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Review of Literature Addressing Vehicle Pedestrian Safety Market Trends

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16. Abstract

NHTSA seeks to understand relationships between vehicle size and weight and 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. This Task 3 report details the literature findings on vehicle market trends related to changing pedestrian safety technologies and testing requirements in the United States and other countries in peer-reviewed academic articles and conference proceedings, to market forecasting reports and press releases, to consumer forums and online videos. Data was gathered on the 40 best-selling vehicle models by year in the United States from 2011 to 2022, and vehicles tested by the EuroNCAP. Key findings:
* While pedestrian fatalities in Europe decreased by 37 percent from 2004 to 2013, it is difficult to prove the reason is due to the regulations or other factors;
* Including pedestrian crashworthiness tests in consumer ratings programs seems to have influenced design of new vehicles performing well in tested conditions in Europe;
* Pedestrian automatic emergency braking technology may have prevented many pedestrian collisions, and some pedestrian safety technologies like AEB on global vehicle models penetrated the 40 top-selling vehicles in the U.S. market while others -- such as active hoods -- were not;
* Variation in bump construction differs in European markets versus the U.S. markets, with European bumpers design elements that perform better in EuroNCAP upper and lower legform test conditions.
* In the United States, exterior bumper beams were only found on off-road use, especially pickups.

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List of Abbreviations

ACEA	Association des Constructeurs Européens d’Automobiles (European Automobile Manufacturers’ Association)
ADAC	Allgemeiner Deutscher Automobil-Club (General German Automobile Club)
ADAS	advanced driver assistance system
AEB	automatic emergency braking
ATZ	*Automobiltechnische Zeitschrift* (*Technical Automotive Journal*)
AVAS	acoustic vehicle alerting system
BASt	Bundesanstalt für Straßenwesen (German Federal Highway Research Institute)
CIDAS	China In-Depth Accident Study
CPC	Cooperative Patent Classification
ECU	electronic control unit
EU	European Union
Euro NCAP	European New Car Assessment Programme
FE	finite element
GIDAS	German In-Depth Accident Study
HIC	head injury criterion
IIHS	Insurance Institute for Highway Safety
ITARDA	Institute for Traffic Accident Research and Data Analysis
MAIS	Maximum Abbreviated Injury Scale
NCAP	New Car Assessment Program
OEM	original equipment manufacturer
Pedestrian AEB	pedestrian automatic (or autonomous) emergency braking
THUMS	Total Human Model for Safety
TTC	time-to-collision

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Table of Contents

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 relative to pedestrian injuries and fatalities. NHTSA is interested in research that (1) identifies key vehicle crash data sources; (2) supports NHTSA's policy decisions; and (3) identifies market trends in changes to vehicle design that affect pedestrian safety, including both U.S. and international trends. NHTSA contracted the Federal Research Division at the Library of Congress to conduct this literature review on pedestrian safety.

This report details the review team's findings in literature related to the third topic—vehicle market trends related to changing pedestrian safety technologies and testing requirements in the United States and other countries. It describes trends and notable findings from sources ranging from peer-reviewed academic articles and conference proceedings to market forecasting reports and press releases, to consumer forums and online videos, among others. Data was gathered on the 40 best-selling vehicle models by year in the United States from 2011 to 2022, and vehicles tested by the European New Car Assessment Programme and sold in the European market during that period.

The key findings from the literature review:

- While the numbers of pedestrian fatalities in Europe were reported to have decreased by 37 percent from 2004 to 2013, a time in which pedestrian protection safety regulations came into effect, sources have noted that it is difficult to prove that the reason for any improvement is entirely due to the regulations as opposed to other possible factors (European Commission, 2016; Pastor, 2013).
- Including pedestrian crashworthiness tests in consumer ratings programs appears to have influenced the design of new vehicles performing well in tested conditions in Europe.
- Some European researchers found that pedestrian automatic emergency braking technology may have been successful in preventing many pedestrian collisions, though the calculated reduction in crashes was not statistically significant, possibly due to the small sample size of vehicles equipped with pedestrian AEB at the time of the study (Strandroth et al., 2014).
- Some pedestrian safety technologies on global vehicle models, such as pedestrian AEB, were penetrating the 40 top-selling vehicles in the U.S. market at an increasing rate during the period of this study, while others, such as active hoods, were not.
- The literature review found there may be variation in how bumpers are constructed for vehicles in the European market versus the U.S. market, with European bumpers having design elements to perform better in Euro NCAP upper and lower legform test conditions.
- In the United States, exterior bumper beams were only notably found on vehicles designed for off-road use (e.g., pickups in particular); however, the research team's assessment was limited to visual inspection.

The next two sections outline the research topics that guided the literature review, as well as the review team's search methodologies. The sections following describe findings on the impact of pedestrian safety standards and consumer testing scores on vehicle market trends in the United

States and Europe, the impact of these standards and scores on actual pedestrian safety in Europe, market trends and developments in bumper construction and exterior bumper beams, and specific questions related to active hood technology. Two appendixes, described in further detail in the text, conclude the report.

Overview

This report details the review team's findings about vehicle market trends related to changing pedestrian safety technologies and testing requirements and protocols in the United States and other countries. The narrative has nine research topics and tasks.

1. Review U.S. and foreign academic publications and popular magazines (*Car and Driver*, *MotorTrend*, *Consumer Reports, Automotive News* [U.S. and European editions], *Autocar* [U.K. edition], *ADAC Motorwelt* [Germany], *Automobiltechnische Zeitschrift* [Germany], and *L'Automobile* [France]) for articles, interviews, commentaries, or other information addressing whether and how vehicles have changed to conform to pedestrian safety standards in the United States and other nations.
2. Examine vehicle manufacturer information on model generations that might suggest how an original equipment manufacturers' means of meeting non-U.S. pedestrian regulations, such as pedestrian regulations in the European Union, may have changed over model generations.
3. Examine vehicles sold in the United States that may not have changed pedestrian safety features at all since 2011.
4. Examine literature to understand if designs of vehicles affected by pedestrian safety regulations and testing protocols in markets such as the European Union are becoming effective in protecting pedestrians.
5. Research bumper construction developments, especially on North America-only vehicles and particularly pickups, and those not required to conform to 49 C.F.R. Part 581, the U.S. bumper regulation.
6. Investigate articles on active hood technologies (hoods that pop up upon impact with a pedestrian to provide a softer landing). The review team will note whether technologies include a sensor tube in the bumper versus some other sensor, as the information allows.
7. Identify international sources focusing on false deployments of active hoods.
8. Research information from vehicle owner manuals, repair manuals, and similar sources (YouTube videos, U.S. patents, consumer forums) that explain if or how the active hood systems are reset, and whether they need to be reset for the vehicle to remain operable.
9. Research international vehicle repair records, part supplier sales records, and anecdotal evidence (consumer forums, etc.) that would show how often active hoods deploy.

The sections addressing these research topics are organized by theme and, where appropriate, source type.

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Methodology

The review team conducted a literature review using keyword searches to identify relevant sources published from 2011 to 2023 on vehicle market trends related to changing pedestrian safety technologies and testing requirements and protocols in the United States and other countries. This section details how the literature review was done, and change-over-time information on market trends in pedestrian safety features and bumper beam designs.

Literature Review

The review team searched many databases using combinations of keywords such as “pedestrian,” “safety,” “regulation,” “rule,” “pedestrian AEB,” and “pedestrian protection system,” among others. They applied Boolean operators to refine the queries. For example, the review team searched for sources on AutoCar.co.uk using the search terms, “pedestrian AND (regulation OR rule*) AND ("European Union" OR EU).” This specific search identified 16 articles published since 2011. The review team then reviewed each source to determine its relevance to the project. For non-English-language sources, the review team used translations of the same terms used in searching English-language sources.

The media searched:

1. English-language, peer-reviewed journals, such as *Accident Analysis and Prevention, Journal of Automobile Engineering, Journal of Safety Research, Stapp Car Crash Journal, and Traffic Injury Prevention*, via Library of Congress holdings
2. Select non-English language journal articles via the Library of Congress’s holdings and public databases such as the China National Knowledge Infrastructure (CNKI)
3. Conference proceedings, such as those hosted by the International Research Council on Biomechanics of Injury (IRCOBI) and NHTSA
4. Monographs and book chapters
5. Reports and studies from relevant academic institutions, non-profit organizations, market forecasters and other entities, such as the Insurance Institute for Highway Safety, the Euro NCAP, and the Association des Constructeurs Européens d’Automobiles (European Automobile Manufacturers' Association)
6. Reports and standards from international rulemaking bodies, such as the European Union and the United Nations
7. Web sources from Federal departments and agencies such as the U.S. Department of Transportation and National Transportation Safety Board, via the Repository and Open Science Access Portal
8. Patents and patent applications from the U.S. Patent and Trademark Office, European Patent Office, and Google Patents
9. Press releases from vehicle manufacturers

10. Articles in popular magazines such as *Car and Driver, MotorTrend, Consumer Reports, Automotive News (U.S. and European editions), Autocar (U.K. edition), ADAC Motorwelt (Germany), Automobiltechnische Zeitschrift (Germany)*, and *L'Automobile (France*), via proprietary websites and research databases such as Nexis Uni
11. Owner's manuals and repair manuals
12. Company information on replacement part manufacturers and insurance companies
13. Web sources such as YouTube videos, consumer forums, and vehicle enthusiast websites

Where necessary, the review team also contacted organizers of national crash sampling projects for further information on the data they possess.

The sources reviewed by the review team were primarily in English. The review team also conducted a review of select German-language press publications in the original language. In addition, reviewers examined several French-, Korean-, and Chinese-language sources. For these, reviewers used machine translation to gain basic understanding of the source material and, when necessary, confirmed technical details with in-house speakers of the relevant language.

Not all source types were consulted for each section of this report. One part of the section Impact of Pedestrian Safety Requirements and Testing on Market Trends, for example, exclusively examines articles and other media in the popular press, while another part examines press releases from vehicle manufacturers. Other sections synthesize several sources in the analysis. As such, this report describes which sources were consulted in each part.

In addition to using targeted searches, the review team examined citations of relevant sources to identify further references of interest. The review team also identified two sources in the Task 1 literature review relevant to this task's research topic. These overlapping sources are listed in Appendix I.

Data Review

In addition to locating and analyzing the sources described above, the review team consulted vehicle safety ratings databases such as those managed by NHTSA, IIHS, and Euro NCAP; auto manufacturer publications; owner's manuals; and supplementary publications for information on the presence of exterior bumper beams, active hoods, whether active hood can be reset, and other pedestrian safety technologies. The information profiled vehicles sold in the U.S. and European markets from 2011 to 2022. The 40 best-selling vehicles in the United States by year were examined, while all vehicles tested by Euro NCAP tested during that period were included. This approach allows for a change-over-time analysis.

More specifically, the review team examined information, as available, corresponding to the following data.

- Vehicle year or year of Euro NCAP test
- Vehicle make
- Vehicle model
- Vehicle market location
- Vehicle sales (United States only)

- Presence of active hood
- Whether an active hood can be reset
- Presence of pedestrian safety technology (such as pedestrian AEB)
- Presence of exterior bumper beams (U.S. spreadsheet only)

The information lends context to the findings of the literature review and is incorporated throughout the report.

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Impact of Pedestrian Safety Requirements and Testing on Market Trends

Several factors may have led to different pedestrian safety trends between the United States and other markets. As such, this section examines the European market as a case study. It begins with a review of the most recent European regulations, popular media commentary on vehicle pedestrian safety, and commentary from vehicle manufacturers. This is followed by an overview of pedestrian safety testing in the United States, a comparison between the U.S. and European market, and a review of reports examining vehicle pedestrian safety trends in the United States. The literature review found that European passenger vehicle market is governed by stricter pedestrian safety requirements and consumer testing protocols during the period of this study.

European Market

In November 2003 the European Commission introduced Directive 2003/102/EC for pedestrian protection. The directive required that all new types of passenger cars sold in Europe starting in October 2005 must meet a specified level of performance in headform and legform tests.[*] Over the ensuing years, the new test methods and requirements have been implemented in stages.

