The association between passenger-vehicle front-end profiles and pedestrian injury severity in motor vehicle crashes

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CONTENTS

ABSTRACT

Introduction: Vehicles play an important role in pedestrian injury risk in crashes. This study examined the association between vehicle front-end geometry and the risk of fatal pedestrian injuries in motor vehicle crashes.

Method: A total of 17,897 police-reported crashes involving a single passenger vehicle and a single pedestrian in seven states were used in the analysis. Front-end profile parameters of vehicles (2,958 vehicle makes, series, and model years) involved in these crashes were measured from vehicle profile photos, including hood leading edge height, bumper lead angle, hood length, hood angle, and windshield angle. We defined a front-end-shape indicator based on the hood leading edge height and bumper lead angle. Logistic regression analysis evaluated the effects of these parameters on the risk that a pedestrian was fatally injured in a single-vehicle crash.

Results: Vehicles with tall and blunt, tall and sloped, and medium-height and blunt front ends were associated with significant increases of 43.6%, 45.4%, and 25.6% in pedestrian fatality risk, respectively, when compared with low and sloped front ends. There was a significant 25.1% increase in the risk if a hood was relatively flat as defined in this study. A relatively long hood and a relatively large windshield angle were associated with 5.9% and 10.7% increases in the risk, respectively, but the increases were not significant.

Conclusions: Automakers can make vehicles more pedestrian friendly by designing vehicle front ends that are lower and more sloped. The National Highway Traffic Safety Administration can consider evaluations that account for the growing hood heights and blunt front ends of the vehicle fleet in the New Car Assessment Program or regulation.

***Keywords**:* Pedestrian fatality; front-end shape; hood leading edge height; bumper lead angle; hood length; hood angle; windshield angle

INTRODUCTION

Pedestrians are an essential component of the transportation system. In 2021, over 3.8 million Americans reported walking as their primary method of commuting to work in the past week (U.S. Census Bureau 2022). Pedestrians are also among the most vulnerable road users to injuries. A total of 7,388 pedestrians were killed in 2021, accounting for 17% of all motor vehicle crash fatalities (Insurance Institute for Highway Safety 2023). Since reaching their lowest point in 2009, pedestrian deaths have increased 80%. As the nation works toward the goal of zero roadway fatalities (U.S. Department of Transportation 2022), countermeasures from all aspects of the transportation system should be identified to improve pedestrian safety.

Numerous engineering treatments, such as leading pedestrian intervals, rectangular rapid flashing beacons, and visibility enhancements at crosswalks (Federal Highway Administration 2023), have been identified to effectively reduce pedestrian crashes. Speed is an important factor in the injury risk to pedestrians in crashes. Measures to reduce speeds, such as traffic-calming devices (Retting et al. 2003, Rothman et al. 2015, Hu and Cicchino 2020a), lowering speed limits in densely populated areas (Hu and Cicchino 2020b, 2023b), and speed safety cameras (Retting and Farmer 2003, Retting et al. 2008, Wilson et al. 2010, Hu and McCartt 2016) can also increase pedestrian safety.

Vehicles play an important role in pedestrian injury risk in crashes. Previous research that examined pedestrian crash data or hospital records found that light truck vehicles (LTV), including sports utility vehicles (SUVs), pickups, and passenger vans, were associated with higher risk of severe or fatal injuries to pedestrians in motor vehicle crashes when compared with cars (Ballesteros et al. 2004, Lefler and Gabler 2004, Roudsari et al. 2004, Longhitano et al. 2005, Paulozzi 2005, Roudsari et al. 2005, Monfort and Mueller 2020, Edwards and Leonard

2022). The relatively tall and blunt front ends of LTVs might have contributed to these findings. However, this could not be confirmed in these studies due to the lack of vehicle geometry data. Even within the same vehicle type, vehicle front-end profiles may vary.

