Pedestrian Injury Patterns in the United States and Relevance to GTR

Becky C. Mueller, Joseph M. Nolan, David S. Zuby, Anne G. Rizzo

Abstract Global Technical Regulation No. 9 on Pedestrian Protection (GTR 9) was adopted in 2008 to encourage vehicle front-end designs that mitigate the consequences of vehicle-to-pedestrian collisions. The objective of the current study was to compare the types and sources of real-world pedestrian injuries with the parts of the vehicle that would be affected by the tests prescribed by GTR 9. Among the 67 pedestrian crashes in a special Crash Injury Research and Engineering Network (CIREN) dataset, the most frequently injured body regions were the leg and head, the body regions directly addressed by GTR tests and requirements. However, only 5 of the 45 head-injured pedestrians' heads hit vehicle hoods, the object of GTR 9 head impactor tests. Thirty-one heads hit parts of the vehicle not included in specified test areas. Thirty-two pedestrians had tibia or fibula injuries associated with contact by the bumper, which also is evaluated by GTR 9 procedures. However, for those cases where leg injury data were available, as many as half of the leg fractures involved vehicle locations below the height of vehicle bumpers and below the instrumented portion of the GTR 9 legform testing device, suggesting the tests may not be sensitive to a significant portion of the leg injury problem. Overall, 46 of the 67 pedestrians in this sample may have benefitted if the striking vehicles had complied with GTR 9. However, 59 of the 67 pedestrians had injuries to body regions not addressed by GTR 9 test procedures, indicating that a significant pedestrian injury problem may persist even if GTR 9 completely eliminates the injuries it addresses.

Keywords GTR 9, injury patterns, pedestrian crashes, United States

I. INTRODUCTION

In 2010, 70,000 pedestrians were injured and 4,280 pedestrians were killed in U.S. traffic-related crashes, accounting for 13 percent of all traffic fatalities [1]. In a representative sample of U.S. pedestrian crashes, Jermakian and Zuby [2] found that 96 percent of pedestrians struck and 80 percent of pedestrians killed in single-vehicle crashes were struck by a passenger vehicle. More than 70 percent of pedestrians injured or killed in single-vehicle crashes were struck by vehicle front-end components.

Two vehicle-based countermeasures address injuries sustained by pedestrians. Recently, systems using forward-looking sensors (e.g., radar and cameras) have been developed to predict possible collisions with pedestrians and either warn the driver to undertake evasive maneuvering or brake, or initiate autonomous braking when the collision is unavoidable, thereby reducing the severity of collisions that do occur. Examples of these systems include the latest versions of Volvo's Pedestrian Detection with Full Auto Brake and Subaru's Eyesight [3]-[4]. An alternative strategy is to design the front ends of vehicles to mitigate the consequences of impacts with parts of pedestrians' bodies. Examples of this strategy date back to the 1970s and include providing crushable hoods and fenders to cushion head impacts as well as inserting padding into bumper systems to mitigate leg injuries [5]-[6]-[7].

Both European and U.S. governments have invested considerable effort in developing test procedures that could be used in safety regulations to compel injury mitigating designs for vehicle front ends [8]-[9]. Although the United States never adopted pedestrian protection regulations, the European efforts resulted in a two-tier regulation that went into effect in 2004, with tier one compliance by 2013 and tier two compliance by 2018. The European pedestrian regulation addresses head impacts to vehicle front ends (hoods, windshields and A-pillars), femur/hip impacts to hood (bonnet) leading edges (HLE) and leg impacts with bumpers [10]-[11]. In the future, vehicles with pedestrian crash avoidance systems may be exempt from the second tier of testing. The European regulation also is the basis for Global Technical Regulation No. 9 (GTR 9) that was adopted by the World Forum for the Harmonization of Vehicle Regulations Working Party 29 (WP 29) in 2008 [12]. As a result, the countries participating in the GTR process, including the United States, are obligated to consider implementing GTR 9 as a

B. C. Mueller is a Research Engineer with the Insurance Institute for Highway Safety (bmueller@iihs.org, 434-985-4600 tel, 434-985-2202 fax). J. M. Nolan is Chief Administrative Officer with the Insurance Institute for Highway Safety. D. S. Zuby is Chief Research Officer with the Insurance Institute for Highway Safety. A. G. Rizzo is a critical care surgeon at INOVA Fairfax Hospital and co-principal investigator at the INOVA Fairfax CIREN center.

safety regulation. The U.S. National Highway Traffic Safety Administration (NHTSA) is currently in the process of such an evaluation [13]-[14].