The most recent stage went into force under E.U. Regulation 2019/2144. This represented a significant change in the European regulatory landscape regarding passenger vehicle safety, particularly as it relates to pedestrians and other vulnerable road users such as bicyclists (European Union, 2019). This regulation entered into force on January 5, 2020, and applied to all E.U. member states beginning on July 6, 2022. This regulation made and will continue to make a range of new safety technologies—including intelligent speed assistance, reversing detection systems, and event data recorders, among others—mandatory for new vehicle types to receive type-approval in the European Union (Gesley et al., 2021). More important for pedestrian safety, the regulation requires new passenger cars and light commercial vehicle types to be equipped with

- Advanced emergency braking systems capable of detecting obstacles, motor vehicles, and vulnerable road users, such as pedestrians and cyclists, and
- An enlarged head-impact protection zone that can mitigate injuries to vulnerable road users in collisions (European Union, 2019).

Currently, new vehicle types must have advanced emergency braking systems able to detect and respond to stationary and moving vehicles. Systems that detect and respond to vulnerable road users and an enlarged head-impact protection zone must be implemented in new vehicle types by July 7, 2024, and all new vehicles by July 7, 2026 (Federal Ministry for Digital and Transport, 2022).

While Euro NCAP does not have the force of an E.U. regulation, it can significantly affect safety features of E.U. vehicles. It first evaluated vehicles for pedestrian protection in 1997. According to a historical review of the program by the organization's then secretary general Michiel van Ratingen (2016), , and others, Euro NCAP made its testing and assessment protocols stricter in 2002 to encourage vehicle manufacturers to improve pedestrian safety. This change in testing

[*] For pedestrian safety implementation purposes, a "vehicle type" is a new model vehicle that differs from a previous model forward of the A-pillar.

protocols resulted in far more vehicles receiving 1-star ratings for pedestrian safety in 2002 compared to 2001. The ratings then moderately improved in the following years. Van Ratingen et al. (2016) also credited Euro NCAP with further improvements in vehicle pedestrian safety scores since 2009.

Notably, Euro NCAP (2016) began including AEB technology for pedestrians in its safety rating in 2016. These pedestrian AEB tests were expanded in 2020 to include more scenarios, such as a car reversing into a pedestrian, a pedestrian crossing a road into which a car is turning, and a pedestrian crossing the road at night.

Popular Media Perspectives

Popular press material gives perspectives on the impact of pedestrian safety standards and consumer ratings scores on vehicle market trends in Europe. The methodologies in such sources were not usually explicitly described, but their authors often referenced information from vehicle manufacturers or safety organizations. Several articles included interviews with experts in the field. However, one difficulty with popular press methodologies is establishing the causality of why a manufacturer included pedestrian safety features on a vehicle. Possible reasons may include regulatory requirements, consumer ratings and other information highlighting pedestrian safety, and consumers preferring safer vehicles for pedestrians. At times, these article authors suggested reasons why automobile manufacturers may have incorporated pedestrian safety measures in their vehicles.

This subsection reviews articles in non-U.S. publications that mention pedestrian safety features, pedestrian safety standards, and Euro NCAP tests. Occasionally U.S. publications are mentioned, but only when the material is relevant. The non-U.S. publications include

- *ADAC Motorwelt* (Germany),
- *AutoBild* (Germany),
- *Autocar* (U.K. edition),
- *Automobiltechnische Zeitschrift* (Germany),
- *Automotive News Europe* (European edition of *Automotive News*), *and*
- *L'Automobile* (France).

German publications were selected because Germany is a major manufacturer in Europe. *Automobiltechnische Zeitschrift* (*ATZ*) and *Automotive News Europe* are technical magazines for industry professionals. *ADAC Motorwelt* and *AutoBild* are marketed to a broader demographic. *ADAC Motorwelt* is the magazine of Germany's largest motorist association and *AutoBild* is the automotive branch of the popular German tabloid, *Bild* ["picture" or "photo"] *Autocar* and *L'Automobile* are each intended for broad audiences and provide perspectives from elsewhere in Europe.

This range of magazines gave an effective overview of developments in pedestrian safety features since 2011. However, there is a risk that topic selection is limited in these sources. Since most magazines are written for general audiences, content and the vehicle technologies discussed may be limited to "newsworthy" items of interest to general consumers, not necessarily automobile industry professionals (*ATZ* is a noted exception to this trend), much less automobile safety professionals. For example, while these magazines referenced a variety of pedestrian safety technologies, including pedestrian sensing technologies and adaptive headlights, they did not reference changes to vehicle front-end design because of an enlarged head-impact testing area (Federal Ministry for Digital and Transport, 2023). Due to this omission, it is unclear from a review of popular press whether vehicle manufacturers have changed vehicle designs to respond to this development.

However, European pedestrian safety protocols that affect front-end design were mentioned in two articles in *AutoBild*, providing examples of articles discussing changes in shape rather than entirely new technology. Yet, even in these articles, changes in vehicle front-end designs were only superficially referenced. For example, a December 2015 article passingly referred to the more "upright" front design of the 2017 BMW X3 being a result of new pedestrian safety protocols (BMW X3: Vorschau, 2015). An article about the 2017 Mercedes-Benz G-Class, an SUV with military styling elements designed for off-road capability, discussed with some surprise that the automotive designers were able to shape the "edgy" front end to align with pedestrian safety protocols by creating a bumper that was thicker and extended further down than previous G-Class models. The article applauded Mercedes-Benz for developing a pedestrian safety-compliant G-Class while other automotive manufacturers simply discontinued similar vehicles (Braun, 2017).

One pedestrian safety feature that the European popular press did discuss is acoustic vehicle alerting systems on hybrid and electric vehicles. Regulations requiring minimum sound requirements for hybrid and electric vehicles in the United States preceded those in the European Union, which required AVAS on new electric vehicles beginning July 1, 2021 (European Commission, 2019). A 2015 article in *Autocar* pointed to the international impact of pedestrian safety regulations when it discussed an E.U. AVAS system before it became mandatory in the European Union, noting that laws mandating AVAS on electric vehicles already existed in the United States (Moss, 2015). The article was likely referring to the Pedestrian Safety Enhancement Act of 2010, which directed the Secretary of Transportation to initiate rulemaking to promulgate a safety standard regarding alert sounds for electric and hybrid vehicles, although the final rule resulting from this act was not finalized at the time of the article. The article noted that "the development of the system is partly in response to research conducted by the National Highway Traffic Safety Administration in the United States," which points to the global impact of domestic pedestrian safety research and rulemaking (Moss, 2015).

Various automobile manufacturers are employing AVAS in different ways, according to a 2020 article in *Autocar* that said sound designers were trying to craft AVAS sounds that were distinctive to the vehicles, but not so unique or obscure as to be ineffective in warning pedestrians of a vehicle's presence (Attwood, 2020). This is an example article that suggested how the automobile industry creatively responded to AVAS requirements appearing in more regions of the world by applying them on new hybrid and electric vehicles.

Two articles in *ATZ* similarly mentioned international rulemaking as a reason automotive parts manufacturers were exploring how to develop effective AVAS systems. A 2020 article by a senior director at Harman, an American audio electronics company, described the efficacy of the company's AVAS system, its conformity to regulations, and some of its technical features, including its size, weight, and, importantly, compatibility with vehicle models and regulations (Augustine, 2019). The other *ATZ* article is from 2012 and discusses a similar system by LMS, a German automotive parts supplier (Van der Auweraer, 2012).

Active hoods, or hoods that pop up from near the seam between the hood and the windshield to provide more deformable space between the engine and a pedestrian in case of a collision, were not mentioned in the European popular press in relation to pedestrian regulations. However, this technology was referenced in some press releases, as discussed below. Pedestrian AEB and pedestrian air bags likewise were not mentioned in European popular press in relation to pedestrian regulations. However, some U.S. outlets discussed how some vehicles for sale in the European market are equipped with these features while vehicles for sale in the U.S. market are not; this is addressed below.

In addition to technologies currently required by regulation or tested by safety organizations such as Euro NCAP, some publications discussed emerging technologies that are not yet regulated or tested by consumer testing organizations. An example of headlight technologies that may improve pedestrian safety and have not yet been systematically tested or considered by ratings agencies is headlights that project images onto the roadway. This is proposed by industry as a future method by which an automated or partially automated vehicle can communicate to a pedestrian that it “sees” them and that it is safe to cross in front of the vehicle by projecting an image such as a crosswalk onto the roadway (Wartzek et al., 2020; Reschke et al., 2019). Another example of an as-yet-unstandardized pedestrian safety feature concerns vehicle-to-everything technology. Specifically, this technology may improve pedestrian safety by locating pedestrians relative to the vehicle by having the vehicle “communicate” with a pedestrian’s cell phone, if equipped (Leseman et al., 2019). There recently has been considerable discussion about the safety of automated vehicles for pedestrians, both in European and U.S. publications (see for example Reschke et al., 2019; Barry, 2021; Beresford, 2019; Taylor, 2016).

Along with these specific technologies, the European automotive press sometimes discussed the effects of European pedestrian safety regulations on market trends more broadly. One 2011 article in *Automotive News Europe*, for example, stated that automotive designers needed to be creative to meet pedestrian safety requirements in the European Union while keeping with the automaker’s aesthetic brand identity. For instance, the sharp edges of Audi’s A3 concept car needed to be rounded to conform with pedestrian safety requirements in Europe (Gibbs, 2011). Another 2011 article from the same publication noted fears that Chinese automakers would sell significant numbers of vehicles in Europe did not become reality. The article credited pedestrian safety regulations, as well as stricter emissions rules, with keeping Chinese manufacturers out of the European market as the Chinese vehicles did not meet the European requirements. Specifically, the article mentions that the longer front ends on European vehicles designed to meet pedestrian safety requirements were more expensive to produce (Ciferri, 2011).

Two articles in *Automotive News* from 2013 and from 2014, discussed the potential impact of stricter European safety regulations, including pedestrian safety regulations, on the global demand for safety technology. The 2013 by Greimel article reported that, in addition to creating in-creased demand for active hoods, Denso Corporation, a major Japanese automotive parts supplier, expected significant increases in its sales of sensors that detect pedestrians and other hazards as a vehicle is traveling. Both articles noted that the increase in demand would be driven by more sensors being applied to mass-market vehicles, as compared to premium and near-premium vehicles—often from German manufacturers—which had been outfitted with these sensors previously (Greimel, 2013, 2014).

Original Equipment Manufacturer Press Releases

In reviewing press releases from the six best-selling vehicle brands in Europe in 2022, according to ACEA data, several trends emerge. These vehicle brands were, in order of sales, Volkswagen, Toyota, Peugeot, Renault, Mercedes, and BMW (European Automobile Manufacturers' Association, 2023). The review team found 112 press releases by these six automakers referencing pedestrian safety features. The press releases often highlighted favorable scores on Euro NCAP tests, suggesting the tests have a strong influence in driving safer designs and the adoption of safety technologies. While manufacturers publicized a range of pedestrian safety features in their press releases, none of the sources claimed the features were included because of pedestrian safety regulations. For example, even though pedestrian AEB technology will be required in the European Union for all new vehicle types beginning July 7, 2024, the review team identified no source asserting the technology was added because of the law. Instead, sources may only refer to a brand's commitment to safety or cutting-edge technology.

Considering all press releases, eight pedestrian safety features were mentioned. These features and the number of press releases highlighting them are listed below.

- Pedestrian AEB technology (43)
- Hood or body design of a vehicle (26)
- Autonomous steering to avoid pedestrians (14)[*]
- Sensors alerting when a pedestrian is in the path of a turning vehicle (12)
- Active hood (10)
- AVAS systems (4)
- Clear line-of-sight to surrounding pedestrians (2)
- Pedestrian-marking headlights (1)

As this list shows, pedestrian AEB and vehicle hood or body design were the most referenced features. These were the most referenced features in articles that also mentioned a Euro NCAP score.

More specifically, among the 112 press releases referencing the pedestrian safety of vehicles, the review team identified 33 statements highlighting a favorable Euro NCAP score or another award. Four pedestrian safety features—often described as a cause of the strong Euro NCAP score—were listed in these statements.

