- Section 4 – vehicle size and related design changes discusses Topics 1, 7, and 12 on how vehicle size affects injury outcomes, as well as how vehicle manufacturers have changed the designs of large passenger vehicles and smaller passenger cars in response to Euro NCAP and Japan NCAP testing protocols.

- Section 5 – thoracic injuries and testing requirements discusses Topics 2 and 10, addressing how vehicle size and specific front-end components affect thoracic injuries in collisions with pedestrians, as well as whether existing pedestrian testing protocols address thoracic injury outcomes.
- Section 6 – lower-leg injuries and high-ground-clearance vehicles discusses Topics 5 and 6 on whether high-ground-clearance vehicles such as pickups and SUVs tend to cause lower-leg injuries in collisions, and how high-ground-clearance pickups might be designed to avoid extensive tibia bending and ligament elongation.
- Section 7 – hood design and pedestrian kinematics discusses how Topics 3, 4, and 9 address hood design that affects pedestrian kinematics during collisions, and how a hypothetical hood-only impact requirement would affect injury risk for smaller pedestrians.
- Section 8 – testing requirements, injury patterns, and fleet composition discusses Topics 8 and 11 on whether Euro NCAP and Japan NCAP testing protocols improved real-world injury outcomes, as well as differences between U.S. and European or Japanese variants of the same vehicle models.

Vehicle Size and Related Design Changes

This section details the review team's findings on Topics 1, 7, and 12, which address the relationship between vehicle size and injurious vehicle components, as well as design changes to large and small light vehicles following Euro NCAP testing protocol implementation.

- Topic 1 – Pedestrian injury sources that relate to vehicle size, particularly any source that describes the injurious component of a vehicle.
- Topic 7 – Research demonstrating whether or how larger vehicles have changed vehicle designs in response to pedestrian impact requirements.
- Topic 12 – Studies that show whether smaller vehicles have changed designs outside the United States and Canada to conform to international pedestrian protocols (i.e., "flatter" and higher front ends).

The review team found several studies reporting that large light vehicles such as pickups and SUVs, were more likely to cause severe or fatal injury to pedestrians. When considering injured body regions at the component level, several studies reported that the higher hood leading edges of LTVs were more likely than passenger cars to cause severe or fatal head injuries. A few sources also suggested that LTVs' higher leading-edge components, such as bumpers and grilles, were more likely to cause severe leg, hip, and pelvic injuries.

The review team found several scholarly sources that highlighted design changes implemented after the implementation of pedestrian crashworthiness testing protocols, such as "softer" front ends of passenger vehicles and higher hood leading edges of smaller passenger cars. The review team also found several patents from the study period that reference Euro NCAP pedestrian testing protocols as motivation.

Vehicle Size and Injurious Vehicle Components

Much of the literature published from 2011 to 2023 on the effects of vehicle size on pedestrian safety found that in comparison to small passenger vehicles, large passenger vehicles were involved in pedestrian crashes at a higher rate, potentially due to increases in LTV sales and reduction in passenger car sales during that time. Larger passenger vehicles were also reported to be more likely to result in severe pedestrian injury or fatality in the event of a collision. For example, in a paper on the growing role of SUVs in pedestrian fatalities in the United States, Tyndall (2021) incorporated crash data from NHTSA's Fatality Analysis Reporting System, with a focus on 362 metropolitan areas from 2000 to 2018. He used vehicle registration data to "construct annual estimates of vehicle fleets by vehicle body types" to calculate the proportion of large vehicles involved in pedestrian fatalities. He found "an increasing impact of SUVs, particularly large SUVs, on pedestrian fatalities" and estimated that replacing all light trucks (including SUVs, pickups, and minivans) with cars over the 18-year study period would have reduced pedestrian deaths by 8,131. Tyndall ascribed large vehicles' propensity for causing higher rates of injury and fatality to two causes: Large vehicles' greater weight caused them to decelerate at a slower rate, which resulted in "more force as compared to a lighter vehicle," and large vehicles' taller front ends made them more likely to strike a higher point on the body, such as the thorax or head.

International studies on injuries and fatalities by vehicle body type, however, have produced varying results. For example, Malczyk et al.'s 2012 study using German In-Depth Accident Study (GIDAS) data found that SUVs were not more likely than passenger cars to result in more severe injury to pedestrians. On the other hand, D'elia and Newstead (2015) analyzed real-world crash data from Victoria, Australia, to find differences in the risk of injury or death between vehicle body types. They used generalized linear models to compare injury outcomes for various vehicle market groups "relative to large passenger cars." Compared with large passenger cars, utility vehicles were 28.5 percent more likely to cause pedestrian injury or fatality. D'elia and Newstead also found differences between vehicle body types for the likelihood of pedestrian injury or death related to the head, face, and neck body region. Analysis of these body regions found a 27.1 percent higher likelihood of injury or fatality for small cars compared with large passenger cars, and likewise a 53.9 percent higher likelihood for minivans, a 44.5 percent higher likelihood for large SUVs, a 65.1 percent higher likelihood for vans, and a 53.6 higher likelihood for light commercial utility vehicles.

In general, the most recent study period literature emphasized the role of large light vehicles in causing serious injuries to vital body regions, including the head. For instance, in their study of Illinois crash data on vulnerable road users from 2016 to 2018, Edwards and Leonard (2022) found that pedestrians and pedalcyclists struck by pickups sustained AIS 2+ (non-minor) head injuries in 11.1 percent of cases, while SUVs yielded AIS 2+ head injuries in 9.9 percent of cases. The other vehicle types studied – van/minivans and passenger cars – produced AIS 2+head injuries in 10.6 percent and 9.5 percent of pedestrian collisions. Child pedestrians and pedalcyclists experienced non-minor head injuries in 12.7 and 11.0 percent of cases when struck by vans/minivans or pickups.

However, another international study illustrated differences in injury types between different large vehicle body types. Oikawa and Matsui (2016/2017) distinguished between "passenger" van-type vehicles and "cargo" van-type vehicles in their study on the effects of vehicle front-end geometry on serious pedestrian injury outcomes. The study analyzed Japanese data from 1999 to 2009 to find that light cargo vans and box vans[†] more frequently injured the head, while minivans, sedans, and other passenger cars more frequently injured the legs. They ascribed this to differing first-impact locations between vehicle models, noting that the bumpers of passenger cars first contacted pedestrians' lower legs, while the front panels and bumpers of vans contacted pedestrians' heads and legs at the same time.

Several studies on pedestrian injury sources demonstrate that vehicles with higher hood leading edges cause more severe head and neck injury outcomes in collisions with pedestrians. For example, an Australian study by Anderson and Doecke (2011) employed simulated collisions between a pedestrian model and sedan, SUV, and pickup models to evaluate pedestrian head kinematics and injury outcomes. The study demonstrated higher head injury criterion values for the SUV and pickup models than the sedan models, although head-to-hood contact forces were slightly greater in simulations with sedan models than SUV and pickup models. Anderson and Doecke ascribed the SUVs' and pickups' higher HIC values to higher neck forces due to taller hood leading edges, but cautioned against relying on subsystem impact tests, which have

[†] Also called one-box vans or microvans. These vehicles fall within the Japanese "kei car" classification and are smaller than multipurpose vehicles.

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.

In addition to hood leading-edge height, other factors such as hood angle also influence head injury outcomes. Hu et al.'s 2023 study examined the effects of vehicle front-end geometry to determine which design characteristics posed a higher risk of pedestrian fatalities in collisions. The study employed logistic regression models to police collision data from 2017 to 2021 from Connecticut, Florida, Maryland, Michigan, New Jersey, Ohio, and Pennsylvania. Analysis focused on hood leading-edge height, bumper height, hood angle, hood length. and windshield angle to determine which factors were most significant to injury outcomes. In addition to higher front ends, flat hoods resulted in greater risk of pedestrian fatality, a result that was "consistent with previous research findings that vehicles with tall front ends were associated with increased risk of serious or fatal head and thorax injuries to struck pedestrians." They observed that lower hood angles might have been more likely to result in severe head injury due to the comparatively small deformation space between the pedestrian's head and the engine block. However, the study did not find other design features, such as hood length or windshield angle, to be as "statistically significant" to fatality, although they noted that a crash in which the pedestrian did not contact the hood or windshield might have "obscured" the effects of these design elements. Gunasekaran's 2021 thesis on traumatic brain injuries in pedestrian–vehicle collisions using a computational approach also identified high hood leading-edge heights and low hood angles to be associated with severe (Abbreviated Injury Scale[‡] 4+) head injuries.