GTR 9 includes tests to address pedestrian head-to-hood impacts for both children and adults. The test areas are specified in terms of a wrap-around distance (WAD), which is the curvilinear distance from the ground below the bumper up and around the HLE and along the hood surface. The child test area is defined as a WAD of 1000 to 1700 mm, and the adult test area is defined as a WAD of 1700 to 2100 mm or the trailing edge of the hood, whichever is shorter. GTR 9 also addresses pedestrian leg-to-bumper impacts and defines the portion of the bumper subject to the requirements as the portion between the bumper corner references, which are defined as the points that contact a vertical plane oriented at a 60-degree angle relative to another vertical plane aligned with the vehicle longitudinal centerline.

Attempts have been made to link real-world injuries to pedestrian tests. Standroth et al. [15] found a positive relationship between the vehicle rating in the European New Car Assessment Program (EuroNCAP) and the pedestrian injury risk for the two lowest ratings categories. Many crashes were excluded from this study due to other crash factors; therefore, observed real-world differences in injury risk between ratings categories may be less when considering the entire population of pedestrian crashes. Comparisons of real-world injuries with pedestrian tests also have examined the estimated benefit — that is, the number of pedestrians whose injuries could be mitigated with improved vehicle designs and avoidance technologies [16]-[17]. Liers and Hannawald [18] estimated that the proportion of severely injured pedestrians compared with all struck pedestrians would drop from 16.2 to 9.7 percent overall if all vehicles reflected the current average EuroNCAP fleet performance

The objective of the current study was to compare the injuries and sources of injuries in a sample of real-world pedestrian crashes from the Crash Injury Research and Engineering Network (CIREN) dataset with parts of the vehicle that would be affected by the tests prescribed in GTR 9.

II. METHODS

The CIREN database includes a sample of 67 vehicle-to-pedestrian collisions that occurred during 2002-2006. In-depth investigations, including vehicle and crash scene inspections, crash reconstructions, medical records review, and driver and pedestrian interviews, were conducted to collect detailed data such as vehicle damage patterns, contact points, and pedestrian injuries. A multi-disciplinary team reviewed each case to establish probable injury sources. Each of the 67 pedestrians was admitted to the level 1 trauma center at the INOVA Fairfax Hospital in Fairfax County, Virginia, with at least one Abbreviated Injury Scale (AIS) 2+ injury using the 1998 AIS coding protocols. As such, pedestrians in this sample were injured more severely than the average pedestrian struck by a motor vehicle in the United States. Additional details of the case selection and data collection procedures were described by Longhitano et al. [19]. The types of injuries and their associated impacts with parts of the striking vehicle were compared with the vehicle parts covered in the tests specified in GTR 9. Head and leg injuries received special focus because these are specifically addressed by the GTR 9 tests.

In many of the cases, the WADs for head impact locations on the vehicle fronts were recorded by crash investigators. Thus, head impact locations for these pedestrians could be compared directly with test zones prescribed in GTR 9. For some cases, contact evidence was not available because the vehicle had been repaired before the investigation occurred. The WADs for vehicle landmarks (HLE, trailing edge of hood and rear edge of windshield) also were recorded for most of the crashes.

Leg impact locations on the bumper were recorded relative to the vehicle centerline. Although CIREN investigators did not record the lateral location of leg impacts with the bumper relative to the GTR 9 test zone, measurements from exemplar vehicles were obtained for the current study as described in Appendix A.

The cases involving leg injuries included radiography, which was examined to understand the location of leg fractures relative to the bumper heights of striking vehicles. The overall stature and knee heights of leg-injured pedestrians also were recorded, so fracture locations could be compared with bumper heights.