- Pedestrian AEB technology (12)
- Hood or body design of a vehicle (12)
- Active hood (8)
- Sensors alerting when a pedestrian is in the path of a turning vehicle (2)[†]

[*] All but one of the press releases highlighting autonomous steering were by Toyota, which published the most press releases discussing pedestrian safety features.
[†] The sum of statements in this list does not equal the number of press releases highlighting a favorable Euro NCAP score because some articles mentioned specific pedestrian safety features, while others did not mention any.

Because these press releases note high Euro NCAP scores, it appears that Euro NCAP testing on pedestrian AEB technology and vehicle hoods may be effective in encouraging vehicle manufacturers to adopt such technologies.

U.S. Market

NHTSA's New Car Assessment Program, known as the 5-Star Safety Ratings program, did not test pedestrian safety features during the timespan assessed in this report, though NHTSA recently proposed updating the program to include an assessment of pedestrian AEB systems, among other revisions in a Notice of Proposed Rulemaking about automatic emergency braking systems for light vehicles (FMVSS, 2023). IIHS, however, has tested various aspects of a vehicle's pedestrian safety features for years. IIHS added pedestrian AEB technology to its assessment criteria in 2019 and expanded this assessment to include nighttime conditions in 2022 (IIHS, n.d.-b). However, they do not have a vehicle crashworthiness rating for pedestrian safety akin to GTR No. 9 or Euro NCAP using pedestrian headforms and legforms.

Because fewer regulations exist and consumer testing organizations have only recently begun testing vehicles for some pedestrian safety features, relatively few press articles discuss how vehicles have changed to conform to pedestrian safety regulations or consumer testing in the United States. However, a range of articles have discussed ways some U.S. vehicles have become safer for pedestrians. In addition, several articles highlighted differences in pedestrian safety features between U.S. and non-U.S. vehicles.

U.S. Versus Non-U.S. Comparison

Articles in the popular press that compare vehicles for sale in non-U.S. markets with vehicles for sale in the United States note differences but suggest that changes in the pedestrian safety designs of global vehicle models appear in the United States as well. For example, reporter Christina Rogers stated in a 2012 *Automotive News* article that this is expected as global automakers seek to comply with new EU safety rules. Because vehicles are often designed for a global market, these changes may affect vehicles sold in several markets. Specifically, Rogers quoted Aaron Bragman, an HIS automotive analyst, that suggested the 2013 Ford Fusion was noticeably redesigned to have a taller front end and a higher hood that effectively would shorten the distance a pedestrian would fall if hit. The article noted the 2013 Chevrolet Malibu and 2013 BMW 3 series were global models with E.U.-compliant front ends. Considering the features of vehicles that have changed to meet E.U. requirements, Rogers said that hoods have become more deformable and higher to create additional space over hard vehicle parts. Rogers reported that designers have lowered front-end bumpers and used softer materials to protect the legs of pedestrians. A 2012 feature in *Car and Driver* similarly noted that European and Asian pedestrian safety protocols have caused vehicle manufacturers to raise the hood height on cars such as the BMW 7 series and that this modification has caused a series of other changes in overall vehicle aesthetics (Hall, 2012). While these changes may affect passenger cars, they are less likely to occur on pickups. As Rogers noted, a Ford representative suggested that to make pickups pedestrian safe may require active pedestrian safety features such as pedestrian AEB systems.

Some reports explicitly noted differences between the same model of vehicle sold in the United States versus elsewhere. An example of a vehicle model sold in the United States that differs from its European counterpart was discussed in an article by Ezra Dyer (2020) for *Car and Driver* about the Ford Bronco badge. The badge is an emblem of a bronco raised several millimeters from the rear panel of the vehicle. Because European safety regulations specify the shape of protrusions from a vehicle, it was explained that the badge needed to be redesigned to be smoother for the European market. The article, however, expressed doubt that the badge is likely to harm a pedestrian in practice due to its location near an external spare tire on the rear of the vehicle.

Another example of pedestrian safety regulations permitting different external features in the United States compared to Europe is that of the Ford Mustang. According to a 2015 article, the European version of the Mustang could not include an optional hood scoop* due to pedestrian safety regulations. In the United States the hood scoop was permitted and offered as an optional feature (Traugott, 2015).

Several articles said certain pedestrian safety features were debuting in Europe or Japan but did not specify whether these features would appear on U.S. models. One element of interest was Volvo's pedestrian air bag, which was first included on the 2013 Volvo V40. Three articles noted that the technology would debut on the European version of the V40 and that there were no plans to sell the vehicle with this technology in the United States (Emmerson, 2012; Udy, 2012; Wendler, 2012). Similarly, the 2013 Mazda MX-5 Miata sold in Japan reportedly had an active hood (Holmes, 2012). The literature search did not find any evidence that an active hood was ever built into a MX-5 Miata for U.S..

The popular press also discussed pedestrian AEB systems, which may have been equipped on vehicles in the E.U. market earlier than the U.S. market. These are distinct from vehicle AEB systems, which engage to stop or slow a vehicle if the system senses another vehicle stopped, slower moving, or decelerating in its path. Articles and automotive reviews often discussed pedestrian AEB technology in concert with testing conducted by Euro NCAP and IIHS. Both organizations rate the performance of pedestrian AEB systems and publish the results for consumers to reference. While the write-ups did not usually specify that this technology was more common in Europe, articles in *MotorTrend* and *Car and Driver* mentioned that Ford's pedestrian detection system would debut in its European-market vehicles, such as the 2015 Ford Mondeo, before its U.S.-market vehicles (Capparella, 2016; Stoklosa, 2014). The *MotorTrend* article stated that this technology would appear in U.S.-market vehicles such as the Ford Fusion the following year (Capparella, 2016).

Some articles explicitly mentioned that European models were equipped with adaptive driving beam headlights, but that these lights were not legal in the United States at the time those articles were published (Barry, 2022; Frank, 2020). NHTSA has since promulgated a new final rule—which amended in 2022 Federal Motor Vehicle Safety Standard No. 108, *Lamps, reflective devices, and associated equipment*—allowing the use of such headlamps. These headlights may be safer for pedestrians as they could potentially direct light toward pedestrians, drawing a driver's attention to their presence. In 2020 this technology was primarily available on vehicles produced by luxury manufacturers including Audi, BMW, Cadillac, Lexus, Mercedes-Benz, and Porsche (Frank, 2020).

U.S.–Focused Reports

As noted, IIHS began testing pedestrian AEB technologies in 2019. This was accompanied by articles covering the tests, which noted that 4 of the 11 vehicles examined in the original round of testing received the "superior" rating, 5 earned "advanced," 1 earned "basic," and 1 earned a

* Also known as a bonnet scoop/airdam, or air dam, a hood scoop is an upraised component on the hood of a vehicle that allows a flow of air to directly enter the engine compartment.

zero. However, a series of articles have described various U.S.-market vehicles as being outfitted with pedestrian AEB since 2013, suggesting that a legal requirement or testing by a consumer ratings organization is not necessary for this technology to be incorporated into new vehicles. Several articles focused on the pedestrian AEB capabilities of Toyota and Lexus vehicles, as well as the 2018 Ford F-150 and 2018 Ford Mustang, with discussion expanding to automatic emergency pedestrian-avoidance steering in the early 2020 vehicle model year timeframe (See, for example, Atiyeh, 2014; Baldwin, 2020, Holmes, 2013; Lin, 2017; Muller, 2017; Sanchez, 2017).

In another specific example of a particular vehicle feature being made safer for pedestrians, Collin Woodard noted in 2019 in *MotorTrend* that a retractable hood ornament for the Bentley Flying Spur likely needed to be retractable to meet pedestrian safety requirements, as well as to protect the ornament from theft.

An analysis by *Consumer Reports* and an accompanying website article discussed vehicles in the U.S. market that lack the safety features of pedestrian AEB and blind-spot warning (Douglas, 2020; Barry, 2021). This analysis found that of the 15 best-selling vehicle models in the first two quarters of 2019, there were 13 that had pedestrian AEB as standard options. The feature was not available on the Ram 1500, while it was an optional feature on the Chevrolet Silverado 1500. The article noted it was alarming that equipping the Chevrolet Silverado 1500 with pedestrian AEB would require a customer to pay $16,735 over the base model price, likely due to the consumer needing to upgrade three trim levels to get the feature (Douglas, 2020).

In a separate press release, analysts at *Consumer Reports* noted that pedestrian AEB had become much more prevalent in the years leading up to 2020. The analysts attributed this increase in pedestrian AEB adoption in part to plans by *Consumer Reports* and IIHS to include pedestrian AEB in future vehicle ratings. The press release (Douglas et al., 2020) stated,

> In February 2019, when pedestrian detection came standard on only 38[percent] of new U.S. vehicle models, both Consumer Reports and IIHS announced plans to emphasize pedestrian safety in their scoring. Manufacturers are rising to the challenge, and now **61[percent] of 2020 models come with pedestrian detection standard** to go along with automatic emergency braking (AEB) (emphasis in original).

No sources were located in which auto manufacturers stated that the changing testing procedures at *Consumer Reports* and IIHS were a reason for making pedestrian AEB standard equipment on their vehicles. Even so, consumer testing programs such as these, as well as proposed U.S. NCAP and regulatory proposals under development at that time may have encouraged automakers to equip their vehicles with this technology.

According to the literature examined for this report, pedestrian AEB systems have become standard on almost all recent top-selling vehicles. In model year 2022, for example, nearly all 40 of the best-selling vehicles in the United States had standard or optional pedestrian AEB; the Ford Transit was the only model with no pedestrian AEB option. Apart from the GMC Sierra, Chevrolet Malibu, and Chevrolet Tahoe, pedestrian AEB was a standard feature on all models. However, each of these three vehicles was equipped with pedestrian AEB as a standard feature in model year 2023 (Lopez, 2022; IIHS, n.d.-a). Information was not found on whether the 2023 Ford Transit has standard or optional pedestrian AEB.

Unlike pedestrian AEB, however, active hoods remain exceedingly rare in the U.S. vehicle fleet. The literature review did not identify this technology on any of the best-selling vehicles in the United States. The literature review did identify one vehicle equipped with an active hood in the European market, but not in the U.S. market: the 2022 Honda Civic.

Impact of Pedestrian Safety Requirements and Testing on Pedestrian Safety

While the preceding section focused on the impact of pedestrian safety regulations and consumer ratings procedures on the vehicle market trends of pedestrian safety features, this section focuses on whether there is literature to support that pedestrian safety standards or consumer ratings scores have been effective in protecting pedestrians since 2011. It examines the causal link between pedestrian safety efforts and actual pedestrian safety.

This section examines the causal relationship between the impact of new pedestrian safety efforts and actual pedestrian safety from two perspectives: studies that use a prospective methodology and studies that use a retrospective methodology. The first section explores articles and reports that prospectively estimate the expected safety impact of new regulations. This is followed by a review of studies investigating the expected safety impact of three specific vehicle technologies. The next section reviews sources incorporating a retrospective methodology to examine the observed safety impact of new regulations.

Prospective Studies: Expected Safety Impact of Pedestrian Safety Measures

This section reviews literature that sought to predict the impact of pedestrian safety measures on actual pedestrian safety. While most of the sources focus on the expected impact of pedestrian safety measures in the European Union, the findings may remain relevant to the context of the United States.

Particularly detailed and relevant sources include a series of reports published by TRL Limited, a U.K. transport consultancy and research service firm, and the European Commission from 2015 to 2018, which examined new pedestrian safety technologies not mandated in regulations. A 2015 report written by David Hynd and others at TRL under a contract with the European Commission provided a benefit-cost and feasibility analysis of a range of possible measures for inclusion in the European Union's vehicle safety regulation. Hynd et al. conducted this analysis by identifying benefit-cost information in the literature and then estimating a benefit-cost ratio when sufficient information about technology costs, target population, and effectiveness was available. This report was followed by a 2017 study by Matthias Seidl and others at TRL for the European Commission, which drew on the Hynd et al. (2015) report and provided more recent data, as well as an additional examination of available evidence. The Seidl et al. (2017) report similarly included an analysis of the costs and benefits of various measures that could be implemented in the regulation, but it added a "PESTLE" analysis[*] to examine other political, economic, societal, technical, legal, and environmental effects of proposed measures. The Seidl et al. report was followed a year later by another report for the European Commission written by Seidl and a different group of researchers (2018), which examined the cost-effectiveness of specific sets of policy measures as proposed by the European Commission for mandatory implementation in new vehicles starting from 2021.