Several studies published from 2011 to 2023 emphasized the roles of front-end components beyond the hood, including windshields, A-pillars, and cowl-tops, in causing serious head and face injuries. In a 2012 conference paper analyzing real-world injury data for 67 pedestrian cases, Mueller et al. observed that windshields, cowls, and A-pillars "were far more common sources of head injuries" than vehicle hoods. Another 2012 study by Mallory et al. comparing GIDAS and Pedestrian Crash Data Study data accorded with Mueller et al.'s results about vehicle components beyond the hood. Specifically, Mallory's group found head injuries from windshields to be the second most common serious and disabling injury source, after lower-extremity injuries from bumpers. They noted that this injury type accounted for a greater percentage of PCDS than GIDAS cases. Furthermore, when Mallory et al. accounted for only passenger cars in the PCDS dataset, head-to-windshield injuries accounted for an even greater percentage of serious and disabling injuries than when light trucks were included in the analysis. Study authors ascribed the higher incidence of head-windshield impacts to the shorter front-end designs of passenger cars relative to other vehicle body types.

Many studies comparing pedestrian injury outcomes across vehicle body types also investigated differences in lower-extremity injury severity levels between vehicle types. For example, the Australian study by D'elia and Newstead (2015) found that for risk of injury or death from lower extremity impacts, analysis at the 5 percent level did not suggest significant differences between vehicle body types. On the other hand, analysis at the 10 percent level found that medium cars and vans "had statistically significantly lower odds of death or lower-extremity injury compared

‡ The AIS is "an anatomically based, consensus derived, global severity scoring system" used by research and policy experts to classify "an individual injury by body region according to its relative severity on a 6-point scale (1=minor and 6=maximal)" ("Abbreviated Injury Scale," Association for the Advancement of Automotive Medicine, https://www.aaam.org/abbreviated-injury-scale-ais-position-statement/).

to large cars." However, they did not posit which vehicle components might account for these differences.

A few studies, including the 2012 study by Mallory et al., report findings that design parameters such as hood leading-edge height were also associated with hip and pelvic injury outcomes in pedestrian collisions. In their analysis of Vulnerable Road User Injury Prevention Alliance data, Monfort and Mueller (2020) cited the leading edges of SUVs, including bumpers, grilles, and headlights, as common sources of severe hip and thigh injuries. In another study addressing thigh and pelvic injuries in pedestrian–vehicle collisions, Gunji et al. (2012) analyzed the effects of pedestrian body mass on injury outcomes in collision simulations with various Japanese vehicle models, including two sedan models representing different hood edge heights, an SUV model, and a minivan model. They compared outcomes between a baseline pedestrian finite element model and a model that introduced variations in the mass densities of the lower extremities. In collisions with the baseline pedestrian model, the front end of the SUV model contacted the greater trochanter, and the front end of the minivan model contacted the ilium. The resultant likelihood of pelvic fracture for the SUV and minivan models surpassed 90 percent, in contrast to a 5 percent likelihood for the sedan model with the lower hood edge.

In addition to literature on vehicle components, the review team identified several studies published from 2011 to 2023 that discussed injury risk due to ground contact in relation to vehicle body type and front-end geometry. Specifically, these studies found factors related to hood design — such as hood leading-edge height — that influenced pedestrian kinematics as the pedestrian subsequently contacted the ground after collision. For example, in a 2011 conference paper, Anata et al. analyzed Japanese crash data from the Institute for Traffic Accident Research and Data Analysis from 1993 to 2001. They divided the 104 cases in the database according to vehicle type: sedan, van, and SUV. The study found the van type caused the highest number of head injuries from the road surface versus the other two vehicle types. Anata et al. subsequently employed multibody collision simulations to examine the mechanisms of pedestrian ground contact with various vehicle types. The highest HIC values at any point in a collision, including primary and secondary impacts, were, on average, highest for the sport-utility type vehicle models, followed by the van type model, with the sedan type model having the lowest values.

Three studies evaluated the mechanisms of ground contact in simulated collisions. Crocetta et al.'s 2015 study on secondary ground contact, which did not employ real-world crash data, simulated collisions with six different vehicle models and three pedestrian models in six different gait stances. SUVs' and vans' higher front ends more often resulted in the pedestrian being projected forward in the simulated collisions. They noted more severe pedestrian head-ground contact for SUVs and vans than smaller passenger cars at speeds at or lower than 30 km/h. However, Crocetta et al. noted that in simulations at 40 km/h, passenger cars also resulted in high head-ground contact speeds for adult pedestrians. Vehicle simulations with higher hood leading-edge heights more often resulted in high head contact speeds for child pedestrian models, due to a mechanism in which the pedestrian was projected forward, and the upper body rotated "towards the ground." Simms et al.'s 2011 conference paper also assessed various ground contact mechanisms according to different pedestrian sizes and vehicle body types through simulation. They demonstrated a correlation between vehicle models with higher hood leading edges and higher HIC values from ground contact, observing that simulated collisions with high hood leading-edge vehicles caused the pedestrian to rotate less than 180 degrees so that the head "move[d] towards the ground." Hamacher et al. (2012) also found simulated collisions involving high front-end vehicles to be more injurious to the head, with one-box, SUV, and van models particularly injurious for simulated child models upon ground impact.

Gupta and Yang (2013) simulated collisions using U.S.-based mid-size car and SUV models and three different sizes of pedestrian multibody models—a 6-year-old child, a 5th percentile adult female, and a 50th percentile adult male—to determine the influence of vehicle front-end geometry on ground impact. They adjusted the dimensions of the vehicle models to investigate the effects of raising or lowering the front-end profiles of different vehicle models. The outcomes demonstrated that for all simulations with SUV models, collisions at 40 km/h or faster resulted in the pedestrian's head striking the ground. Just one SUV variant with a taller bumper and hood leading edge resulted in the pedestrian avoiding head-ground impact at 30 km/h.

Design Changes in Response to Testing Requirements

Only a few studies published in peer-reviewed journals or conference proceedings from 2011 to 2023 addressed the direct influence of the Euro NCAP and Japan NCAP on vehicle design in relation to pedestrian safety. Strandroth et al. (2011, 2014), discussed in greater detail below, noted significant injury reductions for pedestrians (and pedalcyclists) who were struck by high performing vehicles in the Euro NCAP pedestrian crashworthiness tests versus lower performing vehicles. In a 2019 thesis, Su noted that Japan NCAP protocols have also coincided with design changes in active pedestrian safety, including innovations in active hoods and AEB systems. In a study analyzing potential benefits to low- and middle-income countries from addressing traffic injury risk factors, Bhalla et al. (2020) identified passive safety measures associated with Euro NCAP protocols, including "softer" bumpers, hoods, windshields, and A-pillars.

Literature on design changes in response to pedestrian safety requirements reported that design trends have largely shifted after the implementation of international pedestrian testing protocols. In one of the few academic studies published from 2011 to 2023 addressing design changes in response to international pedestrian protection protocols, Nie and Zhou (2016) noted that passenger vehicles changed designs after a 2003 directive that mandated pedestrian safety testing of a vehicle's front end to receive type-approval in the European Union. They stated that SUVs manufactured after the directive incorporated "flatter front-end design[s]" with a more forward-projecting lower valence.

Some LTVs, including pickups, have earned overall 5-star ratings in Euro NCAP tests. For example, in 2011 Euro NCAP tests, the Ford Ranger earned an overall 5-star rating with a score of 81 percent in pedestrian protection due to improvements in its front-end design. An article from *Fleet World* ascribed the vehicle model's high pedestrian safety rating to its "softer and well-engineered front end, absorbing the impact energy and better protecting pedestrians" (Ford Ranger becomes first pickup, 2011).

Smaller passenger vehicles have also undergone design changes following the implementation of Euro NCAP and Japan NCAP testing protocols. Research from the study period highlighted changes to the front-end geometries of smaller vehicles, including a study by Li et al. (2018), which noted the "wider and flatter bumpers," higher hood leading edges, "shorter and steeper" hoods, and "shallower windscreen[s]" of small light vehicles. Li et al.'s findings accorded with descriptions of newer vehicle models in a 2012 *Automotive News* article (Rogers, 2012), which identified design changes such as "higher hood lines and lower bumpers." The same article cited as an example the 2013 Ford Fusion, which incorporated a raised front end and hood to "shorten the distance a pedestrian would fall if hit."

Besides English-language academic studies on design changes following the implementation of international pedestrian protection testing protocols, the review team found two Chinese-language sources discussing front-end design parameters implemented after Euro NCAP pedestrian testing protocols were established. Tan et al. (2017) referenced design changes to the front bumpers of vehicle models in response to Euro NCAP protocols, citing the Honda CR-V and Audi A4L as examples of the trend toward increasingly convex bumper shapes and decreased bumper width to minimize the potential area of pedestrian contact with the vehicle. On the other hand, Lv et al. (2011) pointed to the BMW 5 Series' hood design, specifically the positioning of the hood's character lines, as conferring good pedestrian protection according to Euro NCAP tests.