III. RESULTS

The 67 pedestrians in the study sample ranged from 2 to 79 years old, with an average age of 37. Twelve were younger than 18. Stature ranged from 65 to 190 cm, with an average height of 166 cm. Weight ranged 12 to 134 kg, with an average of 73 kg. Seventy-six percent of pedestrians in the sample were male.

Striking vehicles were manufactured during 1986-2006. Figure 1 compares the distribution of study vehicles by class with the composition of the U.S. vehicle fleet in 2006. There were more large cars and minivans and fewer light trucks and vans (LTVs, i.e., pickups and SUVs) in the sample than would be expected from the fleet composition in 2006.

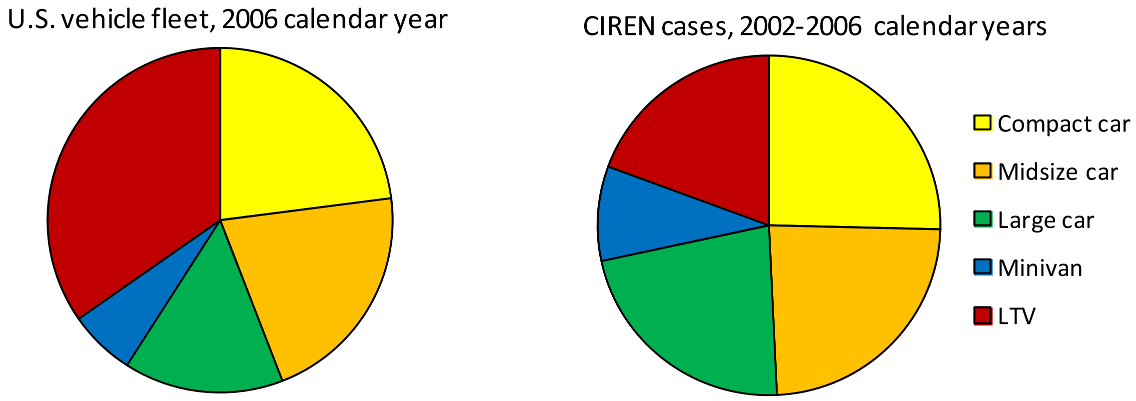

Fig. 1. Distribution of vehicles by class for U.S. vehicle fleet and CIREN pedestrian-striking vehicles

Fifty-nine of the 67 crashes occurred on straight roadways, and 60 crashes involved dry pavement. Twenty-nine crashes occurred at intersections, and there were traffic controls at 15 intersections. Forty-eight crashes occurred at night.

Police-estimated vehicle pre-impact speeds ranged from 8 to 90 km/h, with an average speed of 56 km/h. No speed estimate was provided for 9 cases. Vehicle braking was reported in a little more than one-third of the cases.

The number of pedestrians with at least one AIS 2+ injury to each body region is provided in Table 1. In the current study, the lower extremities were separated into pelvis, thigh and leg. The two most commonly injured body regions were the head (67 percent) and leg (63 percent). Most pedestrians had more than one injured body region. Twelve percent of pedestrians had injuries to only the head, leg or both. Seventy-eight percent of pedestrians had injuries to other body regions in addition to the head, leg or both. Ten percent had injuries that did not include either the head or leg.

TABLE 1

DISTRIBUTION OF AIS 2+ INJURIES BY BODY REGION

	Number of pedestrians*	Percent of cases
Head	45	67
Thorax	26	39
Spine	19	28
Abdomen	17	25
Upper extremities	32	48
Pelvis	22	33
Thigh	6	9
Leg	42	63

*Pedestrian may have more than one AIS 2+ injury per body region

Figure 2 shows the distribution of maximum AIS (MAIS) scores by body region for injuries of AIS 2 and greater. Injuries with severities greater than MAIS 3 most commonly involved the head, thorax or abdomen. The majority of AIS 4+ head injuries involved brain injuries, the majority of AIS 4+ thorax injuries involved rib fractures or lung contusions and the majority of AIS 4+ abdominal injuries involved spleen or liver lacerations. The MAIS 6 spinal injury was a complete cord syndrome, and the MAIS 5 pelvis injury was an open book pelvis fracture with greater than 20 percent blood loss. Seventy percent of all cases had MAIS 3 or greater injuries to the torso, spine, abdomen or pelvis.

