Bicyclist crashes with cars and SUVs: injury severity and risk factors

April 2023

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ABSTRACT

Objective: The current study was conducted to investigate the differences in injury outcomes between bicyclists struck by SUVs and those struck by cars. This study was designed to complement an earlier investigation using a similar methodology but focusing on pedestrian crashes.

Methods: We analyzed 71 single-vehicle crashes from the Vulnerable Road User Injury Prevention Alliance (VIPA) pedestrian crash database, focusing on crashes involving an SUV or car. Each crash from this database included an in-depth analysis of police reports, bicyclist medical records, crash reconstructions, and injury attribution by a panel of experts.

Results: Bicyclist injuries from crashes with SUVs were more severe than those from crashes with cars, particularly with respect to head injuries. The greater injury severity associated with SUVs was related to these vehicles' tendency to produce injuries from ground contact or from vehicle components near the ground. In contrast, cars were much less likely to produce ground injuries, and instead tended to distribute less severe injuries across multiple vehicle components.

Conclusions: The pattern of results suggest that the size and shape of SUV front ends are responsible for the differences in bicyclist injury outcomes, which is consistent with our past findings on pedestrian crash outcomes.

INTRODUCTION

The popularity of bicycles in the United States has increased dramatically over the past decade (NPD Group 2021; U.S. Census Bureau 2015) alongside a similar increase in injuries and fatal crash numbers—particularly among adult riders (Coleman and Mizenko 2018; Ferenchak and Marshall 2020; Sanford et al. 2015). From 2010 to 2018, per capita and per-kilometer bicyclist fatality rates increased by 11% and 33%, respectively (Buehler and Pucher 2021b), and the number of bicyclist fatalities as a proportion of all transportation-related deaths has also grown over this period (Robartes and Chen 2017), particularly among adult riders (Ferenchak and Marshall 2020).

During the COVID-19 pandemic, large numbers of people turned to bicycles when other modes of transport became impractical (Buehler and Pucher 2021a; Monfort et al. 2021), and survey data suggests that American adults anticipate using bicycles more even after COVID-19 is no longer a concern (Ehsani et al. 2021). The pronounced growth in bicycle traffic in 2020 capped off a larger trend of people turning to bikes for their transportation needs. In the United States, the share of bicycle commuters rose by 67% between 2005 and 2015 (Robartes and Chen 2017; U.S. Census Bureau 2015). Similarly, data from the National Household Travel Surveys suggest that travel by bicycle for any reason also increased among 16–44 year-olds between 2001 and 2017 (Buehler et al. 2020). The growing preference for bicycles has encouraged cities and towns to invest in bicycle infrastructure with an eye toward expanding transportation options in the future (Brooks et al. 2021).

The increasing popularity of cycling together with the risk of injury or death for those cyclists presents a pressing need to understand how and why these riders are being injured in crashes with motor vehicles. Although past work is clear enough that larger, taller vehicles pose an outsized risk to pedestrians and bicyclists alike, we seek to understand why certain vehicle characteristics (e.g., size, shape) are associated with more severe bicyclist injury outcomes. If certain vehicle features can be linked to an outsized risk of bicyclist injuries, then automakers can work to modify those features and mitigate that risk.

A large body of research has investigated factors that contribute to bicyclist fatalities from crashes with motor vehicles. Unsurprisingly, we find that more severe injuries result from higher preimpact speeds (particularly over 30 mph; Ackery et al. 2012; Kim et al. 2007; Macioszek and Granà 2022). The presence of drug or alcohol intoxication, either in the driver or the bicyclist, similarly exacerbates injuries (Moore et al. 2011; Kim et al. 2007), as well as bicyclist age (older is more risky; Boufous et al. 2012), time of day (night crashes are more dangerous; Boufous et al. 2012; Zahabi et al. 2011), and lack of a helmet on the bicyclist (Boufous et al. 2012; Kim et al. 2007).