Vehicle manufacturers in the United States and abroad have patented designs to improve pedestrian protection in response to international testing protocols, with many U.S. and international patents referencing specific vehicle body types, including LTVs. Research on patents does not independently demonstrate real-world design changes, as patented innovations are not necessarily implemented by vehicle manufacturers. However, patents nonetheless provide useful information about possible design trends in vehicle manufacturing, particularly when they are assigned to large-scale vehicle manufacturers. The review team identified 11 relevant U.S. and international patents on front-end design components that cited international pedestrian testing protocols. For example, two U.S. patents issued in 2017 and filed by Ford Global Technologies described a bumper structure with stiffeners designed to reduce pedestrian leg injuries in SUV and light truck collisions (Farooq et al., 2017a, 2017b). One further recent patent, published in 2022 and assigned to Ford, specified a bumper assembly structure to minimize leg injuries (Shenaq et al., 2022). Similarly, a 2019 German patent, which was subsequently patented in the United States by the same company, detailed a grille reinforcement structure designed to decrease pedestrian leg bending during collisions with SUVs and pickups (Shenaq et al., 2019, 2021).

Many patents from the study period responding to international pedestrian testing protocols also specified design parameters without reference to specific vehicle body types, including international patents. For example, a 2019 Chinese patent specified a design for a hood with a core of aluminum and expanded polypropylene foam (Zhang, 2019). Similarly, a 2016 U.S. patent outlined an energy-absorbing "ladder honeycomb hood structure", and an additional 2017 U.S. patent described a hood structure with an inner insert designed to be "brittle relative to" the "outer panel" to "[allow] controlled deformation of [the] outer panel during frontal loading" (Ray et al., 2016, Shastry et al., 2017). Several international patents during the study period also described inventions to mitigate pedestrian windshield impacts, without citing any specific vehicle body type or model. For example, a 2020 Japanese patent (Hirano et al., 2020) described a laminated glass windshield invention designed to protect pedestrians' and vehicle occupants' heads from breaking through the glass in collisions. Two further innovations patented in the World Intellectual Property Organization in 2019 and 2020 detailed other laminated glass windshield structures designed to control breaking, thereby reducing head injuries (Cleary et al., 2019, 2020).

Thoracic Injuries and Testing Requirements

This section discusses research related to Topic 2 and Topic 10, which address the effects of vehicle size and specific vehicle components on thoracic injuries, as well as whether designing according to headform and legform requirements affect thoracic injury risk in pedestrian–vehicle collisions.

- Topic 2 – Studies presenting the injurious vehicle component (for serious injuries in particular) by vehicle size and injury type, including body regions such as the thorax that are not addressed by current test requirements.
- Topic 10 – Studies that show how designing according to a head-to-hood impact requirement or an upper-leg-to-hood-leading-edge requirement could affect injury risk to the thorax in pedestrian–vehicle collisions.

For Topic 2, the review team found several studies suggesting that the risk of pedestrian thoracic injuries was likely growing due to increasing numbers of larger vehicles. Studies citing the disproportionate effects of large vehicles referenced pickups, SUVs, and vans. Real-world injury data studies also found that larger vehicles were often responsible for the more dangerous thoracic injuries incurred by pedestrians. The literature suggested that vehicles with high and flat front ends, as well as models with sloped hoods, seemed to pose particular danger to pedestrians. These vehicle types tended to produce greater deformation of the chest compared to smaller vehicles and passenger cars. One study suggested that shoulder impact location influenced pedestrian chest injury severity, the worst striking location for a pedestrian being a combination of the cowl, windshield, and glass. Finally, the team found information on pediatric thoracic injuries and fatalities. One small, real-world study found thoracic injuries in pediatric fatalities tended to be associated with high front-end vehicles. The other study used simulation which suggested the SUV models produced greater chest deformations compared to smaller passenger car models, but the smaller passenger car models produced more rib fractures.

For Topic 10, the review team found relatively few mentions in the literature of how head and leg testing requirements affected thoracic injury outcomes. However, several studies suggested a need for this kind of testing requirement, and a few studies discussed relationships between the head and leg Euro NCAP tests with thoracic injury outcomes.

Thoracic Injury Outcomes

Several sources suggested that vehicles with high front ends, as well as vehicles with flat front structures, resulted in higher incidences of thoracic injuries and injury severity levels. A study on U.S. State data by Edwards and Leonard (2022) based on Illinois hospital and crash data from 2016 to 2018 found that pedestrians and pedalcyclists struck by large motor vehicles (SUVs, pickups, and vans/minivans) were more likely to suffer AIS 2+ injuries to their thorax compared to those struck by passenger cars. When considering the proportion of all AIS 2+ thorax injury cases, the greatest proportion (42.1%) were attributable to passenger cars followed by SUVs and pickups at 17.4 percent and 11.1 percent. In general, they found pickups and SUVs were disproportionately responsible for these severe and fatal pedestrian collisions compared to passenger cars when considering their respective crash involvement rates. They attributed the high front ends of larger vehicles as primarily responsible for the “non-minor” and severe thoracic injuries.

Like Edwards and Leonard, Harmon et al. (2021) conducted a study of a U.S. State and found larger vehicles resulted in more severe injuries to the thorax compared to passenger cars. Harmon et al. used linked North Carolina crash and hospital data to determine which vehicle characteristics influenced pedestrian injury outcomes. The study found that while passenger cars were involved in pedestrian crashes at higher rates than SUVs and pickups, larger vehicles disproportionately resulted in serious injuries compared with passenger cars. Additionally, they found that torso injuries were caused by SUVs and pickups more frequently than cars in this study, although the relative percentages were not dramatically different. For example, pickups caused 25 percent of the torso injuries for pedestrians, in contrast with 19 percent for passenger cars.

Han et al. (2016) used FE modeling to examine the chest deformation of a pedestrian with different vehicle models simulated at a speed of 40 km/h. They compared front ends for representative passenger car and one-box van models. According to the findings, the one-box van vehicle model resulted in more extreme chest deformation than the passenger car model. Han also was the lead author of two articles published in 2012. One article used FE models of pedestrians and vehicles to assess resulting chest injuries, finding that a one-box van shape model resulted in greater likelihood of a simulated chest injury compared to two car models (Han et al., 2012a). The other article (Han et al., 2012b) also used FE models to assess the effects of four different vehicle front ends on simulated pedestrian injuries. This study demonstrated that simulated collisions with the one-box van resulted in increased risks of chest injuries compared to the three other simulated vehicle models—an SUV, a small car, and medium-size car.

Martin et al. (2011) analyzed real-world crash data in France to determine the effects of vehicle designs on the severity and location of pedestrian injuries. They linked medical data from the Rhone Department Road Trauma Registry with the corresponding police crash data to determine the vehicle types responsible for the injuries. From this analysis, Martin et al. found that an MPV with a sloping hood resulted in thoracic injuries with an increased severity based on AIS injury score. An injury score of AIS 2+ for thoracic injuries was not as likely for a vehicle with a medium hood. The increased thoracic injury severity for an MPV or sloping hood vehicle also did not apply to other injury regions, such as the head or lower extremities. Vehicles found to offer less chance of thoracic injury were vehicles with more space between the bonnets [hoods] and windshields, smaller cars generally, and cars with short hoods. However, Martin et al. noted that the cars with very short front ends might not have been representative, as there were not many instances of those types of vehicles in the data.

In a study employing simulation data, Watanabe et al. (2011) examined pedestrian chest kinematics and impact locations at varying collision speeds for SUVs. For chest injuries, the Watanabe group's models demonstrated how differing shoulder impact locations corresponded to various chest injuries in simulated pedestrian collisions with an SUV. They conducted the simulated collision tests with speeds ranging from 20 to 65 km/h. At different speeds, the simulated pedestrian impacts occurred on different regions of the vehicle model. The upper testing speeds had impact locations of the cowl (50 km/h) and cowl with windshield and glass (60 and 65 km/h). With increased collision speeds, the simulated pedestrian chest injuries became more extreme. The impact location on the vehicle model also changed with speed, with the worst injury readings being from impacts on the cowl, windshield, and glass of the vehicle model. For example, they found collisions simulated at over 50 km/h resulted in rib fractures to the left and right sides of the pedestrian model. Furthermore, the simulation suggested that the fracturing of the ribs increased the deformation of the thorax.

A few academic studies published from 2011 to 2023 also examined thoracic injury outcomes in collisions with child pedestrians. For example, Halari et al. (2022) examined data from the autopsies of pediatric deaths in Ontario, Canada, to relate them to vehicle characteristics. In the Ontario data used in this study, there were 28 pediatric fatalities due to collisions with vehicles. Only 25 of the fatalities were included in Halari et al.'s study as data on the other 3 deaths either did not exist or conflicting accounts of the collisions existed. Among the 25 included cases, they observed that most of the pediatric fatalities were caused by vehicles with higher hood leading edges, defined as vehicles with "higher hoods compared to cars." The greatest proportion of the fatalities were caused by pickups and the smallest by cars. Of the 25 fatalities, serious thoracic injuries were found for 23 cases. However, the small sample size of this study presents a limitation to generalizing its findings.