[*] PESTLE stands for Political, Economic, Social, Technological, Legal, and Environmental. Examples: Political: Tax policy, trade restrictions, political stability; Economic: Economic growth, interest rates, inflation, unemployment; Social: Cultural norms, health consciousness, population growth; Technological: New technologies, rate of technological change; Legal: Changes to legislation, access to materials, quotas, resources; Environmental: Global warming, need for sustainable resources, ethical sourcing

Each of these three reports for the European Commission examined roughly the same set of pedestrian safety measures:

- Adult head-to-windshield impact protections,
- Backup cameras with reverse sensing,
- Pedestrian AEB, and
- Increased direct visibility from vehicles.*

In addition, the Hynd et al. (2015) report studied the possible effects of third-party replacement parts and front registration plates on pedestrian protection but found no cost or benefit information about these technologies. Hynd's group also sought to study the effect of bonnet (i.e., hood) leading edge characteristics on pedestrian upper leg and pelvis injuries but stated that there were small numbers of such injuries and the benefit-cost ratio likely did not indicate that further action was necessary. The effects of third-party parts, front registration plates, and bonnet leading edge characteristics were not examined in the subsequent reports. It was noted that none of the reports examined the effect of active hoods on pedestrian safety. This technology was found to be included on several European vehicles already in 2011.†

Adult Head-to-Windshield Impact Protections

Concerning adult head-to-windshield impact protections, the Hynd et al. (2015) article found that the benefit-cost analysis may support more stringent regulations. Countermeasures could include changing the windshield design in some way, providing deployable solutions around the periphery of the windshield (such as a pedestrian air bag), and relying on AEB systems to avoid collisions altogether. The authors noted, however, that changing the curvature or angle of the windshield would have significant implications on vehicle design.

Seidl et al. (2017) found that incorporating some of these countermeasures would be beneficial for pedestrians and especially for bicyclists. This was particularly true if the countermeasures included both passive protection, such as improvements to windshield design or deployable systems, and active protection, such as pedestrian AEB. This combination would provide a significantly increased benefit as the active protection would often slow a vehicle before collision, if not prevent a collision entirely, and the passive protection would further reduce injury. Seidl et al. noted, however, that the ACEA expressed concerns about the technological maturity of a deployable air bag and the possibility that such an air bag might restrict the driver's field of vision or be difficult to package on smaller vehicles.

Reverse Cameras and Sensing

As part of a report to the European Commission in support of the General Safety Regulation, Hynd et al. (2015) found that reversing detection and reversing camera systems intended to prevent a reversing car from running into pedestrians (i.e., backover incidents) had a benefit-cost ratio greater than one. Because this means that the population of the European Union would

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* The examination of direct visibility applied to heavy-vehicle classes, often commercial vehicles, not passenger vehicles or pickups.

† Vehicles tested by Euro NCAP and equipped with active hoods in 2011 are the Chrysler Voyager, Fiat Freemont, Jaguar XF, Lancia Thema, and Mercedes-Benz C-Class Coupe.

“save” more money, in terms of a reduction in injuries and fatalities, than it would cost consumers to pay for these systems on new vehicles, the benefit-cost ratio was in favor of requiring the system. The authors noted that it is possible that backup camera technologies may be even cheaper than their latest available data, as they were becoming standard on an increasing number of vehicles. This is a development the authors attributed to NHTSA for requiring the technology from May 2018. The authors further noted that the casualties of backover incidents were often children, which provided further support for implementing such technologies, even if the benefit-cost ratio was less than one.

Pedestrian Automatic Emergency Braking

The effect of mandating pedestrian AEB systems on vehicles has been studied more than other pedestrian safety features. However, a full analysis of articles on the prospective efficacy of pedestrian AEB is outside the scope of this report. The focus here is on studies that examined the expected safety effect of the technology in terms of fatalities and injuries that could be avoided or reduced at the population level if pedestrian AEB were a mandatory feature. For a list of articles discussing pedestrian AEB, see a 2020 feature by Jordanka Kovaceva and others.

Hynd et al. (2015) observed that pedestrian AEB systems functioned well in tests, but they were not able to verify that these systems functioned well in practice. As a result, the team could not calculate a benefit-cost ratio. They did note, however, that pedestrian AEB systems were available in Europe in 2015 in vehicles manufactured by Volvo and Lexus, and in Asia in Subaru vehicles. Writing in 2017, Seidl et al. described a lack of information about the cost of pedestrian AEB systems as a reason for there being no longitudinal benefit-cost analyses.

Academic literature, on the other hand, has gone into greater detail about the expected effect of pedestrian AEB on the European passenger vehicle fleet. In a 2014 report researchers at TRL and Germany’s Federal Highway Research Institute (Bundesanstalt für Straßenwesen [BASt]) estimated the benefit such systems would have in Europe. The authors, led by Mervyn Edwards, calculated the change in impact speed that vehicles involved in pedestrian crashes in Germany and the United Kingdom would have had and then calculated the change in the level of injury that this would have caused. They then extrapolated these findings to all of Europe. The methodology assumed that the entire fleet was to be fitted with these systems, which is unrealistic in the short term, but provides a useful approximation of the expected benefit. Using the same values as Hynd et al. (2015) to calculate the monetary cost of fatal, serious, and slight injuries in the European Union, the authors found that a then-current pedestrian AEB system would provide a nominal benefit of approximately €1 billion and the reference limit system (i.e., the best performance thought to be technically feasible at the time) would provide a nominal benefit of €3.5 billion. Dividing these numbers by the number of new passenger cars registered in Europe per year (about 12.5 million), the authors posited that outfitting all passenger vehicles with a then-modern pedestrian AEB system would need to cost less than €80 to be cost effective. A more effective reference limit system, by comparison, would need to cost less than €280 to be cost effective. This calculation assumes that all passenger vehicles in the fleet are equipped with pedestrian AEB systems (Edwards et al., 2014). This state would be achieved only after the vehicle fleet were replaced by new vehicles with pedestrian AEB systems, which would take considerable time.

Several articles examined the effect AEB would have on pedestrians if it were to be implemented on vehicles in the European Union, but they did not explore the causal relationship between regulation and implementation. Kovaceva et al. (2020), for instance, extrapolated their findings from data derived from the German In-Depth Accident Study to the entire European Union. If pedestrian AEB systems penetrated 20 percent of the market as an example value, they found that pedestrian AEB could prevent 10 to 12 percent of pedestrian fatalities in the European Union.

In 2019 Haus et al. conducted a similar study to Edwards et al. (2014), but they examined the potential of pedestrian AEB on the U.S. vehicle fleet. Like Edwards et al., they assumed all vehicles in the fleet were equipped with pedestrian AEB. They used data from the Pedestrian Crash Data Study, which comprises data on pedestrian crashes from 1994 to 1998 across six urban areas in the United States. They found that, given 1.5 seconds of time for the system to react to a pedestrian in the vehicle's path (referred to as time-to-collision) and no latency for the system to activate, pedestrian fatality risk could be decreased between 84 percent and 87 percent with a pedestrian AEB system. In addition, pedestrian AEB could reduce the pedestrian injury risk scored at 3 or above, including fatalities, on the Maximum Abbreviated Injury Scale by between 83 percent and 87 percent (Haus et al., 2019). A score of 3 or more on the MAIS indicates that the most severe injury is "serious" or more severe. The study predicted that given just 0.5 seconds of TTC and 0.3 seconds of latency, the pedestrian fatality risk could be decreased between 36 and 39 percent, suggesting that TTC and latency have a large effect on a vehicle's ability to reduce injury or avoid a collision with a pedestrian altogether.

Retrospective Studies: Observed Safety Effect of Pedestrian Safety Measures

Several sources provided retrospective or combined retrospective and prospective analyses of the effect of pedestrian safety measures. These sources provide some indications of the causal effect pedestrian safety measures have had on actual pedestrian safety. However, it remains difficult to determine the extent to which changes in vehicle safety are the result of changes in pedestrian safety regulations and ratings practices as opposed to changes that would have occurred without changes to regulations and ratings. While the number of pedestrian fatalities in Europe decreased by 37 percent from 2004 to 2013, a time in which pedestrian safety regulations came into effect, sources have noted that it is difficult to prove that the reason for this improvement is entirely due to the regulations as opposed to other possible factors European Commission, 2016).

The studies in this section all examine the observed effect of pedestrian safety regulations and ratings procedures on actual pedestrian safety. This is important to determine, as it tests whether higher pedestrian safety ratings lead to actual improved pedestrian safety. As vehicles tend to improve in safety ratings over time, this would suggest the European fleet is becoming safer (Strandroth et al., 2014; van Ratingen et al., 2016). Several articles below suggest there may be a high correlation between Euro NCAP scores and pedestrian safety.

Two studies in which Johan Strandroth of the Swedish Transport Administration was the lead author provide information on whether Euro NCAP scores correlate with pedestrian injuries in Sweden. In both 2011 and 2014, Strandroth et al. found that the Euro NCAP scores for pedestrian safety were significantly correlated with the injury severity sustained by pedestrians in actual crashes in Sweden in speed zones of up to 50 km/h. In both studies, the researchers coded pedestrian crashes for injury severity sustained by the pedestrian and the Euro NCAP pedestrian safety rating of the vehicle involved and analyzed the correlations between these variables. In the 2014 article, Strandroth et al. also found a decrease in pedestrian mean injury severity in crashes involving cars with higher pedestrian safety ratings and occurring in speed zones above 50 km/h. The authors further found pedestrian AEB technology may have been successful in preventing many pedestrian collisions, though the calculated reduction in crashes was not significant, possibly due to the small sample size of vehicles equipped with pedestrian AEB in 2014.

For the pedestrian protection crashworthiness protocols, Liers and Hannawald (2011) identified a similar correlation between the number of Euro NCAP points and the injuries sustained by pedestrians. These findings were corroborated in a 2013 study by BASt's Claus Pastor, who examined a much larger dataset covering pedestrian crashes and injury outcomes in Germany and found a significant correlation between Euro NCAP scores and the severity of pedestrian injuries in crashes from 2009 to 2011. Pastor found that each additional point in the Euro NCAP score correlated with a reduction in probability of fatal injury by as much as 2.5 percent and a reduction in serious injury probability by about 1 percent. He did not, however, find that vehicles that were compliant with European pedestrian protection legislation that took effect in October 2005 caused significantly less injury than vehicles that were not compliant. Pastor did not discuss why this might be the case, but noted that, "in general…it is difficult to distinguish effects in the field which are attributed to Euro NCAP and effects attributed to legislation."

Liers and Hannawald (2011) had found that there is significant variation within a single Euro NCAP pedestrian protection point level, suggesting that even more fine gradations in scoring may be appropriate. Since then, Euro NCAP has implemented a finer gradation system for pedestrian crashworthiness scoring. A rating for PAEB has also been implemented since then.

While the previous studies primarily investigated the correlation between Euro NCAP scores and real-world pedestrian safety, the following studies examined the effect of a 2003 E.U. directive that mandated pedestrian safety testing of a vehicle's front end to receive type-approval in the European Union. This regulation introduced various forms of impactor testing, including using legforms and headforms to test a vehicle's bumper, hood, and windshield for pedestrian safety. The protocols went into effect on October 1, 2005.

Li et al. (2018) explicitly focused on effects that this regulation may have had on pedestrian protection. They examined pedestrian collision data from GIDAS and studied the characteristics of crash-involved vehicle front ends that were produced before 2000 or after 2005. The years from 2000 to 2005 were considered a transitional period for changes in car front design as the legislation was being considered and enacted, but its protocols were not yet mandatory. While the authors acknowledged that variables other than European legislation and ratings may have affected car front design, they assume these had the greatest effect during that time period. They found that cars manufactured for the European market after 2005 had flatter and wider bumpers, higher hood leading edges, shorter and steeper hoods, and shallower windshields than cars manufactured before 2000. Further, this shape improved pedestrian leg protection. However, the high hood leading edge was poor for pelvis and femur protection. Li et al. also found that new vehicle front-end shapes were safer for head injuries, positing that this was likely due to reductions in stiffness rather than improved front-end geometry.