Most relevant to the current study, larger vehicles—pickup trucks, heavy trucks, vans, buses, and so on—have consistently been shown to be more hazardous to bicyclists than smaller passenger vehicles (Ackery et al. 2012; Edwards and Leonard 2022; Kim et al. 2007; Macioszek and Granà 2022; Zahabi et al 2011). In fact, a study using two years of crash data from Illinois found that taller vehicles were involved in 26% of all pedestrian and bicyclist crashes, but 44% of fatal crashes (Edwards and Leonard 2022). By contrast, smaller passenger cars were involved in 62% of pedestrian and bicyclist crashes but just 38% of fatalities. Similarly, Robartes and Chen (2017) found that vans, SUVs, and pickup trucks were more likely to fatally (+50.6%) and severely (+21.1%) injure struck bicyclists compared with cars.

The overrepresentation of certain vehicles in bicyclist fatalities is likely due to the way that their front-end height interacts with the person they strike. Our earlier research on pedestrian crashes found that that SUVs were more hazardous than shorter, smaller cars at least partially because of their higher leading edges (Monfort and Mueller 2020). In addition to more critical body regions being higher on the body, being struck above one's center of gravity tends to throw a person forward, possibly resulting in being run over (Crandall et al. 2002). Being run over is generally more injurious than rolling onto the hood and/or being thrown backward over the moving vehicle (Crandall et al. 2002; Monfort and Mueller 2020).

Bicyclists tend to differ from pedestrians in terms of their speed, weight distribution, and vertical location relative to motor vehicles. In particular, they tend to have a higher center of gravity compared with pedestrians, and their body parts are arranged somewhat differently with respect to a striking vehicle: higher legs, bent knees, and a more inclined torso. Although vehicles designed to meet EuroNCAP pedestrian crash protection requirements have also improved bicyclist crash outcomes (Standroth et al. 2014)—suggesting that some risk factors are shared between them—the differences between pedestrians and bicyclists are large enough to warrant separate consideration (Maki et al. 2003). For example, bicyclists are more likely to suffer injuries from impacts with the ground, compared with pedestrians who are more often injured by front-end components (Öman et al. 2016). Bicyclists can even be thrown to the ground without their bodies having been hit by the vehicle at all (i.e., their bicycle alone was struck; Werner et al. 2001). In sum, bicyclists seem uniquely at risk for forward projection (Crandall et al. 2002) and ground-contact head injury (Badea-Romero and Lenard 2013). It remains unclear whether certain vehicle types are more likely than others to produce these injurious kinematics.

Although larger, taller vehicles are associated with greater injury risk to bicyclists than smaller, shorter ones (e.g., Edwards and Leonard 2022), the mechanisms for the increased risk remain unclear. Simulation studies offer some clues, suggesting, for example, that SUVs may imperil bicyclists because their higher leading edges tend to produce crashes that avoid head impacts with the relatively softer windshield glass (Katsuhara et al. 2014). The current study was designed to elaborate on the risk posed by taller vehicles by exploring real-world bicyclist crash injuries and kinematics. These analyses will serve as a complement to our earlier work on pedestrian crash outcomes using the same dataset (Monfort and Mueller 2020).

METHODS

Participants

Bicyclist crash data were collected by the Vulnerable Road User Injury Prevention Alliance (VIPA) as a part of the International Center for Automotive Medicine (ICAM) Pedestrian Consortium. These data contained detailed records of Michigan pedestrian and bicyclist crashes where police were called to the scene, including police reports, scene information, medical records, crash reconstructions, and injury attribution by a panel of experts. The current study focused on the 71 completed injury crashes occurring between 2015 and 2021 involving one adult-sized (i.e., aged 16 or older) bicyclist being struck by the front end of a passenger car (n = 41) or SUV (n = 30). Although VIPA collected data on crashes involving pickup trucks, these were too few in number to form firm conclusions (n = 10) and were excluded from the analysis. Focusing on single-vehicle frontal crashes improves the validity of our analyses by removing potential confounders. In other words, crashes involving small children (n = 8), nonfrontal crashes (n = 10), and frontal crashes involving more than one striking vehicle or struck bicyclist (n = 5) were excluded from the analysis.