Numerous studies examined the mechanisms of pedestrian injuries during vehicle-pedestrian collisions, by using computation simulations of impacts between vehicle and human body models or by examining small samples of pedestrian crashes with in-depth crash information. These studies included vehicle geometry data and evaluated the association between vehicle front-end geometry and pedestrian injury risks. The hood leading edge height has been identified as an important factor. Pedestrians struck by a vehicle with a high hood leading edge were more likely to be thrown forward or knocked down, and to make direct head-ground contacts, which resulted in more frequent and severe injuries to their heads (Otte and Pohlemann 2001, Kendall et al. 2006, Simms et al. 2011, Hamacher et al. 2012, Yin et al. 2017, Shang et al. 2018). A higher hood leading edge also tended to increase injury risks to the torso and pelvis (Matsui et al. 1999, Zhang et al. 2008, Li et al. 2018). Larger bumper lead angles, or more vertically orientated frontal structures, were found to increase the load to a pedestrian's body region being struck for a shorter impact duration (Niederer and Schlumpf 1984, Zhang et al. 2008). Tanno et al. (2000) found that vehicles with the front nearly perpendicular to the road caused more chest injuries to pedestrians, and tended to throw pedestrians forward after an impact. A relatively short hood, a large hood angle, a large windshield angle, and a wide windshield reduced the risks of fatal or severe head injuries to pedestrians (Han et al. 2012, Lyons and Simms 2012, Yin et al. 2017).

Previous studies using computer simulations (e.g., Lyons and Simms 2012, Yin et al. 2017) covered limited crash scenarios that were not representative of all real-world pedestrian crashes. In addition, simulations require assumptions about pedestrian and vehicle parameters, which might not represent all the vehicles and pedestrians involved in real-world crashes.

This study is the first to use a large sample of police-reported crash data and measure front-end profile parameters of the vehicles involved to examine the association between vehicle front-end geometry and the risk of fatal pedestrian injuries in motor vehicle crashes. The analysis controlled for the age and sex of drivers and pedestrians; environmental factors such as light and weather conditions; speed limits; and vehicle pre-crash movements. Previous research found that these factors were related to pedestrian crash and injury risks (daSilva et al. 2003, Lee and Abdel-Aty 2005, Tefft 2013, Fitzpatrick et al. 2014). The study findings could validate how front-end characteristics contribute to the outsize risk LTVs pose to pedestrians, and provide information that could help automakers improve vehicle designs to make vehicles more pedestrian friendly.

METHOD

Crash data

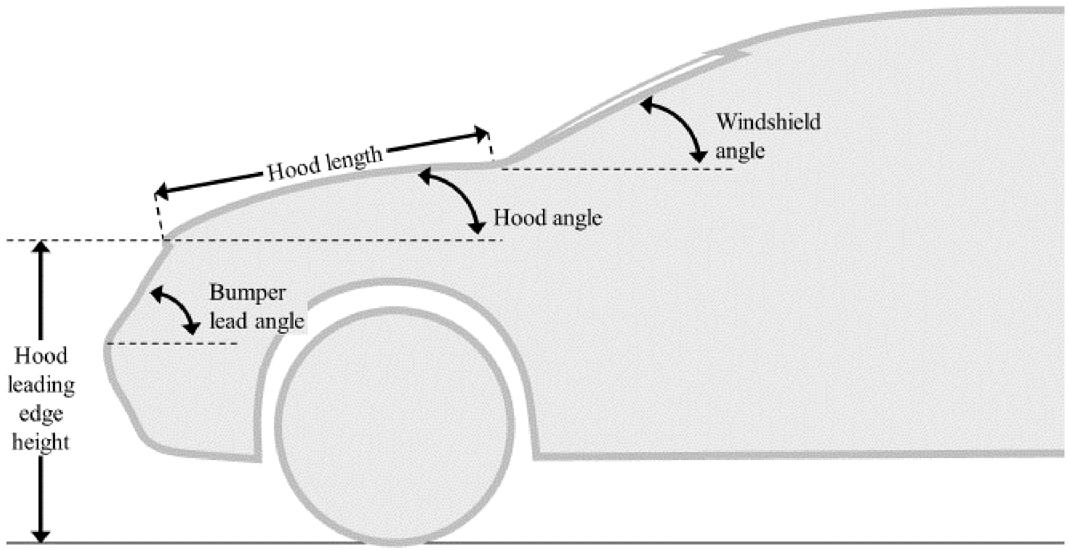
Police-reported crashes involving pedestrians were extracted from state crash data in seven states: Connecticut, Florida, Maryland, Michigan, New Jersey, Ohio, and Pennsylvania. These states were selected because each had relatively large numbers of pedestrian crashes, and the information necessary for analysis such as speed limits, vehicle pre-crash movements, and impact points was available. The crash years included are from 2017 to the latest year for which crash data was available at the time of analysis (2020 or 2021). Crashes were included in the analysis only if a single passenger vehicle and a single pedestrian ages 16 years or older were involved, and the front of a vehicle hit a pedestrian.