Nie and Zhou (2016) similarly compared the front ends of vehicles before and after the new pedestrian safety regulation went into effect in Europe in 2005. They used computer models of representative vehicle front ends manufactured before 2003 and from 2008 to 2011 to run simulations of pedestrian crashes. In contrast to Li et al. (2018), their focus was on lower-leg injuries. They found that newer front ends of SUVs and sedans were “flatter,” with less depth between the secondary, or lower, bumper and the main bumper than previous models. This correlated with a reduction in risk of knee ligament rupture by 36.6 percent to 39.6 percent because the impact to the leg was distributed over a larger area. It was not clear if this also resulted in lower risks of long bone fractures. Importantly, the study did not assess risk to a pedestrian’s pelvis or thorax, which the authors believe may have a higher contact force because of the altered designs.

As a result, newer front ends introduced after pedestrian safety regulation went into effect in Europe in 2005 may reduce risk of lower leg injuries, as Li et al. (2018) and Nie and Zhou (2018), found. However, these newer front-end designs may also increase the risk for pelvic or thoracic injuries, as noted by Nie and Zhou (2016). The overall effect on pedestrian safety of the new front-end designs appearing after the pedestrian safety regulation went into effect remains unclear.

Developments in Bumper Construction and Exterior Bumper Beams

Legform test results can be highly dependent on a bumper's stiffness and its position on the front-end relative to other front-end components, such as the grille and bonnet leading edge. Also, the "bumper test area" (the zone on a vehicle that is subject to legform requirements) can be highly dependent on the length and curvature of a vehicle's bumper. This section is an examination of bumper design trends, differences between American and European designs, bumper construction and pedestrian safety, and vehicles that might have exposed bumper beams.

The first section on industry design trends examines the different materials being explored by auto manufacturers for bumper beams and front fascia, as well as the variety of engineering designs that can be used for vehicle bumpers. The second section describes how American and European versions of the same vehicle models fare in both American and European safety testing. The third details how changes in bumper construction have improved pedestrian safety over time. The final section examines the exterior bumper beams that pose challenges to legform compliance due to their high rigidity. The terms "exterior," "exposed," and "external" are used interchangeably to refer to bumper beams without a covering or front fascia.

Industry Design Trends

A 2020 report by the trade association American Iron and Steel Institute provides information about the two different kinds of bumper systems currently in use. It refers to them as systems with exposed or unexposed bumper beams. According to the institute, a bumper system with an exposed bumper beam is defined as follows:

> Exposed bumper beams are a styled surface of the vehicle and visible to the customer. The exposed bumper beam absorbs most of the energy in a low-speed vehicle collision. It is integral to vehicle high-speed crash performance and provides a structural member for customer step loads. … Plastic or stainless-steel trim is attached to the bar to meet styling requirements.

It further stated that a bumper system with unexposed or covered bumper beams, by contrast, is defined as follows:

> Unexposed bumper beams are covered by the plastic fascia and not seen by the customer. It absorbs most of the energy in a low-speed vehicle collision and [is] integral to … vehicle high-speed crash performance.

For unexposed bumper beams, the institute noted that there are four subtypes, all with plastic fascia:

- Unexposed bumper beams with plastic fascia system,
- Unexposed bumper beams mounted to mechanical energy absorbers with plastic fascia,
- Unexposed bumper beams mounted to body frame with foam or plastic molded energy absorber and fascia, and
- Unexposed bumper beams mounted to mechanical energy absorbers with foam or plastic molded energy absorber and fascia.

The institute further noted that bumper beams accompanied only by plastic fascia are generally confined to rear bumpers. According to the institute, the other system often used for rear bumpers combines the beam, plastic fascia, and mechanical energy absorbers and this system is usually found in Europe and South Korea. According to the institute, the other two types of unexposed bumper beams both have plastic fascia with either foam or plastic molded energy absorbers or mechanical energy absorbers with foam or plastic molded energy absorbers. According to the institute, the former is more frequently found in the United States and China while the latter is used in Europe and South Korea and both systems are common for front bumpers. Additionally, the institute stated that the reason different bumper systems may be used in different countries is due to differing pedestrian safety mandates and testing. For example, it suggested a bumper system comprising mechanical energy absorbers with foam or plastic molded energy absorbers is often used when insurance tests mandate that a bumper must not sustain any damage in a crash up to 9 mph.

For vehicles with unexposed bumper beams, one trend in bumper construction is that the materials manufacturers use to fabricate bumpers are changing. A 2023 report by GlobalData Plc (2023a), a U.K. consultancy, on lightweight vehicle front-end market trends described several developments in bumper construction. According to the report, Mazda, for one, collaborated with two other Japanese companies to create two new materials for use in SUVs. The first material was a new form of high-performance steel. Unexposed bumper beams formed from the new material were found to be stronger and lighter weight than beams from previously used steels. The second new material was a resin for external bumper components. According to the report, Mazda stated that the resin was stronger and thinner than other materials while exhibiting high stiffness and the material was 20 percent lighter than previously used bumper components. According to the report, both materials are used in the Mazda CX-5.

Aluminum is also widely used in vehicle construction. A separate GlobalData report (2023b) from 2023 on trends in global vehicle lightweighting noted several vehicle models primarily used aluminum instead of steel in the vehicle body at the time of publication. Additionally, according to the report, Ford was exploring the possibilities of using aluminum for bumper beams, while traditionally, bumper beams have been made of steel. However, it noted that the 2013 Range Rover and 2013 Honda Accord are examples of older vehicles where aluminum bumpers were used. While aluminum is slightly weaker than steel, according to the report, it is lighter and offers a potentially acceptable trade-off for manufacturers seeking to produce lighter vehicles. The report, however, did not discuss any aluminum versus steel trade-offs that might exist for pedestrian safety.

Most notably, the report on lightweight front ends acknowledged that pedestrian protection requirements appear to have an influence on market trends in bumper construction. It stated that many European automakers have altered their bumper designs in response to E.U. pedestrian protection requirements. While the report did not identify which automakers or models have changed in response to these requirements, it explicitly stated that bumper construction has developed to include plastic components attached to the bumper. According to the report, these components increase energy absorption and are intended to mitigate the leg and head impacts tested by Euro NCAP.

For exposed bumper beams, the American Iron and Steel Institute (2020) noted that they were exclusive to North America. Furthermore, they noted exterior bumper beams are primarily used on trucks while unexposed bumper beam systems are used on a wider variety of vehicle types.

According to the institute, exposed bumper beams are made of either low- or high-strength steel. In contrast, unexposed bumper beams can be formed with steel, aluminum, or plastic. However, the institute noted that unexposed bumper beam materials are primarily steel, sometimes aluminum, but rarely plastic. This contrasts slightly with the previous report, which noted that aluminum may become a more prevalent material in bumper construction (GlobalData, 2023b). Both reports do agree that the choice of materials depends on what tradeoffs the manufacturer is willing to accept.

Finally, the American Iron and Steel Institute (2020) acknowledged that different approaches are necessary for exposed and unexposed bumper beams when designing bumper systems to account for potential pedestrian safety regulations and consumer testing scores. It suggested that when designing a bumper system for lower-leg protection, two approaches are possible: "softening" the front end of the vehicle or equipping the vehicle with pedestrian air bags. For unexposed bumper beams, the institute suggested that softening of the vehicle front end can effectively increase pedestrian leg protection and on passenger cars, this means a soft energy absorber in front of the bumper beam and a lower bumper stiffener. It further suggested that SUVs require the same elements, but with the addition of an upper bumper stiffener to achieve the same protective effect, and that for bumper systems with an exposed beam, pedestrian air bags may be a viable solution. However, the institute noted that such an air bag has not been implemented in North America as there are currently no pedestrian regulatory requirements or NCAP pedestrian safety tests pertaining to bumpers, though it does anticipate NCAP pedestrian testing protocols in the future.

European and American Bumper Construction

Direct comparisons between European and American bumper systems may be useful to understand how varying pedestrian safety and vehicle regulations produce different constructions. In a 2020 report for NHTSA, Suntay and Stammen attempted to examine how a bumper could be constructed to meet both Euro NCAP pedestrian testing protocols and U.S. bumper damageability regulations. The Euro NCAP pedestrian impact tests used by Suntay and Stammen are the upper and lower legform tests, which assess injury risks to the tibia, knee, femur, and hip. U.S. bumper damageability standards, by contrast, set parameters for the level of damage a bumper should be able to sustain under low-speed collision conditions. Suntay and Stammen tested vehicles against four of the provisions most applicable to pedestrian safety. Those tests were:

- A front impact at 2.5 mph and twelve inches right of centerline;
- A front impact at 1.5 mph to the front bumper left corner;
- A front impact at 2.5 mph to the front bumper on the centerline; and
- A front impact at 1.5 mph to the front bumper right corner.

Using pedestrian testing protocols, Suntay and Stammen (2020) compared U.S. and European versions of the Ford Focus to both sets of standards. As such, their study provides a useful direct comparison of a U.S. and European vehicle model. Primary differences between the bumper construction of the two vehicle models were in the formation of the holes stamped into the bumper beams and the placement of energy absorbers affixed to the beams. The E.U. model had foam energy absorbers on each side of the beam, while the U.S. model's absorbers extended along the entire length of the beam; the beams were of similar dimensions. Suntay and Stammen attributed the difference in the positioning of the energy absorbers to the more pronounced damage in the center of the E.U. Focus model during the testing. The empty center space in the E.U. version helped to mitigate legform bending in the tests.

Relationship Between Changes in Bumper Construction and Pedestrian Safety

Eight years before Suntay and Stammen (2020), Hu and Klinich (2012) likewise found bumper design plays a significant role in pedestrian injuries, specifically lower limb injuries, and reviewed changes in bumper construction over time. According to their 2012 study, the most critical bumper construction aspects to consider in pedestrian protection are height, depth, and rigidity. Differences in these elements, as well as the speed of the collision, lead to different injuries on a struck pedestrian. Higher bumpers result in more femur injuries compared to lower bumpers. In contrast, a lower bumper causes more knee injuries and tibia fractures.

Hu and Klinich (2012) also noted that bumper design has changed quite significantly since the 1970s and 1980s, comparing car front ends from the 1970s and 1980s and the 2010s in a few representative images. The older bumper designs feature prominent, pointed front geometry. In contrast, the newer bumper area is more rounded. Previously, the models with protruding front ends (e.g., a deeper bumper) caused more injuries. Now, front ends are smoother, effectively minimizing pedestrian impacts. Hu and Klinich (2012) stated that previous studies found this outcome was achieved by an increased contact area between the bumper and pedestrian. Finally, they noted that designing bumpers for pedestrian leg protection usually results in bumpers with softening materials and energy absorbers or stiffeners. Both designs increase pedestrian protection.

Three years later, in 2015, Mo and five other researchers used impact simulations to predict how different vehicle front ends affect pedestrian injuries, specifically leg injuries. They compared lower limb kinematics with injury indexes developed for tibia bending and knee strain. The simulations were done for four different kinds of passenger cars ranging in size from a small car to a minivan. No SUVs or pickups were used in the simulations. Like Hu and Klinich (2012), Mo et al. (2015) found aspects of bumper beam placement (e.g., height and depth) could either mitigate or exacerbate predicted injury severity. They concluded from their simulation that low bumper beam placement mitigates the negative outcomes for leg kinematics for joints and knees. For tibia injuries, the impact of the bumper beam depended on where the simulated collision occurred in relation to the pedestrian model's tibia shaft. Mo et al. also noted that wider bumper beams and larger deformation spaces may lead to superior outcomes for tibia fractures.

Vehicles With an Exterior Bumper Beam

As noted, of the best-selling vehicles in the United States, pickups feature most prominently in the list of vehicles with an exposed bumper beam. Some SUVs such as the Jeep Wrangler also feature an exterior bumper beam, but, of the best-selling models, most vehicles with an exterior bumper beam are pickups. Sales figures for these vehicles are provided in Appendix II. The review team found that the best-selling models with exterior beams have remained consistent over time and, notably, the design of these vehicles does not seem to have changed significantly.