Data

Injury data for each crash were recorded using ICD-9 codes; these injuries were coded with one of eight body regions (head, face, neck, spine, thorax, abdomen, upper extremity, or lower extremity) and a severity score using the Abbreviated Injury Scale (AIS), ranging from 1 (minor) to 6 (maximal). The three highest AIS scores per bicyclist per body region were squared and summed to represent the aggregate level of injury per bicyclist, capped at 75 (i.e., the Injury Severity Score [ISS]). The ISS data were used to provide a single score that could characterize overall injury severity and how it differed by striking vehicle type.

We then reduced body region coding from eight to four categories: head (including injuries to the head, face, and neck); torso (including injuries to the thorax, abdomen, and spine); lower extremities (including injuries to the hip, leg, and feet); and upper extremities (including injuries to the arms and hands). This reduction was conducted to align with past research on crash injury data (e.g., Fredriksson and Rosén 2012) and to increase the power of our statistical tests.

Analyses

We were primarily interested in differences in crash outcomes related to striking vehicle type. First, we analyzed overall injury severity differences between cars and SUVs as represented by ISS. Second, we analyzed injury data for each body region using AIS scores. Finally, we explored the mechanisms of injury using crash kinematics and injury attribution data.

Crash severity depends on a number of factors, not all of which are related to vehicle design differences. To control for unrelated factors, we included a number of covariates in the model: vehicle preimpact speed, time of day (day, night, or dawn/dusk), location of the crash (straightaway/curve or mixing area), bicyclist age, and bicyclist gender. Poisson regression models were used for all inferential tests to model positively skewed outcomes. Relative average injury severity estimates were computed by exponentiating the Poisson model parameter estimates.

RESULTS

Crash characteristics

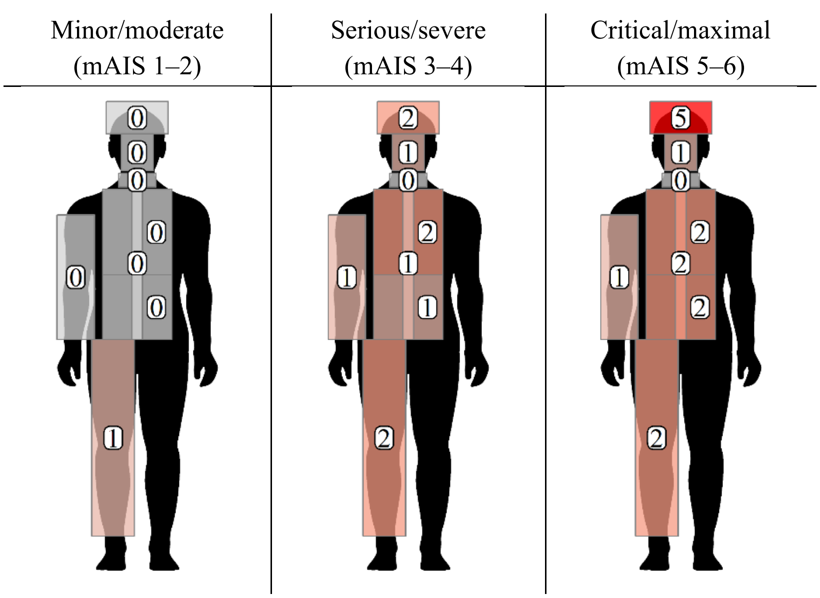
The average model year for involved vehicles was 2011 (*SD* = 5.9 years); the average preimpact speed was 26 mph (*SD* = 15 mph). Crashes tended to occur at crossings or junctions (65%) followed by straightaways or bends away from intersections (27%). A few (8%) occurred at property exits. Among intersection crashes with data on preimpact maneuvering, most involved a vehicle turning right (53%), while most midblock crashes involved acceleration or no input from the driver (71%).