While Halari et al. analyzed pediatric fatalities and discovered high incidences of thoracic injuries among the deaths, Lv et al. (2017) examined how different vehicle models affect pediatric injuries. The study used FE simulations at 30, 40, and 50 km/h to compare the injury variances of a mid-size car model and an SUV model on simulated pediatric chest impacts. According to Lv et al., simulated pediatric impacts from the SUV model resulted in greater chest deformation than the mid-size car model, but no rib fractures. In contrast, a simulated pedestrian impact with the mid-size car model resulted in less deformation of the pediatric chest but more rib fractures compared with the SUV model.

Thoracic Testing Requirements

Few studies examined whether designing vehicles to meet head or leg impact requirements influenced outcomes for thorax injuries. For example, in their NHTSA-sponsored report on the relative frequencies of different injury types, Mallory et al. (2019) noted that the effects of other countries' head and leg testing requirements on thoracic injury outcomes were rarely mentioned in the current literature. They referenced a single study by Han et al. (2012a) noting a correlation between simulated headform testing requirements and simulated thoracic injury outcomes. The Han et al. study employed simulations between pedestrian FE models and several different vehicle front ends to compare chest injury differences across vehicle types. In examining the simulated differences between injury outcomes with different vehicle models, Han et al. observed that headform tests may be helpful in predicting thoracic injury outcomes for one-box vans.

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Leg Injuries and High-Ground-Clearance Vehicles

This section addresses Topics 5 and 6 on leg injury outcomes in collisions with high-ground-clearance vehicles, including whether high-ground-clearance vehicles tend to cause knee and tibia injuries, and how a high-ground-clearance pickup can be designed to avoid high leg-bending values in collisions.

- Topic 5 – Studies that address whether high-ground-clearance vehicles tend to produce lower-leg injuries, even at lower speeds. This includes real-world studies of ligament versus tibia injuries by vehicle size.
- Topic 6 – Research showing whether and how a high-ground-clearance pickup may be designed so that the flexible pedestrian leg impactor "bounces off" the front end before it gets a chance to wrap around (and thus does not produce high tibia bending or ligament elongation).

A large portion of the literature on vehicle design and pedestrian safety focused on leg injury outcomes in collisions with high-ground-clearance vehicles. The review team found several simulation studies demonstrating higher incidences of knee and tibia injuries in high-ground-clearance vehicles relative to passenger cars. However, results from studies using real-world injury data complicated these findings, as one source found higher rates of lower-leg injuries in collisions with passenger cars than collisions with light trucks.

Most optimization studies for vehicle front ends described ideal bumper systems for passenger cars or did not explicitly specify vehicle body type. However, the review team found a few scholarly sources that discussed optimized bumper systems for high-ground-clearance vehicles, including one source that described a bumper structure for a commercial pickup and two further sources that described bumper structures for SUVs. Additionally, four patents discussed in Section 4 included bumper or grille systems designed to mitigate leg wraparound in collisions with SUVs or pickups. These patents, however, should not be interpreted as conclusively solving the issue of leg wraparound in collisions with high-ground-clearance vehicles, as patents do not provide extensive data validating the design innovations they describe. Still, they nonetheless provide helpful insight into the ways engineers are considering designing safer front ends.

High-Ground-Clearance Vehicles and Lower-Extremity Injury Outcomes

Several studies published from 2011 to 2023 demonstrated the tendency of high-ground-clearance vehicles to cause knee ligament injuries in pedestrian–vehicle collisions. In a 2011 article investigating pedestrian injury outcomes in collisions with high bumper vehicles, Sáez et al. (2011/2012) simulated collisions at 40 km/h between a 50th percentile male THUMS (Total Human Model for Safety) software model and five high ground clearance FE vehicle models, which were built using a baseline Toyota SUV model. Sáez et al. found the vehicle models striking the pedestrian model above the knee to be especially injurious for ligaments, due to pulling "from the tibia through the knee ligaments." However, all high-bumper vehicle models resulted in ligament ruptures, with the first rupture occurring at the medial collateral ligament and afterwards, the anterior cruciate ligament. The high-ground-clearance vehicle models also tended to simulate fractures in the bones closest to the knee. For all five of the high bumper vehicle models tested, the pedestrian model experienced fractures on the tibia head and femur condyles.

In a 2015 article on lower limb injuries during pedestrian–vehicle collisions, Mo et al. simulated collisions between an FE pedestrian model and four vehicle models representing various body types. The pedestrian model incorporated a biofidelic model of the lower leg. Analysis of shearing, bending, and strain suggested the MPV vehicle model, which incorporated a higher bumper beam than the other vehicles tested, caused more severe ligament injuries than the other vehicle models.

A 2016 conference paper by Wang et al. employing real-world injury data generally aligned with Sáez et al. and Mo et al. simulation studies regarding bumper height, although Wang et al. only included data on passenger cars. Wang et al. used a sample of 404 cases from the GIDAS to analyze the relationship between lower-extremity injuries and front-end features, such as lower and upper bumper height and hood leading-edge height. They applied analysis of variance to vehicle design parameters and collision speed to determine which variables were statistically significant for AIS 2+ lower-extremity injuries, then evaluated the variables for likelihood of sustaining AIS 2+ lower-extremity injuries with logistic regression. The ANOVA tests suggested that the lower bumper height, hood leading-edge height, and impact speed were significant at $p<.05$. Higher impact speeds were associated with higher rates of AIS 2+ lower-extremity injuries in general. However, vehicles with raised lower bumper components and hood leading edges were more likely to cause AIS 2+ lower-extremity injuries at slower speeds than vehicles with shorter lower bumpers and hood edges. Wang et al. found that a 42.5-centimeter lower bumper height resulted in a 50 percent risk of AIS 2+ injury at speeds of 30 km/h, while a 20-centimeter lower bumper resulted in the same risk of AIS 2+ injury at 56.5 km/h. Similarly, a high hood leading edge of 85 centimeters corresponded to a 50 percent risk of AIS 2+ injury at 18.5 km/h, while a low hood leading-edge height of 65 centimeters resulted in a 50 percent risk of AIS 2+ injury at 69 km/h.

On the other hand, Matsui, Hitosugi, and Mizuno (2011) used physical impact tests with a Transportation Research Laboratory impactor and vehicles representing a sedan, an SUV, a K-car[§] with a tall roof, and one-box K-car to evaluate the effects of bumper contact location and front-end design on lower-extremity injuries. The impact experiments with the SUV models generally resulted in higher knee shear displacements than experiments with the sedan models, as the bumpers of the SUV models contacted the leg above the knee, while the bumpers of the sedan models contacted the lower leg and knee at the same time. The higher contact location for SUVs caused greater posterior cruciate ligament (PCL) elongation than the sedans.

However, several studies potentially complicate these findings that high bumper vehicles, such as SUVs, result in more severe knee injuries. For example, Harmon et al. (2021), one of the few peer-reviewed studies on this topic incorporating real-world crash data, found that passenger cars were more likely to cause lower-extremity injuries than SUVs and pickups, although they did not distinguish injury risk according to parts of the lower leg. Li et al.'s 2016 conference paper incorporating PCDS and GIDAS data found that both passenger cars and SUVs caused higher rates of AIS 2+ lower-extremity injuries than vans, although like Harmon et al., Li et al. did not further differentiate the results according to knee versus tibia injuries. Kerrigan et al.'s 2012 study using real-world crash data and postmortem human subjects (PMHS) also potentially contradicts the findings that SUVs cause tibia and knee injuries more frequently than other vehicle types. In impact tests between PMHS and sedan and SUV models, they found that all but one of the 17 PMHS experienced knee or leg injuries. That is, lower-extremity injuries were

[§] "Kei car" is the smallest category of Japanese passenger vehicles.

observed at a similar rate in the PMHS subjects between both sedan and SUV impacts. A second study (Mo et al., 2015) used physical tests with isolated knee specimens to find that in the study conditions, both high and low bumper vehicles resulted in knee injuries, although the types of knee injuries differed. Mo et al. applied medial shearing directions to the knee specimens to simulate the effects of low bumper vehicles and lateral shearing to simulate high bumper vehicles. The physical tests with isolated knee specimens demonstrated that medial translation resulted in more ACL failures, while lateral translation resulted in more PCL failures.

The study by Nie and Zhou (2016) on whether design changes in response to international pedestrian protection testing protocols mitigated injury outcomes also suggests a complicated relationship between vehicle bottom height and pedestrian leg injuries. Nie and Zhou noted that the average bottom heights of both sedan and SUV models in Europe had increased due to testing protocols, and that the resulting dimensions demonstrated a higher risk of tibia fractures but a lower risk of femur fractures.