Figure 3 shows the injury sources associated with the most severe injury for each body region for all pedestrians in the sample. With the exception of spinal injuries, impacts with vehicle components accounted for the majority of injuries in each body region.

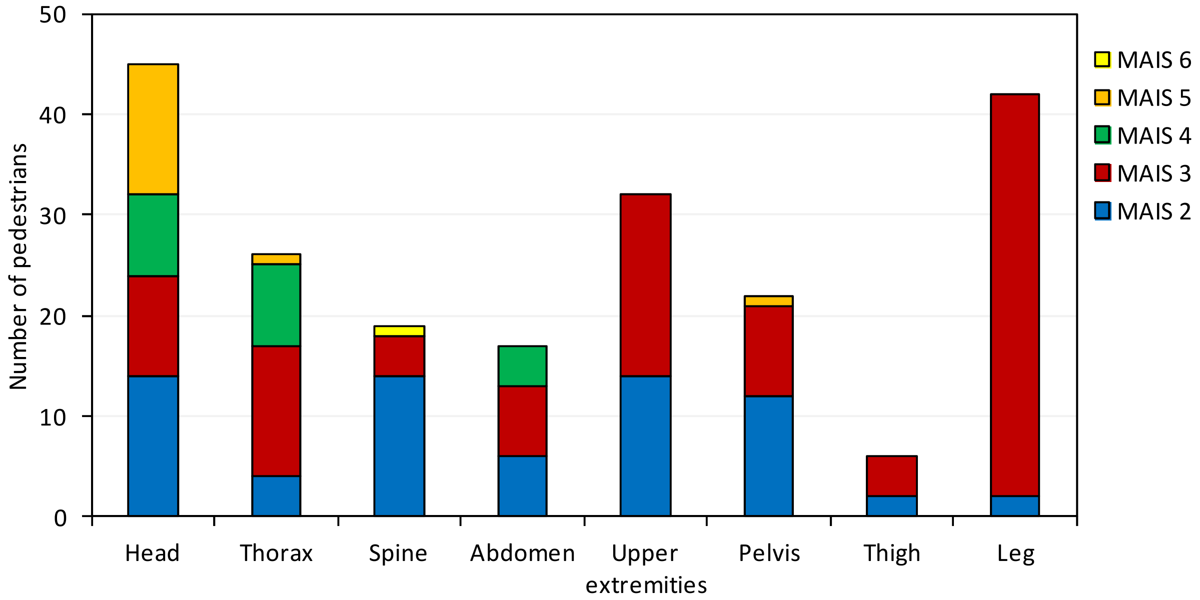

Fig. 2. Distribution of MAIS scores by pedestrian body region

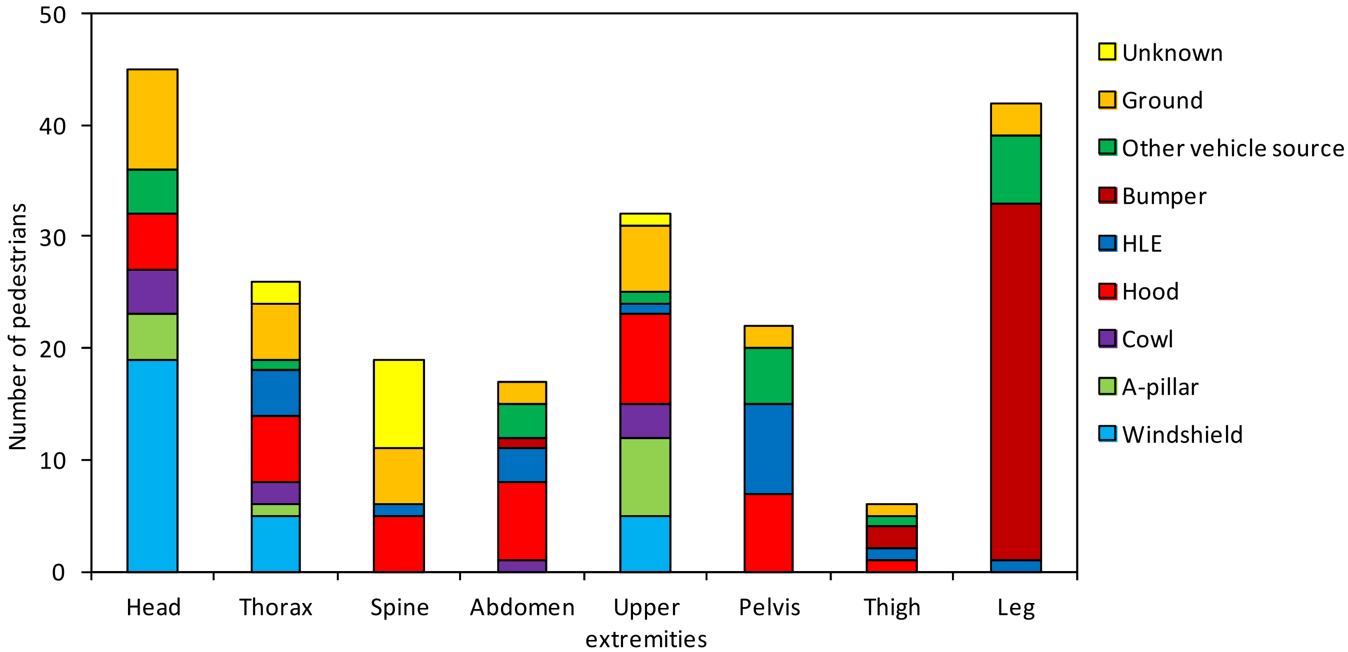

Fig. 3. Injury source associated with the most severe injury by body region

Head Injuries

Nine pedestrians received the most severe head injury from an impact against something other than the vehicle. Among vehicle components, the windshield was the most common source of head injuries. Only 5 pedestrians received the most severe head injury from impact with the vehicle hood; two were children and three were adults, one of whom was short statured (157 cm).