Vehicle Identification Numbers (VINs) of the vehicles involved in these pedestrian crashes were obtained when available. VINs were decoded to identify vehicles and match to vehicle information databases using VINDICATOR, a VIN-decoding program maintained by the Highway Loss Data Institute. Vehicle information obtained included vehicle type; vehicle make, series, and model year; vehicle model redesign year; and the availability of pedestrian automatic emergency braking (AEB) systems. Pedestrian AEB can detect pedestrians and mitigate or avoid a crash with a pedestrian by automatically applying the brakes. Only vehicles without pedestrian AEB systems were included in the analysis because the presence of such systems would confound the effects of vehicle front-end profiles. Eight percent of the crashes were excluded because the vehicles involved were equipped with pedestrian AEB.

Vehicle front-end geometry measurements

Vehicle front-end profile parameters included in the analysis were hood leading edge height, bumper lead angle, hood length, hood angle, and windshield angle (Figure 1). Previous research found that these parameters are related to pedestrian injuries, as described earlier. Additional parameters such as bumper height were measured but not included in the analysis, due to the high correlation among measurements. For any pair of measurements with a Pearson correlation coefficient larger than 0.5, only one measurement was included in the analysis. For example, the bumper height was highly correlated with the hood leading edge height (Pearson correlation coefficient = 0.8).

Figure 1. Vehicle front-end profile parameters



Measurement was performed using ImageJ, which is a free image-analysis tool. A side view photo of each vehicle was input into ImageJ, and front-end profile parameters were manually labeled on the photo and measured. Most of the photos used were taken by the Insurance Institute for Highway Safety (IIHS). All measurements were calibrated using the vehicle's wheelbase, which was obtained by decoding VINs using VINDICATOR.

One measurement was performed for every unique combination of vehicle make, series, and redesign year. For vehicles with the same make and series but different model years, as long as the model years belonged to the same redesign year, only one measurement was performed. Due to the large sample size, it was not practical to measure all vehicles involved. Most vehicle models selected for measurement (by make, series, and redesign year) were involved in at least 10 single-vehicle single-pedestrian crashes in the study. Some vehicles were not as frequently involved but were also measured because of their involvement in crashes collected by the Vulnerable Road User Injury Prevention Alliance (VIPA), for their inclusion in a follow-up analysis using these data.

Measuring of vehicles was performed by two research associates. The authors of this study reviewed all measurements and made corrections when necessary.

Pedestrian injury severity analysis

Logistic regression analysis evaluated the effects of vehicle front-end profile parameters on the risk that a pedestrian was fatally injured in a single-vehicle crash, while controlling for other factors that might have affected pedestrian fatality risk. The dependent variable was a binary pedestrian-fatal-injury indicator (crash-involved pedestrian was fatally injured or not). Pedestrian fatality in police-reported crashes was a rare event (below 10%), so the odds ratio produced by logistic regression approximately equals the risk ratio. All results are interpreted as relative risk.