Another study by Asgari and Keyvanian (2019) simulated the effects of on-knee and below-knee bumper impacts on knee ligament injuries using lower leg FE models based on CT and MRI scans of human models. The simulated impacts demonstrated greater ligament and tibia injuries for below-knee impacts, as the bumper contacted the tibia directly, which also resulted in "higher tension" in the ligaments. However, below-knee impacts also resulted in injuries less severe to the menisci and cartilage than on-knee bumper impacts.

The two articles by Han et al. (2012a, 2012b), discussed in relation to thoracic injuries in Section 5, conducted simulation modeling and found that the passenger car models resulted in lower-leg injuries that were more severe than the SUV and one-box vehicle models. In the study that simulated collisions at 40 km/h with a pedestrian model, the passenger car model caused larger bending moments in the knee and tibia than the SUV model, while the SUV model caused larger bending moments in the femur. The passenger car model also exhibited higher tibia and femur bending values than the one-box vehicle model (Han et al., 2011/2012c). However, the simulations in the second study suggested that SUVs with ground clearances of 400 to 600 mm also caused high knee bending values in simulated collisions with pedestrian models.

Pedestrian size was also found to be an additional factor influencing injury outcomes, as together with vehicle size and body type, it influences where the pedestrian contacts the vehicle in collisions. In a 2013 conference paper, Luo et al. investigated the significance of pedestrian size, as well as vehicle body type, in affecting injury types and severity levels in collisions. They simulated collisions between three multibody pedestrian models and three vehicle models representing a small family car, large family car, and SUV. Analysis of the resultant knee bending angles and tibia acceleration values suggested that the pedestrian model height and weight greatly influenced knee and tibia injury outcomes by vehicle model body type. The SUV model resulted in higher knee bending angles and maximum shear displacements for the 95th percentile pedestrian model than the smaller pedestrian models and resulted in lower maximum tibia accelerations for the 5th percentile model. Conversely, the small and large family car models caused lower knee bending angles in collisions with the largest pedestrian model than the smaller models.

Beside vehicle type and pedestrian size, pedestrian kinematics at the moment of collision was found to influence lower-leg injury outcomes. Li et al.'s 2015 study simulated collisions between a 50th percentile adult male pedestrian model and sedan and SUV models at 40 km/h to determine the effect of pedestrian gait stance on lower-extremity injuries. The analysis incorporated six different gait cycles with various combinations of flexed and extended knees on both the struck and non-struck legs of the model. They found that, in their simulations, gait stance affected lower-leg injury outcomes for sedan and SUV models, and that a flexed knee resulted in lower likelihood of injury. However, for the SUV simulations, knee lateral shearing values were similar regardless of gait stance, as none of the gait stances resulted in contact between the struck and non-struck legs, as was the case in some of the sedan simulations. The SUV model caused higher knee bending angles than the sedan model in all simulations, as "the lower legs fold[ed] under the bumper due to inertial loading."

Optimized Front-End Designs for High-Ground-Clearance Vehicles

Although the review team did not locate any academic sources directly identifying designs for a high-ground-clearance passenger pickup that resulted in the Flex-PLI "bouncing off," rather than wrapping around, the vehicle front end, the review team did find several sources discussing optimized bumper shapes, positions, and material, as well as a technical paper describing an optimized commercial pickup bumper. Many scholarly sources from the study period discussed ideal bumper materials and placement without reference to specific vehicle body type. For example, Kulkarni et al. (2017) used FE models and impact tests to optimize a bumper structure for pedestrian collisions. The research suggested decreasing the bumper mounting position to 100 mm from the knee joint and constructing the beam from glass mat thermoplastic. Two other sources that discussed optimized bumper materials without reference to any specific vehicle body type were Zhou et al. (2017), who described an energy absorber comprised of polyurethane foam, and Ramaswamy et al. (2017), who discussed the use of EPP foam.

Many other studies published from 2011 to 2023 analyzed ideal design parameters for passenger cars. Although in the United States, light trucks such as SUVs and pickups are not subject to the same bumper requirements that apply to passenger car models, sources about bumper design for passenger cars nonetheless provide useful information about the energy-absorbing bumper materials typically used to mitigate pedestrian leg injuries. For example, Shojaeifard et al. (2017) described ideal bumper materials for B-segment automobiles, including a GMT beam, steel stiffener, and upper radiator rail, and a soft polypropylene bumper shell. However, they also noted that the GMT material resulted in greater damage to the bumper structure in FE simulations between a vehicle front end and pedestrian legform. In an additional technical paper, Kulkarni and Mana (2012) described a thermoplastic front end designed to perform well in Euro NCAP pedestrian testing protocols. Similarly, Gil et al. (2016) described the use of a plastic energy absorber in a bumper system designed to "crumple" on contact with the pedestrian's leg, thereby decreasing knee bending angle and tibia acceleration values.

A few scholarly sources published from 2011 to 2023 examined bumper structures for high-ground-clearance vehicles such as SUVs and pickups. Pathak et al. (2015) conducted simulations to investigate design parameters for minimizing lower-leg injury metrics in commercial pickup–pedestrian collisions, including tibia peak deceleration, knee shear displacement, and knee bending angle values. They employed simulations using the LS-DYNA software package to alter the pickup's front end in the model, including reducing the bumper fascia thickness from 3.5 to 3 mm and decreasing the distance from the lowest portion of the bumper to the ground. The model design also incorporated two steel energy absorbers with thicknesses of 1 millimeter and 0.6 mm between the bumper fascia and cross member. The resultant vehicle model simulated tibia and knee injury values below Euro NCAP testing criteria. Although this source described simulated design parameters for commercial pickups, it may provide useful information in the design parameters for high-ground-clearance vehicles.

Two sources discussed bumper materials and placement for SUV bumper structures. In a 2020 conference paper, Lv et al. considered several materials with different thicknesses to design a safer SUV bumper structure for pedestrian lower-leg injury outcomes. They employed the successive Taguchi method to select ideal materials for the bumper structure's upper and middle energy absorbers. The analysis suggested the optimum bumper absorbers were comprised of DC03 and B340/590DP steel materials. A 2016 technical paper by Gnanaswamy and Dhas proposed a crash bar designed to reduce pedestrian leg injuries in collisions. They described the proposed crash bar for the representative SUV, the Mahindra Scorpio, measuring 2,100 mm long and having three longitudinal bars, with one bar positioned close to the hood leading edge. Gnanaswamy and Dhas further proposed that the bar's core should be comprised of a honeycomb-shaped, jute-reinforced polypropylene composite plastic encased in a middle layer of 10 mm of polypropylene foam and an outer layer of 0.127 mm of aluminum foil.

Besides scholarly and technical sources on potentially optimized LTV bumper systems, several sources published in popular online automotive magazines have highlighted pickup models designed to reduce pedestrian lower-leg injuries in collisions. The Ford Ranger became the first pickup model to earn a 5-star Euro NCAP safety rating and an 81 percent rating for pedestrian protection, which an additional article from *Automotive Fleet* ascribed in part to "a pedestrian-friendly front bumper design incorporating energy-absorbing materials."

Several U.S. and international patents have also proposed innovations designed to mitigate pedestrian leg injuries in collisions with high-ground-clearance vehicles. For example, the 2019 German patent (Shenaq et al., 2019) filed by Ford Global Technologies included a grille reinforcement structure for light trucks and SUVs designed to distribute load forces evenly across the pedestrian's leg and minimize tibia and femur bending. The patent noted the reinforcement structure was designed so the bumper and grille impacted the pedestrian's leg at the same time, with the bumper and rods hitting the pedestrian above and below the knee, thereby decreasing "relative movement between the femur and tibia." Ford Global Technologies subsequently patented this innovation in the United States in 2021 (Shenaq et al., 2021).

Other patents filed from 2011 to 2023 detailed bumper structures for pickups and SUVs designed to prevent pedestrian leg injuries. The 2017 patents filed by Ford Global Technologies described a bumper structure with movable front stiffeners to prevent "the legs of a pedestrian from sliding under a vehicle bumper during a vehicle-pedestrian impact" (Farooq et al., 2017a, 2017b). The patent specified the stiffener could be deployed in environments with heavier volumes of pedestrians and retracted in off-road conditions where high ground clearance was necessary, thereby maintaining the vehicles' utility function. More recently, Ford Global Technologies patented a bumper structure (Shenaq et al., 2022) designed to mitigate pedestrian leg injuries comprised of a plastic bumper assembled over a cavity, and a crossbeam more rigid than the bumper. The patent specified that the plastic bumper and underlying cavity align with the knee of the pedestrian, represented by a Flex-PLI, and that, upon impact, the cavity should allow the bumper to collapse and minimize injury.