Struck bicyclists were mostly male (83%), ranging from 17 to 87 years old (M = 43.5, *SD* = 18.3). These bicyclists suffered an average of three injured body regions each (*SD* = 2). When a body region was injured, it was typically mild (i.e., an average AIS of 1.8, *SD* = 1.1). The typical ISS—the summary injury score for the entire body—was similarly mild, with half of the crashes falling between 2 and 16 (*M* = 12, *SD* = 18). However, 30% of crashes involved a serious injury or worse (i.e., AIS 3+), and 13% of crashes were fatal.

Injury regions

By categorizing crashes according to the most severe injury suffered, we can visualize how injuries were distributed across the body for crashes of various severities. For the purposes of this analysis, we divided crashes into minor/moderate (mAIS 1–2), serious/severe (mAIS 3–4), and critical/maximal (mAIS 5–6). As seen in Figure 1, injuries to the lower extremities were a common factor in all crashes (occurring in approximately 80% of crashes overall). As crashes became more severe (i.e., produced more severe injuries), injuries to the head and torso became more frequent. Head injuries were common among the most severe crashes but occurred alongside injuries spread diffusely across the body: in the thorax and abdomen, as well as in the spine and extremities.

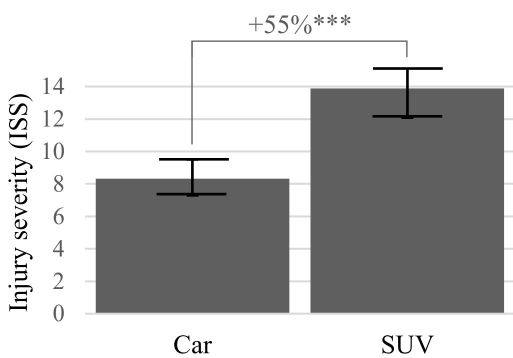
Figure 1. Mean maximum Abbreviated Injury Scale (mAIS) scores by body region and crash severity.



Vehicle type

The primary interest of the current study was to investigate potential injury differences by striking vehicle type. Looking first at overall severity, we saw that SUVs inflicted significantly more severe injuries (i.e., ISS +55%) on struck bicyclists compared with cars, 95% confidence interval (CI) [33%, 81%], $p < .001$ (Figure 2). These differences remained significant after controlling for a number of crash variables, which themselves also predicted injury severity: Higher vehicle preimpact speeds resulted in more severe injuries than lower ones, night and dawn/dusk crashes were more severe than daytime ones, and crashes along straightaways were more severe than crashes in mixing areas (crossings, junctions, and exits). Demographically speaking, older and female bicyclists were more vulnerable than younger and male bicyclists. Complete test statistics for vehicle type and the covariates are listed in Table 1.

Figure 2. Estimated marginal means for a Poisson regression model predicting ISS with striking vehicle type and covariates.



Note. Error bars represent 95% confidence intervals.
***p < .001

Table 1. Model statistics for a Poisson regression predicting injury severity with vehicle type and covariates.

Parameter		Exp(B)	95% CI	*p*	
Vehicle type	Car	—	—	—	
	SUV	1.55	[1.33, 1.81]	< .001	***
Preimpact speed		1.91	[1.76, 2.07]	< .001	***
Time of day	Day	—	—	—	
	Night	1.49	[1.24, 1.80]	< .001	***
	Dawn/dusk	1.38	[1.10, 1.73]	.005	**
Location	Straightaway	—	—	—	
	Mixing area	0.76	[0.65, 0.89]	< .001	***
Bicyclist age		1.52	[1.40, 1.66]	< .001	***
Bicyclist sex	Female	—	—	—	
	Male	0.70	[0.58, 0.84]	< .001	***

Note. CI = confidence interval, Exp(B) = exponentiated regression coefficients. Preimpact speed and age were standardized prior to inclusion in the model.
***p < .001; **p < .01.