Active Hoods

Active hood systems are pedestrian safety features that sense when a vehicle crashes or will crash into a pedestrian and then raise a portion of the hood to provide more deformable space between the relatively “soft” hood and the “hard” engine parts beneath it to mitigate pedestrian injury. Often the rear of the hood near the windshield seam is raised rather than the entire hood. Active hoods are also known as deployable hood systems (Ford), pedestrian protection systems (Buick), pop-up hoods (Nissan, Honda, Toyota, and Lexus), and reactive hoods (Volkswagen), depending on the vehicle manufacturer. In most non-U.S. markets, the same terms are used, replacing the word “hood” with “bonnet.”

Despite being commonly known as active hoods, these are not technically an active pedestrian safety measure, as the term is usually used. Active pedestrian safety measures are intended to avoid crashes altogether and usually involve systems that recognize a pedestrian is in the vehicle’s path and either alert the driver to the danger or autonomously take corrective actions, such as by steering away from the pedestrian or, more commonly, braking. Passive safety measures mitigate the damage caused in case of a crash and include engineering the front end of a vehicle to make potential impacts with a pedestrian less severe. While active hoods react by suddenly making the hood “softer” in a crash with a pedestrian, they do not deploy until a crash is unavoidable or has already occurred, making them a form of passive pedestrian protection.

Current State of Active Hood Technologies

From the literature reviewed, the review team found that active hoods generally consist of three basic parts, namely sensors, an electronic control unit, and actuators. There also can be specialized hinges that allow the hood to pop up in a direction that is safer for pedestrians. Each of these parts can be configured in different ways, as discussed below. The sensors collect information indicating whether a pedestrian has been struck, often by detecting pressure on a vehicle’s bumper, but they also can detect a pedestrian prior to getting hit using various kinds of cameras, radar, or lidar. This information is relayed to the ECU, which uses algorithms to determine whether the signals from the sensors indicate a pedestrian has been or will be struck. If the ECU concludes that the vehicle struck a pedestrian, it sends a signal to the actuators to lift the hood. These actuators then activate, often by either detonating a small pyrotechnic or triggering a spring to push the hood up. To have the desired effect, this process must be completed quickly before the struck pedestrian contacts the hood.

To date, the review team found that the market penetration of active hoods appears relatively low, even in the European market, although it was found to increase over the course of this study. According to the review team’s inspection, none of the 40 best-selling vehicles in the United States by year from 2011 to 2022 were found to have an active hood. A 2015 NHTSA report (Ames & Martin), however, found that active hoods were equipped on an increasing number of vehicles tested by Euro NCAP over time, with about 25 percent of the tested vehicles in 2014 having the equipment. More recently, the German Federal Highway Research Institute (Gruschwitz et al., 2021) found that 8 percent of the passenger vehicles in use in Germany were equipped with active hoods in 2021, compared to 7 percent in 2019, 4 percent in 2017, and 2 percent in 2015 and 2013; a much larger percentage of luxury vehicles (45%) had active hoods. This suggests that the technology was increasingly used in Europe during the course of this study, particularly in luxury vehicles.

Academic Literature and Reports on Sensors

From the literature reviewed, the team found that many different types of sensors can be used to detect a pedestrian crash. These can be divided into contact sensors and non-contact sensors. Contact sensors include various kinds of fiber-optic, accelerometer, and pressure sensors. Non-contact sensors include radar, lidar, ultrasonic sensors, infrared cameras, video cameras, and RFID transponders (Nuß et al., 2013). Advanced driver assistance systems such as AEB technology and lane departure warnings use non-contact sensors. Furthermore, it is possible to fuse the inputs from several types of sensors to improve their accuracy.

From the literature reviewed, the team found that most active hood designs may involve a type of pressure sensor that measures the force of an object on a vehicle's bumper. Sometimes these are combined with accelerometers mounted on the front end to provide data about the change in vehicle velocity when a vehicle strikes a fixed object versus a pedestrian leg. Such a sensor configuration was tested in a 2013 conference paper by Swaraj S. Kore, which described how a "membrane switch" type contact sensor mounted on foam behind plastic fascia combined with accelerometers was effective in distinguishing a leg form from a light pole in crash tests up to 40 km/h. Kore also found that the active hood effectively reduced head injury criterion values at several impact speeds.

Other articles about then described sensor accuracy in distinguishing between a pedestrian and a fixed metal pole. This is important as an inaccurate sensor may trigger a false deployment, resulting from a false positive reading, or not deploy when it was designed to activate. The next subsection discusses real-world false deployments, while this section explores the sensors discussed in academic literature and patents.

In 2014 Ito et al. at Nagoya University and the Denso Corporation in Japan studied a similar sensor array as Kore (2013) and tested whether the sensor could distinguish between a legform and a pole. They developed a finite element model of a sensor consisting of a soft plastic deformable pressure chamber and tested how well it distinguished between pedestrians and other objects in computer simulations. In the simulations, the researchers placed the sensor on top of the bumper energy absorber for a simple car model, a multipurpose vehicle with a flat front-end shape, and a minicar. They then conducted crash simulations at 40 km/h with a pedestrian representing a 50th percentile American male using the THUMS software. This represents a person 175 cm tall (5 ft, 9 in) and weighing 77 kg (170 lb) (Iwamoto et al., 2007). The authors found that a simulated pedestrian collision could be distinguished with high reliability from other simulated colliding objects, such as a roadside pole, based on the unique pressure characteristics (Ito et al., 2014).

These simulation findings were corroborated by a 2013 study by Takahashi and others at the Toyota Motor Corporation. Using a pressure chamber mounted directly above the impact-absorbing foam behind a vehicle's fascia, these researchers similarly found the pressure chamber was able to distinguish between a pole and a pedestrian model in a computer simulation. However, they tested different pedestrian models than Ito et al. (2014), including a THUMS 6-year-old child and 5th percentile American female model. In addition, Takahashi et al. (2013) conducted actual crash testing with a physical car and a dummy representing a six-year-old child and confirmed their own findings.

In an older study from 2007, Lee et al. tested the sensor accuracy of accelerometers and a membrane switch on the bumper fascia front surface by striking the front end of a test vehicle with pedestrian legforms and rigid poles and simulating a rough road. They found that the system distinguished between the pedestrian legforms and the rigid poles well.

While it is important to distinguish between a pedestrian leg and a metal pole, an ideal sensor system would also be able to distinguish a pedestrian from other objects. One potential way to increase sensor accuracy may be to fuse sensor information. For example, in a 2023 Chinese-language article, two researchers from the Hefei University of Technology (Zhang & Shi, 2023) fused the readings from a Mobileye 630 camera and a Continental advanced radar sensor using millimeter-wave radar with more traditional contact sensors. The non-contact sensors were like those already used in ADAS technology. The researchers found that fusing the non-contact sensors with the contact sensors increased the accuracy of the active hood deployment decision. Specifically, if the non-contact sensors detected a pedestrian, they could lower the threshold for the contact sensors to trigger the active hood and heighten the threshold if the non-contact sensors do not detect a pedestrian.

According to a 2023 industry report by GlobalData, there was at least one non-contact sensor system on the market in the early 2010's that allowed for deformation of a vehicle's front end—Valeo's Safe4U product. According to literature, this system was not an active hood system, but instead provided pedestrian protection by allowing the upper part of a vehicle's front end to swing back away from a pedestrian, reducing the impact force on the pedestrian (FenderBender, 2019). This system comprised a radar on the upper crosspiece of the front end and a camera on either side of the bumper, which work together to distinguish pedestrians from other objects. If these sensors detected a high likelihood of a collision with a pedestrian, two actuators released the upper front-end crosspiece from its supports, allowing the upper part of the front end to move back. Safe4U was not only notable because it used non-contact sensors exclusively, but because the actuators were also resettable. That is, if a false deployment occurs, the actuators can be moved back into their original positions and the front end remains in its original state (GlobalData Plc, 2023a). However, the resetting mechanism of this system is likely to be very different from the resetting mechanism of an active hood.

The GlobalData report (2023a) also discussed two active hood systems that use contact sensors: Continental's Air Hose and TRW's Pedestrian Protection System. According to the report, Continental's system uses two pressure sensors connected to either end of an air hose that spans the entire width of the bumper, behind energy-absorbing foam blocks. These sensors detect pressure exerted on the air hose and relay this to an air bag control unit, which then determines whether a pedestrian was struck, and the active hood should be activated. A representative of Continental was quoted in the report as saying Continental's "reliable and robust impact detection algorithms us[e] either accelerometers or pressure sensors mounted in the bumper structure," which are used in contact-based active hood systems. Continental also noted in the report that they are developing a stereo camera for detecting, classifying, and tracking pedestrians for use in pedestrian AEB or driver warning systems, but did not suggest using this in an active hood system.

According to the GlobalData report (2023a), TRW's Pedestrian Protection System uses pressure sensors in combination with acceleration sensors. The pressure sensors detect impacts on a flexible tubing that is placed along the width of the front bumper. The inputs from these pressure sensors are supplemented by three acceleration sensors that detect which side of the vehicle struck a pedestrian. These pressure sensors and acceleration sensors send data to an ECU, which uses an algorithm to detect a pedestrian crash.

Patents Related to Sensors

Patents and patent applications are useful source types because they describe technologies that were under development at the time of filing. These descriptions often provide technical details about aspects of active hoods, such as the sensors used to detect a collision with a pedestrian. Reviewing the number of patents issued and patent applications filed for a particular technology over time may also provide insights into the amount of research and resources devoted to developing new technologies. However, neither issued patents nor patent applications describe which technologies were subsequently implemented in large scale. Another limitation of patents and patent applications is that they cannot discuss how effective pedestrian protection technologies are after they have been implemented.

From the literature reviewed, the team found that patent applications filed at the U.S. Patent and Trademark Office and European Patent Office are classified by the harmonized Cooperative Patent Classification scheme. This is a hierarchical structure in which there are broad categories and many sub-categories to classify patent applications. The review team identified one CPC classification of particular interest to this research topic: B60R 21/38 (U.S. Patent and Trademark Office, 2024). The hierarchical structure leading to this classification is listed here:

- **B** (Performing Operations; Transporting)
  - **60** (Vehicles in general)
    - **R** (Vehicles, vehicle fittings, or vehicle parts, not otherwise provided for)
      - **21** (Arrangements or fittings on vehicles for protecting or preventing injuries to occupants or pedestrians in case of crashes or other traffic risks)
        - **38** (Protecting non-occupants of a vehicle [e.g., pedestrians] using means for lifting hoods/bonnets)

Reviewing all patent applications and issued patents filed under this CPC code in the United States since 2011, the review team found there was a notable spike in filings in 2014, when 31 applications were filed. This trend was found in other countries as well. In addition to U.S. patents and patent applications, the review team conducted keyword searches using Google Patents to identify global trends in patent applications for active hoods in major auto manufacturing market regions. For example, a search for patent applications and granted patents filed since the beginning of 2011 including the Boolean query *"active hood" OR "active bonnet" OR "pop-up hood" OR "pop-up bonnet"* for the United States, European Union, Japan, South Korea, and China resulted in 592 applications and patents. A peak occurred from 2013 to 2015, when 269 applications and patents were filed. The remaining 323 applications and patents were evenly distributed among the remaining 9 years and the first half of 2023.

According to a review of all patent applications and approved patents filed in the United States since January 1, 2011, and classified under the scheme B60R 21/38, the review team found that a variety of sensors are used by active hood inventors. Of the 198 patents issued and patent applications filed, 51 described the type of sensor used. Some reference the sensors as critical to the invention, while others focus on non-sensor parts of the active hood or reference sensors only tangentially. The following is a list of how often each technology was referenced by each patent or patent application:

- Contact sensors only (15),
- Non-contact sensors only (12),
- Non-contact and contact sensors combined (11),
- Sensors could be non-contact or contact (10),
- No sensor required (2), and
- Sensor on side of tires (1).