Independent variables related to front-end profiles were indicators for hood length (> 40 inches vs. ≤ 40 inches), hood angle (≤ 15° vs. > 15°), and windshield angle (> 30° vs. ≤ 30°). These measurements were categorized based on their median values among vehicles included in the analysis. Categorized measurements instead of the actual numbers were used to focus on the relative differences between categories, because the accuracy of the specific measurements was unknown.

Front-end shape was characterized using the hood leading edge height and bumper lead angle to capture the combined effects (Table 1). The bumper lead angle was used to define the blunt (> 65°) vs. sloped (≤ 65°) shape based on its median value. For the hood leading edge height, three categories were defined based on the quartiles of this measurement, as well as the U.S. population's average hip height of 35.1 inches. This average hip height was calculated as a weighted average of hip heights of the 50th percentile man and woman ages 20–65 years (36.9 and 33.4 inches, respectively) (Tilley and Henry Dreyfuss Associates 2001), with the proportions of the female and male population in the United States as the weights (50.5% and 49.5%, respectively) (U.S. Census Bureau 2023). The low hood leading edge height (≤ 30 inches) is far below the average hip height; the medium height (greater than 30 to 40 inches) is around the average hip height; and the tall height (> 40 inches) is far above the average hip height.

Table 1. Definitions of front-end shapes

Front-end shape categories	Hood leading edge height	Bumper lead angle
Tall and blunt	> 40 inches	> 65°
Tall and sloped	> 40 inches	≤ 65°
Medium height and blunt	> 30 inches and ≤ 40 inches	> 65°
Medium height and sloped	> 30 inches and ≤ 40 inches	≤ 65°
Low and blunt	≤ 30 inches	> 65°
Low and sloped	≤ 30 inches	≤ 65°

Other independent variables included indicators for vehicle pre-crash movements (turning vs. moving straight), speed limits (30–35 mph vs. ≤ 25 mph, 40–50 mph vs. ≤ 25 mph, ≥ 55 mph vs. ≤ 25 mph), weather (rain/snow/fog/wind/other vs. no adverse conditions), light conditions (dark vs. day, dawn/dusk vs. day), driver sex (female vs. male), pedestrian sex (female vs. male), driver ages (16–19 vs. 20–29, 30–49 vs. 20–29, 50–69 vs. 20–29, 70+ vs. 20–29), and pedestrian ages (16–19 vs. 20–69, 70+ vs. 20–69).

Estimated coefficients of these independent variables were used to calculate changes in risk that a pedestrian was killed in a single-vehicle crash associated with the front-end parameters and other factors. Variables with p values less than 0.05 were taken as statistically significant.

RESULTS

Vehicle front-end profiles

A total of 17,897 single-passenger-vehicle single-pedestrian crashes were included in the analysis. Among the vehicles involved, 664 unique combinations of vehicle make, series, and redesign year were measured. The measurements applied to 2,958 unique combinations of vehicle make, series, and model year, including 1,425 cars, 149 minivans and large vans, 1,013 SUVs, and 371 pickups. A summary of front-end profile measurements of these 2,958 vehicle models is shown in Table 2.

Table 2. Summary of front-end profile measurements of all unique combinations of vehicle make, series, and model year

Measurement	N	Minimum	First quartile	Median	Third quartile	Maximum
Hood leading edge height (inches)	2,958	20.8	29.6	33.8	38.7	50.5
Bumper lead angle (degrees)	2,958	39.3	56.9	63.1	69.5	92.0
Hood length (inches)	2,958	12.2	35.8	40.3	44.2	58.2
Hood angle (degrees)	2,958	7.4	12.4	14.9	19.1	52.7
Windshield angle (degrees)	2,958	19.5	27.6	30.3	33.6	66.9

Front-end shape varied by vehicle type (Table 3). None of the car models had a tall hood leading edge, while very few of the larger vehicle models had a low hood leading edge. Among cars, the highest proportion had low and sloped front ends. Over 70% of minivans and large vans had sloped front ends of medium heights. A large majority of the SUVs had medium-height front ends, with a slightly higher proportion of them being sloped. Nearly 70% of pickups had tall and blunt front ends. Figures A1–A6 in the Appendix show vehicle examples with different front-end shapes.