Body region

We then analyzed injuries separately by body region—head (including head, face, and neck), torso (including thorax, abdomen, and spine), arms (including arms and hands), and legs (including pelvis, legs, and feet). Because this analysis focused on individual injuries, we used AIS rather than ISS. Injury severity for each body region was predicted using the same variables that were used in the overall injury severity regression. The most notable effects emerged from the head injury analysis. After controlling for preimpact speed, time of day, location of the crash, and bicyclist age and sex, the typical head injury inflicted by SUVs (AIS = 1.43) was 63% more severe than that inflicted by cars (AIS = 0.88), 95% CI [2%, 161%], $p = .042$. The distribution of raw head injury severity for cars and SUVs can be seen in Figure 3. No statistically significant severity differences by striking vehicle type emerged for the other body regions (Table 2).

Figure 3. Prevalence and severity of head injuries for cars and SUVs.

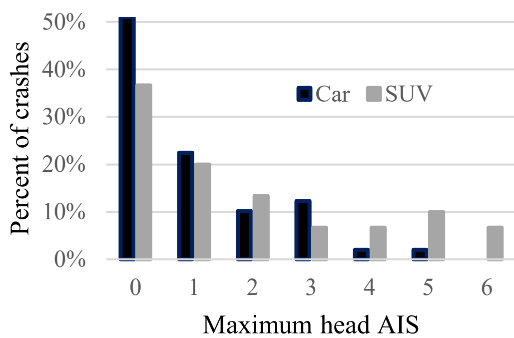


Table 2. Model statistics for four Poisson regression models predicting head, torso, arm, and leg injury severity with vehicle type and covariates.

		Head	Torso	Arm	Leg
Parameter		Exp(B)	Exp(B)	Exp(B)	Exp(B)
Vehicle type	Car	—	—	—	—
	SUV	1.63*	1.31	1.08	0.91
Preimpact speed		1.83***	1.67***	1.38†	1.43**
Time of day	Day	—	—	—	—
	Night	1.29	1.49	1.02	0.98
	Dawn/dusk	1.02	1.20	0.94	0.90
Location	Straight/curve	—	—	—	—
	Mixing area	0.62†	0.87	1.18	0.93
Bicyclist age		1.28*	1.62***	0.97	0.97
Bicyclist sex	Female	—	—	—	—
	Male	0.75	0.64†	0.59	1.29

Note. Preimpact speed and age were standardized prior to inclusion in the model.
***p < .001; **p < .01; *p < .05; †p < .10.

Crash kinematics

A subset of the crashes (23 cars and 21 SUVs) was coded further to include details of how the bicyclist moved after being struck. For example, some bicyclists were thrown forward (forward projection), others were rolled onto the hood and then thrown forward (wrap trajectory), and others were rolled onto the hood and thrown sideways (fender vault). Although only frontal crashes were included in our analysis, a few side impacts did occur when a bicycle was struck on its front tire, causing the bicyclist to rotate around the vehicle and impact its side.

All vehicles were most likely to throw bicyclists forward (forward projection) or roll them onto their hoods and then throw them forward (wrap trajectory). However, cars were the only vehicles to inflict injury by vaulting bicyclists over their roofs (in 20% of crashes) and SUVs were the only vehicles to do so by running over bicyclists (in 10% of crashes). The full breakdown of kinematics by striking vehicle type can be seen in Table 3.

Table 3. Kinematics by vehicle type.