Twelve of the 51 patents and patent applications that provided some description of the sensors used in the invention described the invention as only using non-contact sensors that predict a collision before contact with a pedestrian. These sensors include near infrared cameras, far infrared cameras, visible wavelength cameras, radar, and lidar. Four patents did not describe the sensors in any detail other than by stating that non-contact sensors would trigger the focus of the invention. Several patents and patent applications addressing non-contact sensors referred to using sensors used by ADAS for the active hood feature.

For example, the 2015 patent assigned to Ford Global Technologies, LLC, *Vehicle Front End Structure Providing Pedestrian Protection* (Rao et al., 2015) provided details about many aspects of an active hood system, including that it would activate based on a determination of the "pre-crash sensing module." The patent describes this module as functioning as a part of ADAS and including a variety of possible sensors:

> The pre-crash sensing module (PSM) … detects and tracks objects in the vehicle surroundings using known object detection and object tracking techniques in automotive driver assistance and active safety applications, such as adaptive cruise control, forward collision warning, lane departure warning, lane keep aid and pre-crash sensing-based brake assist systems. For instance, the pre-crash sensing module … may include one or more radar devices …, lidar devices …, stereoscopic cameras …, ultra sound sensors …, time of flight cameras … and other suitable sensors for surround sensing and may use sensor fusion techniques to robustly detect and track objects in real time.

According to the patent applicants, the pre-crash sensing module then interfaces with other vehicle sensors (such as wheel speed sensors or accelerometers) to determine the time to collision, activating when it falls below a predetermined threshold (Rao et al., 2015). While this patent did not describe in detail the sensors that the active hood system would use, it suggests that the sensors would be non-contact sensors.

In contrast, 15 patents and patent applications described the active hood system using exclusively contact sensors, such as pressure sensors in the bumper, which could be in the form of a sensor tube or acceleration sensors. One such patent described using accelerometers on brackets connecting a metal bumper to a vehicle (Lee et al., 2016b).

Eleven patents and patent applications described the inventions as using a combination of contact and non-contact sensors. In most cases, the specific types of sensors were not described. There are no strong trends describing which sensors are most used. The patents that do specify which sensors may be used, however, mention infrared cameras, radar, sonar, or lidar paired with accelerometers, magnetic fields, or pressure tubes. In addition, 10 patents and patent applications do not specifically reference which type of sensor would be used, only stating that they could be either non-contact sensors or contact sensors.

Two patent applications did not require sensors at all, as they were patents for hood hinges that would collapse under the weight of a pedestrian in a collision (Kim & Hong, 2016, 2017). One patent application referred to sensors mounted on the sides of the tires. The stated purpose of this placement was to reduce false deployments of the active hood on rough terrain (Suzuki et al., 2019).

Efficacy of Active Hoods in Reducing Injury

According to the literature reviewed, the response time necessary to activate a hood is an important parameter to how well it can protect pedestrians. The response time depends in large part on the speed with which the ECU computer can process signals from the sensors that indicate a collision with a pedestrian has occurred and the physical speed at which the hood can be deployed by the actuators. Lee and others at Inha University in South Korea reported in two journal articles from 2016 how they used simulations to test the response times of active hood systems (Lee et al., 2016a, 2016b). Specifically, by redesigning latch parts of the systems, changing the placement of the actuators, and optimizing the amount of gunpowder used in the micro gas generator that powers the actuators, Lee et al. found the deployment time could be decreased. A different article with the same lead author found gunpowder actuators deploy faster than a spring-powered actuator (Lee et al, 2016c).

The literature generally suggested that active hoods can effectively reduce pedestrian injury. An early article on active hood systems by Fredriksson et al. (2006) of Autoliv, a Swedish automotive parts manufacturer, and Wayne State University described how an active hood creating 100 mm of space between a hood and an engine was considerably more effective at reducing head rotational acceleration and strain than active hoods creating less space in simulations of a 40 km/h collision. The authors based these findings on tests with headform impactors, full-scale dummies, and a finite element analysis using the Wayne State University Head Injury Model to calculate the risk of brain injury.

Similarly, in a 2020 NHTSA report Suntay and Stammen used headform impactors to assess the HIC values caused by pedestrian headform collisions with vehicles with deployed active hoods compared to the same models without active hoods. They found that a 2014 Cadillac ATS with a deployed active hood resulted in lower HIC values from the headform impactor than the same vehicle with the active hood in an undeployed state. A 2017 Audi A4, however, did not have significantly different HIC values when the active hood was deployed versus not. This suggests there was some variance in active hood headform testing performance between vehicles.

A Ye et al. (2012) study based at Jilin University in Changchun, China, used computer simulations to test the optimal spring stiffness to use in active hood actuators using springs. The purpose was to determine the spring stiffness that would keep the hood activated and provide the greatest safety benefit for pedestrians in terms of reducing the HIC values a pedestrian’s head would experience.

Some research suggests that active hoods may function best in conjunction with other pedestrian safety systems. In 2014 researchers from Autoliv and TNO, a Dutch research organization (Fredriksson et al., 2014b), developed a test procedure to examine how well active hoods combined with pedestrian air bags reduce the risk of injury to a pedestrian surrogate (the Polar II pedestrian ATD), finding that they were very effective at reducing injury risk to the head and thorax. They found the pedestrian air bag prevented the most severe injury values that occurred when the pedestrian ATD's head struck a windshield frame. Fredriksson and Rosén (2014a) of Autoliv also found in 2014 that combining an active pedestrian AEB system with an active hood and pedestrian air bag resulted in predicting much better pedestrian surrogate protection than either system alone. They found that even in relatively high speeds of 40 to 70 km/h, the pedestrian AEB system was able to slow the vehicle enough for the active hood and pedestrian air bag to be more effective. They also suggest that combining these systems may result in more accurate pedestrian detection and fewer false activations of the active hood and pedestrian air bag system because the active system sensors, such as cameras, could identify the object being hit and then sensed by the contact sensors of the passive system.

False Deployments and Deployment Frequency

While active hoods are becoming increasingly common in some markets, the literature review identified that there are still concerns over the false deployments of such systems and how often active hoods deploy, as these deployments often incur financial costs to reset or replace parts of the system and may be dangerous as they could reduce driver visibility. Several sources identify such information. Likely the most useful are national-level crash sampling databases where a subset of crashes in a country are studied in detail when they occur and information on active hood presence and activation is provided. An example of such a dataset is the GIDAS that provides detailed information on a sample of crashes, including active hood presence and activation, in Germany. Academic sources also provide some useful information, as they sometimes discuss ways in which an active hood could falsely deploy and report on instances of such false deployments. Anecdotal evidence found on social websites, such as vehicle brand consumer forums, vehicle enthusiast websites, and YouTube, regarding false active hood deployments can provide some indications about circumstances in which an active hood might falsely deploy, although they are by no means comprehensive.

To address these topics, the review team first looked for databases of false deployments of active hoods using open internet search engine queries and targeted searches of the websites of U.S. government entities; non-U.S. government organizations; agencies that publish statistics on the automotive industry, such as Wards Automotive; insurance companies; vehicle manufacturers; replacement part manufacturers; and market forecasters. The team also examined crash investigation reports and legal proceedings. These searches, however, did not locate sources that satisfactorily indicate how often active hoods falsely deploy or how often they deploy in total.

National Crash Sampling Databases

Of the national crash sampling databases assessed, GIDAS is the most promising source for determining how often active hoods falsely deploy or how often they deploy in total. This dataset comprises in-depth investigations of a representative sample of crashes with personal injuries reported by police at two survey locations in Germany. According to the GIDAS website, the study collects information at several levels to enable a later reconstruction and analysis of the crash: "the description of the course of the accident, the type and kind of accident; sketches of the directions of travel, collision and end positions; characteristics of the persons involved—medical data of the persons involved in the accident and, if applicable, technical data of their vehicles." This technical data includes information on whether a vehicle involved in a crash was equipped with an active hood and whether the active hood deployed.* This data would provide useful information on false deployments of active hoods, by indicating instances when an active hood deployed when a pedestrian was not involved.

However, as crashes in the GIDAS database involve personal injuries reported by police, it is unlikely that false deployments of active hoods caused by a vehicle striking a small animal, for example, will appear. As some academic sources and anecdotal evidence described below suggest, striking a small animal has been a cause of false deployments. Still, the GIDAS database reportedly includes information on whether an active hood deployed in crashes resulting in personal injury, but in which it may have been inappropriate for the active hood to deploy, such as a multivehicle collision or a crash with a fixed roadside object.† This would provide some indication of the frequency of active hood deployments and false deployments, even though the methodology does include all cases of deployments.

The process for a third party to use data from GIDAS is under revision at the time of writing. The two current methods for receiving data from the study are purchasing complete sets of annual data or collaborating with a GIDAS member, such as Germany's Federal Highway Research Institute (Bundesanstalt für Straßenwesen [BASt]) or Research Association of Automotive Technology (Forschungsvereinigung Automobiltechnik).‡ This is subject to change.

Other countries also conduct detailed crash sampling surveys, but they may not provide the same level of information regarding the presence of active hood equipment and its deployment. The Japanese Institute for Traffic Accident Research and Data Analysis, for instance, conducts in-depth investigations of a sample of crashes (ITARDA, n.a.). However, while ITARDA collects information on whether vehicles involved in crashes were equipped with an active hood, they do not collect information on whether the active hood deployed (ITARDA personnel, personal correspondence, October 17, 2023).

It is possible though that the China In-Depth Accident Study collects this information. A Chinese-language research article by Sun and others in 2022 noted the authors used information from CIDAS, along with other sources, to investigate how often false active hood deployments occur, as discussed in the next section. However, the article did not provide detailed information on which data CIDAS collects and the review team was unable to locate information indicating whether CIDAS includes data on active hood presence and deployment in crashes.

* Personal correspondence with Marcus Wisch, a research engineer with Germany's Bundesanstalt für Straßenwesen (Federal Highway Research Institute), October 12, 2023.
† Personal correspondence with Marcus Wisch.
‡ Personal correspondence with Marcus Wisch.

Academic Sources and Reports

The review team also surveyed academic literature for information on the false deployment of active hoods, identifying several sources that briefly discussed such false deployments and one study that examined how often false deployments of active hoods occur in practice (See, for example, Ames & Martin, 2015; Ito et al., 2014; Kore, 2013; Lawrence et al., 2004; Lee et al., 2007; Sun et al., 2022). Most sources also discussed the technologies used to activate hoods and are highlighted above.

A 2022 study by Sun and several other researchers is the only source to specifically examine how often false deployments of active hoods occur in practice. In this article, researchers from the Geely Automobile Research Institute, Hunan University, and the China Automobile Research Institute use data from CIDAS, internet vehicle forums, and online video platforms, as well as maintenance data, to create a dataset of crashes in which an active hood deployed. The authors identified 140 such crashes that took place from 2016 to 2021. Only 23 crashes (16.4%) involved vulnerable road users, and only 3 vulnerable road users were pedestrians. As such, the authors suggest increasing the number of types of objects that are used to test an active hood's sensors to decrease the typical false deployment scenarios of a vehicle striking another vehicle, a dog, road potholes, or guardrails. It is notable, however, that there is a sampling error, as internet vehicle forums and online video platforms may be unlikely to include videos of crashes in which a pedestrian was involved, as discussed in the following section. Further, it is plausible that the kinds of false deployments observed have been resolved since the time of study publication.

Other literature sources tested the ability of active hoods to discriminate between a pedestrian or other vulnerable road user and other objects in a test setting. Kore's 2013 study, discussed below, for example, examined the pressure sensors of active hoods to assess if they could activate the hood in a timely manner, finding that they could distinguish between a legform impactor and a metal pole. Ito et al. (2014), Takahashi et al. (2013), and Lee et al. (2007), also discussed in below, reached similar conclusions with other contact sensors.