Table 3. Front-end shape distribution by vehicle type, of all unique combinations of vehicle make, series, and model year

Passenger vehicle type	Front-end shapes												
	Tall and blunt		Tall and sloped		Medium height and blunt		Medium height and sloped		Low and blunt		Low and sloped		Total
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	
Cars	0	0	0	0	117	8.2	394	27.7	271	19.0	643	45.1	1,425
Minivans and large vans	8	5.4	4	2.7	27	18.1	107	71.8	0	0	3	2.0	149
SUVs	145	14.3	73	7.2	351	34.6	443	43.7	1	0.1	0	0	1,013
Pickups	254	68.5	23	6.2	94	25.3	0	0	0	0	0	0	371

Among cars, larger proportions had relatively long hoods (> 40 inches) or large hood angles (> 15°), while larger proportions of SUVs had relatively short (≤ 40 inches) or flat (≤ 15°) hoods **(**Table 4). All the minivans and large vans had hoods less than or equal to 40 inches in length, and over 90% of them had hood angles larger than 15°. Over 80% of pickups had relatively long or flat hoods. Windshield angles of cars were more frequently small (≤ 30°), while those of larger passenger vehicles were more frequently large (> 30°).

Table 4. Distribution of hood length, hood angle, and windshield angle by vehicle type, of all unique combinations of vehicle make, series, and model year

Passenger vehicle type	Hood length				Hood angle				Windshield angle				Total
	≤ 40 inches		> 40 inches		≤ 15°		> 15°		≤ 30°		> 30°		
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	
Cars	619	43.4	806	56.6	503	35.3	922	64.7	980	68.8	445	31.2	1,425
Minivans and large vans	149	100	0	0	13	8.7	136	91.3	45	30.2	104	69.8	149
SUVs	600	59.2	413	40.8	702	69.3	311	30.7	348	34.4	665	65.7	1,013
Pickups	65	17.5	306	82.5	309	83.3	62	16.7	9	2.4	362	97.6	371

Pedestrian injury severity

Crashes involving vehicles with tall and blunt, tall and sloped, and medium height and blunt front ends had higher proportions of fatal pedestrian injuries than the other front-end shapes (Table 5). Proportions of fatal pedestrian crashes were slightly higher among those involving vehicles with

- hoods longer than 40 inches than vehicles with shorter hoods,
- hood angles smaller than or equal to 15° than vehicles with larger hood angles, and
- windshield angles larger than 30° than vehicles with smaller windshield angles.

Table 5. Proportions of single-vehicle single-pedestrian crashes involving fatal pedestrian injuries by front-end profile parameters

	Single-vehicle single-pedestrian crashes				Total
	Crashes involving fatal pedestrian injury		All other crashes		
	No.	%	No.	%	
Front-end shape					
Tall and blunt	211	13.1	1,398	86.9	1,609
Tall and sloped	64	12.4	454	87.6	518
Medium height and blunt	282	10.3	2,444	89.7	2,726
Medium height and sloped	513	8.7	5,398	91.3	5,911
Low and blunt	144	9.4	1,385	90.6	1,529
Low and sloped	511	9.1	5,093	90.9	5,604
Hood length					
≤ 40 inches	827	8.8	8,590	91.2	9,417
> 40 inches	898	10.6	7,582	89.4	8,480
Hood angle					
≤ 15°	803	11.1	6,430	88.9	7,233
> 15°	922	8.6	9,742	91.4	10,664
Windshield angle					
≤ 30°	879	8.6	9,360	91.4	10,239
> 30°	846	11.1	6,812	89.0	7,658
Total	1,725	9.6	16,172	90.4	17,897