	Forward projection	Wrap trajectory	Roof vault	Fender vault	Run over	Side impact
Car	65% (15)	13% (3)	17% (4)	0% (0)	0% (0)	4% (1)
SUV	62% (13)	14% (3)	0% (0)	10% (2)	10% (2)	5% (1)

Injury source

A further subset of the crashes that were coded for bicyclist kinematics were also coded to include information about the source of each injury (10 cars and 8 SUVs). For example, if a bicyclist was injured on their head and torso, the dataset would link those injuries to components on the striking vehicle or to the ground For the purposes of our analysis, we grouped vehicle components into one of eight groups by their general location on the vehicle: the front end (including the bumper, grille, and headlights), the hood (including the hood and cowl), the side (including the A-pillar and mirrors), the roof (including the roof and header), the underside (including the wheel and undercarriage), the fender, the windshield, and the ground. Together, these eight groups represent distinct regions of the striking vehicle.

In all, the data contained attribution for 347 injuries (from 18 crashes; about 19 unique injuries per crash). To determine whether any regions on the striking vehicles were responsible for a disproportionate amount of injury, we summed the squares of the three most severe AIS scores for each region on the striking vehicle within each crash. We then summed the vehicle regions across crashes to obtain an overall sum. This procedure approximates that used to calculate ISS and conveys at a glance which striking region is responsible for inflicting the largest proportion of net injury severity. This sum can also reveal whether injury severity is distributed differently by vehicle type. The distribution of injury severity by vehicle component and type can be seen in Table 4.

Table 4. Injury severity by striking vehicle component and type.

	Header/ roof	Hood/ cowl	A pillar/ mirror	Ground	Windshield	Front end	Fender	Wheel/ undercarriage
Car	29% (75)	21% (54)	17% (43)	15% (39)	12% (31)	5% (13)	0% (0)	0% (0)
SUV	0% (0)	0% (0)	19% (65)	25% (84)	1% (3)	4% (15)	14% (46)	37% (125)

A Chi-square goodness-of-fit test suggests that the distribution of ISS across vehicle regions differed by striking vehicle type, $\chi^2(7) = 117$, $p < .001$. The main difference between cars and SUVs in terms of how they inflicted injuries was that cars tended to injure bicyclists with a wide assortment of components; injury severity was spread across the entirety of the front and top. This diffuse injury attribution (injuries spread across the front end, hood, windshield, header, and roof) is consistent with the greater proportion of roof vaults observed among cars. In contrast, bicyclists struck by SUVs tended to have their injuries concentrated on a smaller subset of components—mostly the wheel, vehicle undercarriage, and ground. This is likewise consistent with the concentration of run-over crashes among SUV crashes.

Injurious impacts with the ground seem to be a key differentiator between crashes involving cars and those involving SUVs, even in cases where bicyclists were not run over. Among non-runover crashes, ground-contact injuries were more than twice as common among SUVs (40% of all injuries) compared with cars (19% of all injuries). Further, the difference in head injury severity by vehicle type (i.e., Table 2) may have been driven by differences in how bicyclists are thrown after being struck. Among SUV-inflicted head injuries from the subsample coded for injury attribution, 82% resulted from contact with the ground, wheel, or undercarriage; all of the car-inflicted head injuries from this subsample instead resulted from contact with the header, roof, or windshield. In sum, SUV crashes were more likely to involve bicyclists being run over and being injured by impacts with the ground—impacts that disproportionately caused head injuries.

DISCUSSION

Over a series of analyses, we found that bicyclists were injured more severely when struck by SUVs than when struck by cars and that the differences in severity by striking vehicle type were largest for head injuries. Notably, injury differences remained even after controlling for preimpact speed, time of day, location of the crash, and bicyclist demographics. The in-depth nature of our crash data allowed us to elaborate on the excess risk from frontal SUV crashes: we found that SUVs tended to produce more injuries from ground contact than from contact with vehicle components, and that head injuries from SUV crashes (which tended to be the most severe) were overwhelmingly caused by the ground, or by components near the ground. In contrast, cars were much less likely to produce ground injuries, and instead tended to distribute less severe injuries across multiple vehicle components.