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Hood Design and Pedestrian Kinematics

The review team found 9 scholarly sources relevant to Topics 3, 4, and 9, which address the effects of hood design on pedestrian kinematics and injury outcomes, as well as the potential effects of a hood-only pedestrian protocol on smaller pedestrians.

- Topic 3 – Studies showing whether relatively fewer collisions with large light vehicles result in the pedestrian's propulsion over the vehicle hood versus collisions with small light vehicles. These studies may include kinematics in which the pedestrian impacts the windshield or other vehicle components rearward of the hood, or kinematics in which the pedestrian vaults over the vehicle.
- Topic 4 – Research addressing the premise that since larger vehicles have hoods that cover more physical area, the injurious component tends to be the hood (i.e., the regulated component) versus a rearward component (e.g., the A-pillar, roof, or ground impact).
- Topic 9 – Studies that show how designing according to a hood-only protocol may have the unintended effect of vehicle designs that are more injurious for smaller pedestrians.

In general, the literature differentiating pedestrian kinematics by vehicle type found that some high-speed simulated collisions with passenger car models were more likely to cause the pedestrian model to travel over the roof of the vehicle than collisions with MPV models. In related findings, other real-world and simulation studies suggested that pedestrians were more likely to contact the cowl or windshield in collisions with sedans than collisions with LTVs. However, one simulation study noted an important exception to these results, as one-box van models, which lack protruding hoods, resulted in windshield impacts.

The review team did not locate any studies directly opining upon the effects of a hood-only protocol. However, a few sources emphasized additional pedestrian safety areas, such as the disproportionate impacts of vehicle leading edges on smaller pedestrians.

Hood Design and Pedestrian Kinematics

Overall, most of the literature comparing pedestrian kinematics among different passenger vehicle body types found that large light vehicles such as SUVs were less likely than smaller passenger vehicles to result in the pedestrian striking rearward vehicle components, such as the windshield and A-pillars, or traveling over the vehicle entirely in collisions. For example, Han et al. (2018/2019) conducted 200 simulated pedestrian–vehicle collisions with five different vehicle models to analyze whole-body pedestrian kinematics. They found that "roof vault" kinematics in which the pedestrian model traveled over the roof of the vehicle model were most common in collisions with sedan models or very high-speed simulated collisions.

In another 2019 study, Wang et al. found that passenger cars resulted in more roof vault kinematics than MPVs, defined in the study as vans, SUVs, and pickups. They examined real-world crash data from the VIPA database, which began data collection on pedestrian and pedalcyclist crashes in Michigan in 2015 and was ongoing at the time of the study. They found that the most common kinematics in collisions with MPVs resulted in the vulnerable road user being projected forward (18.4%), followed by a wrapping mechanism (14%). These two kinematics types also frequently occurred in collisions with passenger cars, but the roof vault mechanism was relatively common, at 7.4 percent. However, as Wang et al. did not specify whether they had separated out cases involving bicyclists from the pedestrian data, these findings cannot be attributed exclusively to pedestrians.

Several studies published from 2011 to 2023 suggested that passenger cars such as sedans more frequently resulted in windshield impacts in pedestrian–vehicle collisions than larger light vehicles such as SUVs. In a conference paper using VIPA data, Wang et al. (2020) found that sedans were more likely to impact pedestrians and pedalcyclists via the cowl or windshield than MPVs and trucks. Most of the passenger car collisions that caused head injuries resulted in contact with rearward vehicle components behind the hood (84%) while less than half of collisions with MPVs that involved head injuries resulted in contact locations behind the hood (44%). While the 2020 paper did not examine relative frequencies of the different trajectories according to vehicle type, it found that MPVs demonstrated a slightly lower average impact speed when resulting in roof vaults than passenger cars resulting in the same mechanism, at 62 km/h compared with 70 km/h.

On the other hand, Kerrigan et al. (2012) exclusively examined pedestrian impact experiments to determine head contact locations, demonstrating that smaller passenger cars such as sedans more often resulted in the pedestrian striking rearward vehicle components behind the hood. They conducted impact experiments with PMHS, a crash dummy, and SUV and sedan vehicle bucks. In all tests the PMHS heads hit the windshield of the sedan and the hood of the SUV.

One further simulation study by Han et al. differentiated frequencies of hood versus windshield impacts among larger vehicle body types. Han et al.'s 2013 study found that the medium car and SUV models resulted in more hood impacts, while the mini car and one-box van models, which do not have protruding hoods, resulted in windshield impacts. They found windshield impacts for the one-box van model incurred more severe windshield injuries than other vehicle body models, as the pedestrian model's head was more likely to hit the windshield edges of the one-box van model.

Several studies demonstrated the importance of pedestrian size in determining contact location. For example, in his 2014 thesis Gupta simulated three sizes of pedestrian models striking mid-size car and SUV models with different front-end profiles at 40 km/h. The simulations demonstrated that the bumper of one of the SUV models first struck the 5th percentile female pedestrian model's lower legs, the hood leading edge next contacted the pelvis, and the head struck the hood. Simulations with one of the mid-size car models and the 5th percentile female model also resulted in the head contacting the hood, with a larger impact angle. In contrast, while the average-sized pedestrian male model contacted the hood of one of the SUV models, it struck the windshield of a mid-size car model. The child pedestrian model's head contacted the hood in simulations with SUV and mid-size cars models.

Similarly, in a study simulating adult and child head injuries with multibody models, Peng et al. (2011) noted that the adult pedestrian model's head most commonly hit the windshield in simulated collisions with small mini car, small family car, and MPV models, and most frequently hit the hood in simulated collisions with SUVs. In contrast, the child pedestrian model's head struck the hood in simulated collisions with the small mini car, small family car, large family car, and MPV models and contacted the hood edge in collisions with the largest model, the SUV.

Pedestrian Size and Hood Impact Requirements

Although the review team did not identify any sources directly addressing the effects of a hood-only protocol for pedestrian protection, the existing literature suggests that additional protocols may be needed to mitigate certain injury types, especially for smaller pedestrians. A few simulation studies published from 2011 to 2023 showed that smaller pedestrian models, particularly young child models, incurred injuries to several body regions in collisions with high front-end vehicle models. For example, in a 2017 conference paper, Ito et al. simulated collisions between three vehicle models and four pedestrian models representing different sizes, including a 3-year-old, 6-year-old, 10-year-old, and adult 50th percentile male. They found that simulations with the 3-year-old child model resulted in more contact points with the leading edge of the SUV model, including bumper-to-abdomen, grille-to-shoulder, and hood leading edge-to-head impacts.

In a modeling study principally investigating the effects of a frontal guard[**] on injury outcomes, Moradi and Lankarani (2011) compared injury outcomes for pedestrian models of various sizes in collisions with a pickup model with and without a guard. They used a FE pickup model based on the Chevrolet Silverado from the National Crash Analysis Center (NCAC), as well as MADYMO[††] pedestrian models representing a six-year-old child, a mid-size male, and a large-size male. The simulations with the six-year-old child model resulted in the truck contacting a greater portion of the child model's body. Collisions without a guard resulted in the bumper first contacting the thigh and hip and the hood edge contacting the neck and head, with "a slight rotation of upper body parts." On the other hand, the inclusion of a frontal guard entirely prevented the child pedestrian model from striking the vehicle hood. Regardless of whether the guard was included, they found high "torso acceleration" values for the child pedestrian model in all simulations.

[**] Also known as a grille guard. These are most commonly aftermarket additions to pickups and larger SUVs. The purpose of a frontal/grille guard is to protect the front-end and grille, especially in the case of off-roading, though some consumers purely enjoy the aesthetic. These guards tend to have an H- or T-shaped frame and are made up of two vertical members ("risers") and a center horizontal member ("center flange"). The risers have mounting holes to attach the guard to the vehicle frame on either side of the grille. Most guards also have a pair of side brush guards or rings attached to the risers that extend outward to protect the vehicle's headlights, as well a top and bottom tube spanning between the risers.

[††] MADYMO, or mathematical dynamic models, is a software application by Siemens Digital Industries headquartered in Plano, Texas, used in vehicle safety research to simulate collisions.

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Testing Requirements, Injury Patterns, and Fleet Composition

Overall, the review team found comparatively few academic sources about Topic 8 addressing the real-world impacts of pedestrian testing requirements and/or protocols, such as those implemented in Euro NCAP and Japan NCAP.

- Topic 8 – Studies that describe how injury patterns may have changed following implementation of pedestrian testing requirements and protocols.

Although relatively few scholarly sources have discussed the real-world effects of Euro NCAP and Japan NCAP testing protocols, several sources have noted correlations between the implementation of these testing programs and subsequent improvements in pedestrian safety outcomes. In addition to sources studying injury severity levels in Europe and Japan following the implementation of pedestrian testing, this section includes a NHTSA-sponsored report examining the Euro NCAP testing protocols and vehicle models representative of the U.S. fleet.