A 2004 report (Lawrence et al.) for the European Commission also discussed in detail the possible causes of false deployments of active hoods. While the report is quite dated, it provides helpful background information on common faults active hoods have historically had. This report details the state of active hood technology in use around 2004 and features a tree diagram describing the types of faults that could occur in an active hood, causing it to not deploy when it should have or to deploy when it should not, along with the authors' judgment of how likely each fault is to occur. The authors posited that an active hood could falsely deploy due to a damaged sensor, erratic sensor, ECU system fault, or incorrectly defined deployment conditions. These incorrectly defined deployment conditions were believed to be the most likely cause of false deployments and included "unexpected accident scenarios" and "poor pedestrian dummy biofidelity" as specific causes. Considering the findings of Sun et al. (2022), unexpected accident scenarios appear to be a common cause of false deployments. These unexpected scenarios remain a possible issue for testing sensor accuracy. As Ames and Martin noted in a 2015 NHTSA report, there was no test to physically ensure sensor accuracy and reduce or eliminate false deployments in Euro NCAP at that time. It was also noted that pedestrian gait, vehicle speed, vehicle maneuver, and environmental conditions were factors that could potentially affect sensor accuracy.

Anecdotal Evidence

In addition to national crash sampling databases and academic sources and reports, the review team conducted exploratory searches to locate anecdotal evidence regarding false active hood deployments in the United Kingdom, Australia, Germany, China, and Spain. The team identified 22 posts discussing topics related to false deployments on vehicle brand consumer forums, vehicle enthusiast websites, and YouTube. As the search was not exhaustive, the findings here are presented only for illustrative purposes.

These findings also should not be considered representative of all deployments, false or not, of active hoods, as there is likely a self-selection bias. That is, only those who choose to post about an active hood deployment can be included in this review. As no posts were found in which the active hood functioned as intended.

The anecdotal sources identified concerning false deployments of active hoods describe circumstances surrounding the deployment as falling under three general scenarios:

- A vehicle striking an animal, such as a rabbit, dog, deer, or kangaroo (11 incidents);
- A vehicle activating its active hood with no apparent trigger (3 incidents); and
- A vehicle running over a bump or pothole in the pavement (1 incident).

The most common circumstance described was a vehicle striking an animal at a low speed, which occurred in 11 of the located sources. In most accounts identified, the animal survived and often fled after being struck (VTECMatt, 2023; stembridge, 2021; NiuChe.com, 2020; anon14763812, 2020; mcomer, 2018; RadW, 2019; yaniv, 2017; tarabrae, 2016; mcomer, 2015; Jude, 2015). The second most common circumstance was an active hood activating with no apparent trigger reported (Sina Corporation, 2017; SkylineKanagawa[sic], 2018; Anonymous, 2020). There was one occurrence of a vehicle rolling over a bump and then deploying the active hood (DavidR1, 2021). Several sources did not discuss what may have triggered the active hood (ascttt, 2014; SkylineKanagawa, 2018). While the number of posts associated with each circumstance is very small and only illustrative, the top circumstance -- an active hood falsely activating when the vehicle strikes a small animal – was a similar finding as Sun et al. (2022).

The review team found that a related category of incidents concerned vehicles displaying error messages on the instrument panels or heads-up displays indicating malfunctions with the active hood systems. Often, these errors did not accompany the active hood systems deploying, appropriately or inappropriately. The reason for these errors was usually described as either malfunctioning sensors or a malfunctioning computer (See Car Hospital, 2022; LM Auto Repairs, 2023; Mechanic Matt, 2020; Aussie E350 Wag, 2023).

The review team found some forums that also included posts by people seeking to learn how to disable the active hood. The posters usually said they would like to disable the feature because they were concerned that it would experience a false deployment and require expensive repairs, but that a deployment had not actually occurred (MidnightRider, 2022; RavenRandt, 2020).

Finally, the tone of the posts on vehicle forums and other websites was often simply observational by the review team. The user who originally posted to the forum would describe experiencing a false deployment of an active hood and the circumstances under which the deployment occurred, often with a request for advice on how to repair it or information on how much a repair would likely cost. Other users then responded based on their own experiences or conjecture. One Chinese web source from 2020 went into detail attempting to diagnose the alleged false deployment of an active hood on a 2019 Mercedes-Benz C-Class sedan, opining that the sensors were too sensitive, and the actuators and hinges needed to be replaced (Anonymous, 2020).

Resetting Deployed Active Hoods

A review of the same 22 consumer forum posts and online videos described in the previous section located no active hoods that can be easily reset by the consumer, based on consumer accounts. The sources consulted primarily discussed whether it was possible to reset an active hood system after it had deployed and how much resetting the hood would cost. In no case of a false deployment in these sources did the owner report being able to reset the active hood. Instead, resetting the hood resulted in reported out-of-pocket repair fees ranging from approximately $875 to $11,500, depending on the owner's insurance and the level of repairs necessary (RadW, 2019; anon14763812, 2020; EvilAudi, 2015; mcomer, 2018; NiuChe.com, 2020; yaniv, 2017). In the four identified cases where an error message appeared, but an active hood did not deploy, the user stated they were able to resolve the issue by resetting the computer, although some sources noted the sensors needed to be replaced (See Car Hospital, 2021; LM Auto Repairs, 2023; Mechanic Matt, 2020; Aussie E350 Wag, 2023).

While the posts and videos did not indicate that an active hood could be reset, the review team located two academic sources in which the authors developed a theoretical resettable active hood. An article by Xu et al. (2010) described a finite element model for a resettable active hood. A motivation of the study was to design a finite element model of a theoretical active hood that would have reduced or no repair costs to reset it. Similarly, in 2010, Sunan Huang of Chalmers University and Jikuang Yang of Hunan University developed a finite element model of a hood on a production car front end that they modified to make resettable. They found that the model of a resettable active hood was effective in reducing pedestrian model injury. However, the article did not provide any evidence of applications of the model in real-world testing.

The review team found that none of the 40 best-selling U.S. vehicle models by year since 2011 were equipped with an active hood. This is in contrast with European-market vehicle models, which somewhat frequently have an active hood. Of the 511 vehicle models assessed in the European market, 103 of them (20%) were equipped with active hoods.

The data describing whether an active hood can be reset was derived from vehicle manufacturer websites, owner's manuals, and anecdotal evidence from owners describing being able to reset their active hoods or not. Of the 103 European-market vehicles with an active hood, the owner's manuals of nine of them specifically stated that the active hood could be reset by the driver, but it would require professional repairs to restore pedestrian safety functionality. No vehicles were located with active hoods that could be completely reset by the driver so that the hood retained its full pedestrian safety functionality.

While none of the 40 best-selling U.S. vehicles from 2011 to 2022 were found to have an active hood by the review team, a popular press article described an active hood on the 2018 Buick Regal in the U.S. market (Motavalli, 2017). This vehicle can be partially reset. According to the owner's manual for the vehicle described, the hood can be put back into place after activation by simply pushing on the hood above each actuator (General Motors, 2018). The vehicle can then be driven, but the active hood system will not function again until repaired.

In addition, three U.S. patent applications filed since 2011 were for inventions related to resettable active hoods. Two of the patent applications, *Active Hinge With Reset Mechanism* and *Releasable Hood Hinge With Positive Reset*, were subsequently granted patents (McIntyre, 2014; McIntyre & Duffy, 2014; Carothers et al., 2015). Each of these patent applications were for a resettable hinge component of an active hood. Because of this, it appears that novel resettable active hood systems have not been patented since 2011, although the component hinges may be used in already-patented systems.

Summary

This report on vehicle market trends related to changing pedestrian safety technologies and testing requirements in the United States and other countries comprises a survey of available literature on the nine research topics described in the Overview. Sources referenced in this report range from peer-reviewed academic articles and conference proceedings to market forecasting reports and press releases, to consumer forums and online videos, among others. As noted, not all source types were consulted for each section of the report. As such, this report describes which sources were consulted in each part.

The key observations from the literature review are the following.

- While the number of pedestrian fatalities in Europe was reported to have decreased by 37 percent from 2004 to 2013, a time in which pedestrian protection safety regulations came into effect, sources have noted that it is difficult to prove that the reason for any improvement is entirely due to the regulations as opposed to other possible factors.
- Including pedestrian crashworthiness tests in consumer ratings programs appears to have influenced the design of new vehicles performing well in tested conditions in Europe.
- Some European researchers found that pedestrian AEB technology may have been successful in preventing many pedestrian collisions, though the calculated reduction in crashes was not statistically significant, possibly due to the small sample size of vehicles equipped with pedestrian AEB at the time of the study (2014).
- Some pedestrian safety technologies on global vehicle models, such as pedestrian AEB, were penetrating the 40 top-selling vehicles in the U.S. market at an increasing rate during the period of this study, while others, such as active hoods, were not.
- The literature review found there may be variation in how bumpers are constructed for vehicles in the European market versus the U.S. market, with European bumpers having design elements to perform better in Euro NCAP upper and lower legform test conditions.
- In the United States, exterior bumper beams were only notably found on vehicles designed for off-road use (e.g., pickups in particular); however, the research team's assessment was limited to visual inspection.

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Appendix I: Duplicate Sources from Task 1

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Appendix II: Vehicles Equipped With an Exterior Bumper Beam

As noted, a spreadsheet of the 40 best-selling vehicle models by year in the United States from 2011 to 2022 was developed for this report. This appendix features vehicles that feature an exterior bumper beam. It highlights the year and make of the vehicle, as well as the number of sales by year.

The table entries are organized in reverse chronological order by year, and then by highest number of vehicle sales to lowest within that year.

Vehicle Year	Vehicle Make	Vehicle Model	Vehicle Sales by Year
2022	Ford	F-Series	597,020
2022	Chevrolet	Silverado	513,354
2022	Ram	Ram Pickup	448,205
2022	GMC	Sierra	241,522
2022	Jeep	Wrangler	181,409
2021	Ford	F-Series	656,039
2021	Ram	Ram Pickup	544,458
2021	Chevrolet	Silverado	519,774
2021	GMC	Sierra	248,924
2021	Jeep	Wrangler	204,610
2020	Ford	F-Series	721,132
2020	Chevrolet	Silverado	586,675
2020	Ram	Ram Pickup	547,881
2020	GMC	Sierra	253,016
2020	Jeep	Wrangler	201,311
2019	Ford	F-Series	833,378
2019	Ram	Ram Pickup	617,227
2019	Chevrolet	Silverado	570,608
2019	GMC	Sierra	232,323
2019	Jeep	Wrangler	228,032
2018	Ford	F-Series	844,448
2018	Chevrolet	Silverado	585,575
2018	Ram	Ram Pickup	521,046
2018	Jeep	Wrangler	240,032
2018	GMC	Sierra	219,554
2017	Ford	F-Series	763,887

Vehicle Year	Vehicle Make	Vehicle Model	Vehicle Sales by Year
2017	Chevrolet	Silverado	574,876
2017	Ram	Ram Pickup	473,681
2017	GMC	Sierra	217,943
2016	Ford	F-Series	763,887
2016	Chevrolet	Silverado	574,876
2016	Ram	Ram Pickup	473,681
2016	GMC	Sierra	221,680
2016	Jeep	Wrangler	191,774
2015	Ford	F-Series	725,726
2015	Chevrolet	Silverado	600,544
2015	Ram	Ram Pickup	434,435
2015	GMC	Sierra	224,139
2015	Jeep	Wrangler	202,266
2014	Ford	F-Series	701,102
2014	Chevrolet	Silverado	529,755
2014	Ram	Ram Pickup	425,388
2014	GMC	Sierra	211,833
2014	Jeep	Wrangler	175,328
2014	Toyota	Tundra	118,493
2013	Ford	F-Series	713,960
2013	Chevrolet	Silverado	480,414
2013	Ram	Ram Pickup	344,772
2013	GMC	Sierra	184,389
2013	Jeep	Wrangler	155,502
2012	Ford	F-Series	607,854
2012	Chevrolet	Silverado	418,312
2012	Ram	Ram Pickup	283,056
2012	GMC	Sierra	157,185
2012	Jeep	Wrangler	141,669
2011	Ford	F-Series	552,647

Vehicle Year	Vehicle Make	Vehicle Model	Vehicle Sales by Year
2011	Chevrolet	Silverado	415,130
2011	Ram	Ram Pickup Light-Duty	237,236
2011	GMC	Sierra	149, 170
2011	Jeep	Wrangler	122,460

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