Taken together, our results suggest that frontal SUV crashes involved abrupt strikes that concentrated crash energy into the bicyclists' impact with the ground, whereupon they could be run over by the decelerating vehicle. Even in cases where those bicyclists were not subsequently run over, strikes from an SUV were dramatically more likely to cause injurious contact with the ground compared with those from cars. The conception of SUVs as being more dangerous overall, and more likely to throw down those they strike is consistent with past research on pedestrian impacts. The taller front end of SUVs strike pedestrians above their centers of gravity rather than below them (as in the case of car impacts), which results in pedestrians being thrown forward and down rather than rolled backward and up (Crandall et al. 2002; Roudsari et al. 2005). Our findings suggest that, despite bicyclists' somewhat elevated position compared with pedestrians, SUVs nonetheless strike them high enough to throw them forward. Indeed, past research suggests that bicyclists may be uniquely vulnerable to ground impact injuries compared with pedestrians (Badea-Romero and Lenard 2013; Öman et al. 2016), and the elevated front ends of SUVs seem to exacerbate this risk.

Several simulation studies on struck bicyclists found that a simulated SUV inflicted more severe head injuries compared with a simulated car (e.g., Maki et al. 2003; Katsuhara et al. 2014), which is consistent with our findings on head injury severity. These simulations found car head injuries to be less severe because the cars struck bicyclists lower compared with SUVs, causing them to impact the windshield rather than other, stiffer components on the vehicle or in the environment. Consistent with this finding, the cars in our sample were disproportionately likely to inflict injury with their windshields (12% of injuries), compared with the SUVs (only 1% of injuries). Interestingly, we did not find SUVs to inflict severe injuries with their leading edges, which was the primary mechanism for injury in our partner analysis on pedestrian crashes (Monfort and Mueller 2020). Bicyclists are elevated slightly above pedestrians, and so impacts from leading edges may occur on regions lower on the body (where injuries tend to be less severe), or even on the bicycle itself.

The tendency for injuries from cars to be spread across multiple components (and therefore over a longer period of time) may explain the lower bicyclist injury risk associated with cars. When impact load is distributed over a longer period, the risk of injury associated with that load tends to be reduced (Moon et al. 2012). Thus, the fact that SUVs injured bicyclists with fewer components (and therefore over a shorter period of time), may explain the greater injury severity in these crashes. Automakers have been using these principles to develop vehicle front end countermeasures, like pop-up hoods and deployable windshield airbags (Fredriksson and Rosén 2012).

Although curb weight is an important consideration for vehicle-vehicle crashes, vehicle weight differences did not underlie the observed differences in injury outcomes. Vehicles outweigh bicyclists by an order of magnitude, and so small curb weight differences between vehicles are typically not considered a strong predictor of bicyclist injury outcomes (Roudsari et al. 2005). On the other hand, research has shown that front-end shape determines how crash energy is transferred and how crash partners are injured. Maki et al. (2003) found that vehicles with an entirely flat front end (i.e., no hood) were much more likely to fatally injure bicyclists they struck compared with vehicles with a sloping front end (i.e., a hood). Our study expands on these findings by suggesting that the injury risk from taller, flatter-fronted vehicles (i.e., SUVs) replicates in a real-world crash environment. Future research should consider the role of front-end shape in greater detail.

Conclusion

We found that SUVs injured bicyclists they struck more severely than cars did, even after controlling for preimpact speed, time of day, location of the crash, and bicyclist age and sex. The overall difference in injury severity was in large part due to head injury differences: The typical head injury inflicted by SUVs was much more severe than that inflicted by cars. SUVs were disproportionately likely to throw bicyclists forward onto the ground and were the only vehicles to inflict injury by running them over. The pattern of results suggests that the size and shape of SUV front ends are responsible for the differences in bicyclist injury outcomes, which is consistent with our past findings on pedestrian crash outcomes. Future work should investigate specific front-end shapes that underlie these effects. Understanding how vulnerable road users are being injured can inform design changes to help protect them.

ACKNOWLEDGEMENTS

This work was supported and funded by the Insurance Institute for Highway Safety.

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