Logistic regression modeling results of the risk that a pedestrian was killed in a single-vehicle single-pedestrian crash are shown in Table 6. Tall and blunt, tall and sloped, and medium-height and blunt front ends were associated with significant increases of 43.6%, 45.4%, and 25.6% in fatality risk, respectively, when compared with low and sloped front ends. There was a significant 25.1% increase in the risk if a hood angle was less than or equal to 15°, compared with a hood angle larger than 15°. A hood longer than 40 inches and a windshield angle larger than 30° were associated with 5.9% and 10.7% increases in risk, respectively, but the increases were not significant.

Among other factors the analysis controlled for, a turning vehicle prior to the crash was less likely than a straight-moving vehicle to fatally injure a pedestrian, and the association was significant. Crashes occurring on roads with higher speed limits were associated with significantly higher risk of a pedestrian being killed, and the percentage increases were higher when speed limits became higher. A fatal pedestrian injury was significantly less likely in adverse weather conditions such as rain and snow, and more likely in dark or dawn/dusk light conditions. Female drivers and drivers ages 50–69 years and 70 years and older were associated with significantly lower pedestrian fatality risk. A female pedestrian was more likely to be killed in a crash than a male pedestrian, but the difference was not significant. Compared with pedestrians ages 20–69, younger pedestrians (16–19 years old) were less likely to be fatally injured, while older pedestrians (70 years and older) were more likely to be killed. Both effects were significant.

Table 6. Logistic regression modeling results of pedestrian fatality risk in single-vehicle single-pedestrian crashes

Parameter	Estimate	Change in risk	*p*
Intercept	−4.0021		<0.0001
Front-end shape			
Tall and blunt vs. low and sloped	0.3622	43.6%	0.0025
Tall and sloped vs. low and sloped	0.3741	45.4%	0.0361
Medium height and blunt vs. low and sloped	0.2276	25.6%	0.0195
Medium height and sloped vs. low and sloped	−0.0264	−2.6%	0.7376
Low and blunt vs. low and sloped	0.0317	3.2%	0.7773
Hood length			
> 40 inches vs. ≤ 40 inches	0.0573	5.9%	0.3540
Hood angle			
≤ 15° vs. > 15°	0.2238	25.1%	0.0011
Windshield angle			
> 30° vs. ≤ 30°	0.1013	10.7%	0.1262
Vehicle pre-crash movement			
Turning vs. going straight	−2.2934	−89.9%	<0.0001
Speed limit			
30–35 mph vs. ≤ 25 mph	1.0449	184.3%	<0.0001
40–50 mph vs. ≤ 25 mph	1.9657	614.0%	<0.0001
≥ 55 mph vs. ≤ 25 mph	2.7147	1,410.0%	<0.0001
Weather condition			
Rain/snow/fog/wind/other vs. no adverse condition	−0.3151	−27.0%	0.0003
Light condition			
Dark vs. daylight	1.2589	252.2%	<0.0001
Dawn/dusk vs. daylight	0.8324	129.9%	<0.0001
Driver sex			
Female vs. male	−0.2142	−19.3%	0.0004
Pedestrian sex			
Female vs. male	0.0637	6.6%	0.3011
Driver age			
Driver 16–19 vs. 20–29	−0.0745	−7.2%	0.5739
Driver 30–49 vs. 20–29	−0.0790	−7.6%	0. 2994
Driver 50–69 vs. 20–29	−0.1972	−17.9%	0.0137
Driver 70+ vs. 20-–29	−0.3889	−32.2%	0.0007
Pedestrian age			
Pedestrian 16–19 vs. 20–69	−1.1312	−67.7%	<0.0001
Pedestrian 70+ vs. 20–69	1.4292	317.5%	<0.0001