For Topic 11 on whether the growing proportion of pickups and SUVs in the U.S. vehicle fleet are sold in Europe or Japan, the review team used several sales data sources, vehicle manufacturer websites, and one fleet study comparing European and U.S. variants of the same vehicle models. The review team found limited information on differences relevant to front-end design between U.S. and European or Japanese versions of the same vehicle models in both the academic literature and popular automotive news sources.

Testing Requirements and Real-World Injury Outcomes

Although relatively few scholarly sources have discussed the real-world effects of Euro NCAP and Japan NCAP testing protocols, several sources have noted correlations between implementation of these testing programs and subsequent improvements in pedestrian safety outcomes. Two sources in which Strandroth served as lead author (2011, 2014) noted that real-life injury outcomes have improved following the implementation of pedestrian crashworthiness testing protocols in Euro NCAP scoring. In the 2011 study, Strandroth et al. used real-life collision data of about 500 cases from the Swedish Traffic Accident Data Acquisition system and coded the involved car models using their Euro NCAP pedestrian scores. They then examined AIS injury levels, as well as risk of "permanent medical impairment" for each pedestrian before calculating a mean risk value for each group of cars. Subsequent t-tests revealed a "significant correlation" between Euro NCAP scores and real-life pedestrian injuries and suggested greater decreases in injury when considering higher injury severity levels and risk of permanent medical impairment. Strandroth et al.'s subsequent 2014 article on Euro NCAP scores and pedestrian and bicyclist injury outcomes echoed these 2011 findings, demonstrating that pedestrian head injuries showed the largest decreases following implementation of Euro NCAP pedestrian crashworthiness testing protocols.

Similarly, in a 2013 conference paper Pastor also demonstrated a significant correlation between passive pedestrian protection Euro NCAP scores and pedestrian injury outcomes. Pastor used an ordinal probit model to analyze German National Accident Records data from 2009 to 2011, finding that cars with higher Euro NCAP scores were less likely to cause serious or fatal injuries in pedestrian collisions. Specifically, analysis of the crash data suggested that if all German passenger cars achieved a 22-point score in Euro NCAP pedestrian tests, overall fatalities might decrease by 6 percent and severe injuries might decrease by 9 percent.

Although most of the literature on design innovations following the implementation of Euro NCAP protocols observed improvements in vehicle design, TRL produced a 2014 report (Carroll et al.) for the European Commission showing the need for updates to the bumper test area. Carroll's group noted that recent vehicle front-end designs trended towards curved bumpers with less area between the bumper corners, as seen in the post-2009 Volkswagen Polo and post-2006 Vauxhall/Opel Corsa. They noted that this design trend potentially worked against Euro NCAP testing protocols at the time of the report, as large sections of the vehicle front ends fell outside of the test zone.

Although the literature on pedestrian injuries published from 2011 to 2023 included fewer studies on the effects of Japanese testing protocols and regulations on real-world injury outcomes, one source by Oikawa and Matsui (2016/2017) addressed this topic. Oikawa and Matsui applied two-tailed statistical tests to Japanese pedestrian injury data from 1999 to 2009 to investigate the effects of various characteristics, including collision year, vehicle speed, pedestrian age and gender, and vehicle type on pedestrian injuries. The results suggested that Japan's 2005 regulation requiring head-to-hood testing improved injury outcomes for some vehicle body types, including minivans and light cargo vans, but did not mitigate head injuries for collisions with sedans, light passenger cars, and box vans. However, they also cited an overall decrease in fatal head injuries caused by sedans and light passenger cars from 1999 to 2009, as well as the fact that sedans, light passenger cars, and minivans more often caused leg injuries than head injuries.

In addition to these studies more directly comparing real-world injury outcomes prior to and following the implementation of pedestrian NCAP tests in Europe and Japan, Mallory et al. (2019), also discussed in Section 5, provided a comprehensive report estimating the relative frequency of injury types associated with vehicle component-level tests. Although the report did not directly examine real-world injury outcomes before and after the implementation of pedestrian testing protocols, it nonetheless provided information on the potential applicability of testing protocols to the U.S. vehicle fleet. They compared data on injury sources from NHTSA's PCDS and the National Data Trauma Bank with Euro NCAP component-level testing protocols, including the headform, upper legform, and lower legform impacts, to determine whether pedestrian tests covered the vehicle regions most commonly causing injury. The PCDS provided data on the vehicle components causing injury, while the NDTB provided information on the pedestrians' injured body regions, with an emphasis on serious through fatal injury severity levels (Maximum Abbreviated Injury Scale[‡‡] 3+). Mallory et al. used a prior study on "the frequency of real-world impacts within the testable zone" and NHTSA's Vehicle Research and Test Center experiments to determine test zones on 12 different vehicle models and estimate the proportional applicability of various vehicle components to the three Euro NCAP testing protocols. The VRTC vehicles tested included three standard SUVs, two small SUVs, two minivans, one standard pickup, and four passenger cars. Analysis at the MAIS 3+ injury level suggested that "37.8 percent of the total expected potential effects of the test procedures for seriously injured pedestrians (MAIS 3+) was associated with the headform test, 24.6 percent was associated with the upper legform test, and 37.6 percent was associated with the lower legform

‡‡ The MAIS represents "the highest (i.e., most severe) AIS code in a patient with multiple injuries" (Abbreviated Injury Scale [AIS], Association for the Advancement of Automotive Medicine, https://www.aaam.org/abbreviated-injury-scale-ais-position-statement/).

test." Examination of the even more severe injury levels yielded different results, with the headform test's effect on outcomes increasing and the legform tests' effect decreasing.

U.S. Versus European and Japanese Vehicle Fleets

In recent years SUVs and other light trucks have increasingly gained popularity in the United States, although several sources from the study period noted that SUVs have also continued to grow in popularity in Europe and Japan as well. In 2022 SUVs made up nearly half (46.6%) of new vehicles registered in the U.S., compared with 42.6 percent in 2021 (GoodCarBadCar [sic] Automotive Sales Data, n.a.-a). A 2017 *Automotive News* article reported that SUVs made up 26 percent of passenger cars sold in Europe 2016, compared with just 8 percent in 2007 (Ciferri, 2017). Although overall passenger vehicle sales decreased in Europe in 2020 due to the COVID-19 pandemic, SUVs still accounted for 39 percent of new vehicle sales in Europe and the UK in that year (Diaz, n.d.). By 2022 SUV market share in the EU vehicle market reached 52 percent of new vehicles sold (GoodCarBadCar [sic] Automotive Sales Data, n.a.-a). In Japan, SUVs have also grown significantly in popularity in recent years, reaching 40.2 percent of new vehicle registrations in 2022, an increase from 36.5 percent in 2020 (GoodCarBadCar [sic] Automotive Sales Data, n.a.-b).

A review of U.S. vehicle sales for best-selling passenger vehicles from 2018 to 2022 revealed that the top-selling U.S. light truck models exceeded global LTV models, as many of the top-selling LTVs in the U.S. were not offered for sale in Europe and Japan (Wards Intelligence, 2023). For example, the Ford F-150, which consistently outsold all other vehicle models in the U.S. from 2018 to 2022, did not have variants tested in the Euro NCAP or Japan NCAP. The Chevrolet Silverado and Ram pickup models, which alternated for second and third best-selling U.S. vehicle models, also did not have variants tested in the Euro NCAP or Japan NCAP. Considered together, these three vehicle models accounted for over 1.95 million vehicles out of a total 17.71 million vehicles sold in 2018, the largest year for new car sales in the past 5 years. Other popular U.S. LTVs without European or Japanese variants in the top 25 best-selling vehicle models included the GMC Sierra, Toyota Tacoma, and Chevrolet Equinox, which together comprised 850,505 sales (GoodCarBadCar [sic] Automotive Sales Data, n.a.-a).

Although global LTV models made up a significant portion of U.S. sales in the same period, the top-selling global models did not equal sales of U.S. LTV variants not offered for sale in Europe and Japan. The Toyota RAV4, an SUV sold in the United States, Europe, and Japan, was consistently the fourth most popular vehicle model in the United States over the same 5-year period. Toyota sold a total of 427,170 domestically produced and imported RAV4 models in 2018, while the next most popular global SUV models, the Nissan Rogue, sold 412,100 units, and the Honda CR-V sold 379,013 units. The Jeep Grand Cherokee and Wrangler, which have global variants sold in Europe and Japan, sold 224,908 and 240,032 units, respectively. The Mazda CX-5, a compact crossover SUV also sold in Europe and Japan, sold 150,622 models in the same year. Several other top-selling LTV models were sold in Europe, but not in Japan, including the Ford Explorer, Toyota Highlander, and Hyundai Tucson, which together accounted for 648,381 U.S. sales. In total, the U.S.-exclusive light trucks that were in the top 40 best-selling vehicles sold nearly 4 million vehicles while global light trucks sold nearly 3.7 million units (Wards Intelligence, 2023).