DISCUSSION

This is the first known research that used a large sample of police-reported crash data and measurements of the vehicles involved to examine the association between passenger-vehicle front-end profile geometry and pedestrian fatal injury risk. The findings identified the front-end parameters that were significantly associated with increased pedestrian fatal injury risk, and this information could help automakers design more pedestrian-friendly vehicles. The study validated that tall and/or blunt front ends as well as flat hoods, as observed in a majority of SUVs and pickups we examined, contributed to the higher pedestrian fatality risk we saw for these vehicles.

Pedestrian injuries in a crash typically stem from several major phases that could possibly happen during a crash: the first contact between a vehicle's front bumper and the lower limbs of the pedestrian, the second contact between the upper part of the grille and/or the front edge of the hood and a pedestrian's upper legs and pelvis, the third contact between the hood and/or windshield and the head and/or thorax, and the final contact between the pedestrian and the ground (Roudsari et al. 2005, Gupta and Yang 2013, Yin et al. 2017). Every vehicle part that a pedestrian contacts during an impact could possibly affect their risk of injury and the types of injuries they suffer.

Vehicles with tall front ends, regardless of a sloped or blunt shape, as well as vehicles with medium-height and blunt front ends (as seen in all pickups and a majority of SUVs) were more likely to kill a pedestrian in a crash, when compared with vehicles with a low front end (as seen in a majority of cars). A relatively flat hood, which was observed in a large majority of SUVs and pickups, was also associated with higher risk of a pedestrian being fatally injured. These findings are consistent with previous research findings that vehicles with tall front ends were associated with increased risk of serious or fatal head and thorax injuries to struck pedestrians (Matsui et al. 1999, Otte and Pohlemann 2001, Simms et al. 2011, Hamacher et al. 2012, Yin et al. 2017, Li et al. 2018, Shang et al. 2018). For vehicles with a medium-height front end, only blunt shapes were associated with increased fatal injury risk to pedestrians. This is possibly due to increased loading to the struck pedestrian's middle or upper body that is associated with large bumper lead angles, and pedestrians likely being thrown forward after impact (Niederer and Schlumpf 1984, Tanno et al. 2000). With a larger hood angle, there is possibly more free deformation space underneath the hood to prevent the pedestrian's head from contacting rigid parts in the engine bay.

This study did not find statistically significant associations between fatal pedestrian injuries and hood length or windshield angle. It is possible that the potential effects of these two parameters were obscured by the stronger effects of front-end shape. Pedestrians struck by taller vehicles are more likely to be knocked down or thrown forward (Otte and Pohlemann 2001, Simms et al. 2011, Hamacher et al. 2012, Yin et al. 2017, Shang et al. 2018) and might not reach the hood or windshield at all. In these cases, hood length and windshield angle would be irrelevant to pedestrian injury risk. It is possible that the effects of these two measurements would become significant if only crashes where pedestrians impacted the hood or windshield were included. However, due to a lack of information on impact locations, such crashes could not be identified. The effects of the hood and windshield geometries on pedestrian injuries could also be affected by factors such as smoothness of the hood surface (hood effects only), the inner structure of the hood (hood effects only), impact points, and the stiffness or energy-absorbing levels of the materials (Bosma et al. 2001, Han et al. 2012, Shojaeefard et al. 2014, Kim et al. 2017, Ahmed 2020). Such information was not available in the crash dataset and cannot be measured by using vehicle images.

Among all the variables included in the analysis, speed limits, especially the higher ones, had the largest impact on the risk of a pedestrian being fatally injured in a crash. Higher speeds substantially increase the risk of severe and fatal injury to a pedestrian (Tefft 2013). The finding that a turning vehicle was less likely to kill a pedestrian is probably due to a turning vehicle's relatively low traveling speed. Speed management is an important component among efforts to improve pedestrian safety. A comprehensive speed management program should combine engineering, enforcement, and public education to achieve sustainable speed reductions and road safety improvements (Hu and Cicchino 2023a). Furthermore, pedestrian safety benefits of certain vehicle front-end countermeasures, such as increased deformation space under the hood, may dissipate as speeds increase, since there are limits of impact speeds above which the protection becomes minimal (Fredriksson and Rosén 2012, Hutchinson et al. 2012). Conditions with lower levels of lighting were associated with higher injury risks to pedestrians. Measures such as enhanced road lighting and improved headlights can make pedestrians more visible in low-light conditions and thus reduce pedestrian crashes (Wanvik 2009, Brumbelow 2022).

It is worth noting that the vehicle measurements were categorized based on their distributions among vehicles included in this study. These categories may not represent the entire vehicle fleet in terms of each parameter's effects on pedestrian injuries. The state crash datasets do not contain detailed crash and injury information such as the pedestrians' injured body parts, vehicle pre-crash speeds, and impact locations. Research using such detailed crash information and vehicle measurements would generate interesting information to help further understand the roles of vehicle front-end profiles in pedestrian injury patterns and mechanisms.

Safe vehicles are an essential element of a safe system, and together with other elements such as safe speeds and safe roads, they provide layers of protection to promote the safety of all road users. This study adds to the evidence that vehicle design affects pedestrian injury severity and confirms that front-end profiles typical of SUVs and pickups lead to elevated fatal injury risk to pedestrians. As the market share of LTVs, especially SUVs, continues to increase (Environmental Protection Agency 2022), research has found that pedestrian fatalities involving SUVs increased more than those involving other vehicle types (Hu and Cicchino 2018). Automakers should keep pedestrian safety in mind when designing or redesigning larger vehicles by making their front ends lower and more sloped, as the current study's findings suggest. Similarly, NHTSA could consider evaluations that account for the growing hood heights and blunt front ends of the vehicle fleet in the New Car Assessment Program or regulation.

Other design features such as more room between the hood and engine, hood airbags, hoods that automatically lift up upon impact, and bumpers with more give could reduce pedestrian injury severity (Strandroth et al. 2014). The increasing popularity of electric vehicles also offers great opportunities to optimize vehicle design for pedestrian safety. For gas-powered vehicles, the front ends are designed around engines and there is very limited deformation space under the hood due to the engines. The absence of conventional engines in electric vehicles may allow for more freedom in the front-end design. Pedestrian AEB systems have been found to effectively reduce pedestrian crashes (Wakeman et al. 2019, Cicchino 2022). Pedestrian AEB, combined with pedestrian-friendly front-end designs, could considerably reduce the risk of severe pedestrian head injury, compared with pedestrian AEB only or improved vehicle design alone (Fredriksson and Rosén 2012).

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APPENDIX: VEHICLE EXAMPLES OF DIFFERENT FRONT-END SHAPES

Figure A1

Examples of vehicles with tall and blunt front ends: 2015 Ford F-150 Crew cab (top), 2015 Jeep Renegade (bottom)

Figure A2

Examples of vehicles with tall and sloped front ends: 2011 Nissan Titan Crew Cab (top), 2010 Nissan Pathfinder (bottom)

Figure A3

Examples of vehicles with medium-height and blunt front ends: 2016 Mazda CX-9 (top), 2010 Chevrolet Colorado (bottom)

Figure A4

Examples of vehicles with medium-height and sloped front ends: 2015 Nissan Murano (top), 2012 Honda Odyssey (bottom)

Figure A5

Examples of vehicles with low and blunt front ends: 2016 Ford Mustang GT (top), 2014 Infiniti Q50 (bottom)

Figure A6

Examples of vehicles with low and sloped front ends: 2004 Toyota Camry (top), 2011 Nissan Leaf (bottom)