Even in 2022, when overall vehicle sales numbers continued to trend downwards following the COVID-19 pandemic and resultant supply chain disruptions, U.S.-exclusive light truck models continued to outsell global models among the top-selling passenger vehicles (GoodCarBadCar [sic] Automotive Sales Data, n.a.-a). The same top three best-selling vehicles of Ford F-150, Ram Pickup, and Chevrolet Silverado together sold nearly 1.56 million models in the 2022 calendar year. These three vehicle models represented more units sold than the remaining U.S.-exclusive light truck models in the top 25 vehicles of 2022, which accounted for 828,287 vehicles sold. Altogether, U.S.-exclusive light trucks in the 40 top-selling vehicle models accounted for over 3.23 million models, while global light trucks in the top 40 best-selling vehicle models accounted for nearly 2.71 million models (Wards Intelligence, 2023).

For global vehicle models, the review team searched for information on whether European or Japanese variants differed from U.S. variants of the same vehicle model in features relevant to pedestrian protection. However, relatively few academic fleet studies published from 2011 to 2023 addressed design differences relevant to pedestrian safety between U.S. and global variants of light truck models. A 2019 NHTSA-sponsored report by Suntay et al. assessed a representative sample of the U.S. vehicle fleet for pedestrian safety by testing nine representative vehicle models according to Euro NCAP head and leg testing protocols. Additionally, they compared the Euro NCAP headform and legform testing performances of U.S. versus European variants for certain global vehicle models. The results suggested that even the worst-performing global vehicle models in the study performed better than U.S. variants without corresponding European variants, which they ascribed in part to hood and front-end designs that provide better pedestrian protection. For the five global vehicle models included in the study, Suntay et al. noted that the vehicle platforms designed to align with European safety standards “appear to have been carried over to variants sold in the United States.”

However, Suntay et al.’s 2019 replication of Euro NCAP test protocols for U.S. models without corresponding European variants suggested that the two largest models exclusive to the United States, the Ford F-150 and Chevrolet Tahoe, were the worst-performing of all vehicle models in every leg and head impact test. These models’ stiff bumper materials and high placement resulted in high tibia bending values and femur forces in the legform tests, and as testing protocols placed the outermost grid point at a hard location just beneath the hood leading edge, they were also found to result in high injury readings in pedestrian headform tests. In contrast, the Nissan Rogue, an SUV sold in both the U.S. and European markets, performed well in leg and head impact tests. The U.S. and European variants of the Nissan Rogue performed well in the study’s scoring of the Euro NCAP upper and lower leg tests, the headform test, and overall. They noted that unlike passenger cars, SUVs are not subject to the requirements that govern bumper damageability requirements for U.S. variants of sedans, and therefore, SUV bumper systems can more easily be shared between variants. The Ford Edge, the other SUV model with global variants, also received a top Euro NCAP lower leg score for the European variant, but a remarkably low score (0.40 points) in the study’s testing of the U.S. variant.

Information on concrete differences related to pedestrian safety between U.S. versus global variants of the same vehicle models was even more scarce in popular online sources than in scholarly fleet studies published from 2011 to 2023. The few sources referencing design features that might have relevance to passive pedestrian safety did not discuss how the features would affect pedestrians in collisions. Instead, these sources more often discussed similarities and differences according to other metrics of interest to consumers, such as their relative aesthetic appeal. For example, a 2022 news article from *Carscoops* discussing the arrival of a new RAV4 Adventure model in Europe stated that the bumper design of the U.S. variant was carried over to the European variant of the same model (Pappas, 2022). Although the bumper structures would likely influence pedestrian injury outcomes in collisions, they of this article largely discussed the design in the context of other styling features, such as the model's silver skid plates. A 2022 news article on the Honda CR-V also principally focused on aesthetic differences between the U.S. variant and the Japanese version, which is marketed as the ZR-V (Furlong, 2022). That article described the U.S. CR-V's front end as including a "sporty mesh grille," whereas the Japanese variant incorporated "a different grille with vertical slats." Even though grille design could be influential to pedestrian safety, the author of the article did not comment on whether these differences are significant for pedestrian injury outcomes in collisions.

Another popular news article from *Forbes* highlighted differences between the European and U.S. versions of the same SUV model in terms of overall size (Blanco, 2022). This article about the 2022 Hyundai Tucson noted that the U.S. variant incorporated a longer wheelbase than the European and Mexican variants, measuring 108.5 inches versus the international variant's 105.5 inches. An SUV product planner for the vehicle manufacturer stated, "We really tried to make sure we had the right size for the North American market, just to be able to compete." Also, the 2022 U.S. model's length increased relative to the prior model, with 182.3 inches in length compared to the previous model's 176.4 inches. Additionally, the newer model gained 0.6 inches in width and 0.6 inches in height. While these changes in dimension were likely relevant to pedestrian safety, the *Forbes* article did not address their potential impact on pedestrians in collisions.

Another popular automotive news source from 2021 noted size differences between U.S. and European variants of the same SUV models (Glon, 2021). The *Autoblog* article comparing the U.S. and European variants of the 2022 Kia Sportage noted that the European version of the subcompact SUV incorporated a shorter wheelbase, as well as a shorter overall length of 177.7 inches, compared with the U.S. version's length of 183 inches. However, like the *Forbes* article described in the prior paragraph, this source did not address how the U.S. variant's greater dimensions might result in different pedestrian injury outcomes.

One article (Future Car Staff, 2023) on variations between U.S. and European versions of the same model specifically cited Euro NCAP testing protocols as motivating design differences. The 2023 article from *Future Car* on the U.S. and European variants of the 2024 Hyundai Santa Fe noted that the version for sale in Europe will omit the U.S. variant's horizontal LED light bar on the front end, which performed poorly in Euro NCAP tests. However, the article did not state whether the light bar's performance was related to pedestrian protection. In addition to discussing the light bar, the article also cited the Euro NCAP protocol that, to receive top marks, European vehicles must include AEB systems that detect vulnerable road users and avert head-on collisions.

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Summary

The review team identified a considerable body of literature addressing the effects of vehicle size and design on injury outcomes in pedestrian–vehicle collisions. Additionally, the review team identified some studies that discussed correlations between the implementation of international pedestrian protection testing protocols and subsequent reductions in severe pedestrian injuries and fatalities. Overall, the most recent literature the team found incorporating real-world crash data from the United States suggested that large vehicles with higher front ends and flat hoods were found to cause disproportionate numbers of severe pedestrian injuries and fatalities due to their tendency to cause more severe head and chest injuries in collisions.

Key findings from the literature review:

- Some studies suggest that higher hood leading edges and low hood angles result in more severe head injuries in pedestrian–vehicle collisions.
- Some studies suggest that vehicles with higher front ends are more likely to result in severe head injuries from ground contact mechanisms, particularly for child pedestrians.
- Simulation studies suggested that high-ground-clearance vehicles are more likely than lower ground clearance vehicles to result in knee ligament injuries, as well as fractures to sections of the femur and tibia closest to the knee.
- Research on head impact locations for adult pedestrians suggested that collisions with sedans most often result in the head striking the windshield, while crashes with SUVs most often result in hood impacts.
- Although relatively few scholarly sources were found to have discussed the real-world effects of Euro NCAP and Japan NCAP testing protocols, several sources reported correlations between vehicles that had high ratings in Euro NCAP pedestrian crashworthiness testing and reductions of severe injury and fatality levels to pedestrians in collisions.
- A study was found that analyzed real-world data from 1999 to 2009 in Japan and found that Japan's 2005 regulation requiring head-to-hood testing mitigated pedestrian injuries for some vehicle body types, including minivans and light cargo vans.
- Among the 40 best-selling vehicle models in the United States in 2022, sales of U.S.-exclusive light truck vehicle models exceeded global light truck model sales. The United States' top three best-selling vehicle models were pickups not tested in Euro NCAP or Japan NCAP protocols.
- A study found that some vehicle platforms designed to comply with European safety standards were found to have been carried over to variants sold in the U.S.; however, when they differ, some U.S. variants of global vehicle models were found to perform worse in tested pedestrian headform and legform tests than the European variants of the same vehicles.

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Appendix I: Duplicate Sources From Task 1

The review team identified the following sources, originally found during the first literature review that focused the effects of vehicle size and weight on pedestrian safety as being relevant to the second research review. The sources are organized according to this report's five main sections.

Vehicle Size and Related Design Changes

Anata, K., Konosu, A. & Issiki, T. (2011, June 13-16). *Injury risk assessment at the timing of a pedestrian impact with a road surface in a car-pedestrian accident.* 22nd Enhanced Safety of Vehicles Conference, Washington, DC. https://www-esv.nhtsa.dot.gov/Proceedings/22/isv7/main.htm

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Thoracic Injuries and Testing Requirements

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

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