The WAD of the head impact location was available for 19 of the 40 pedestrians with head injuries. Figure 4 shows the distribution of head impact WADs relative to the GTR 9 test zone definitions. Although nearly half of the impacts were within one of the test zones as defined by the WAD boundaries, only two were on the hood. Figure 5, which shows the distribution of WADs for the rear of the hood, indicates that only one of the 19 vehicles had a hood with a rear edge behind the rearward extent of the adult test zone WAD. The locations of the 19 impacts are shown in Figure 6. In this figure, the locations of head impacts were scaled relative to the difference between WADs for the HLE and hood trailing edge of the actual striking vehicle, and windshield/A-pillar impacts were scaled relative to the difference between WADs for the leading and trailing edges of the windshield. Only 2 of the 19 impacts resulted in contact with the hood, while the remaining was beyond the hood in the range of the windshield and A-pillar.

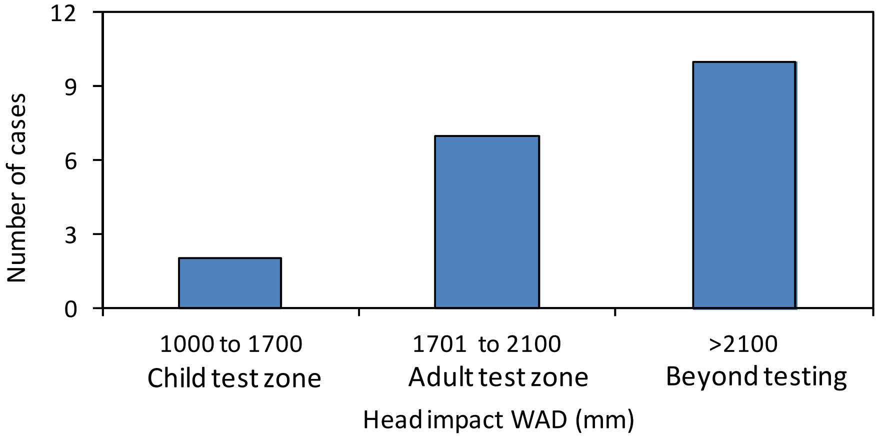

Fig. 4. Measured head impact location WAD for head-injured pedestrians

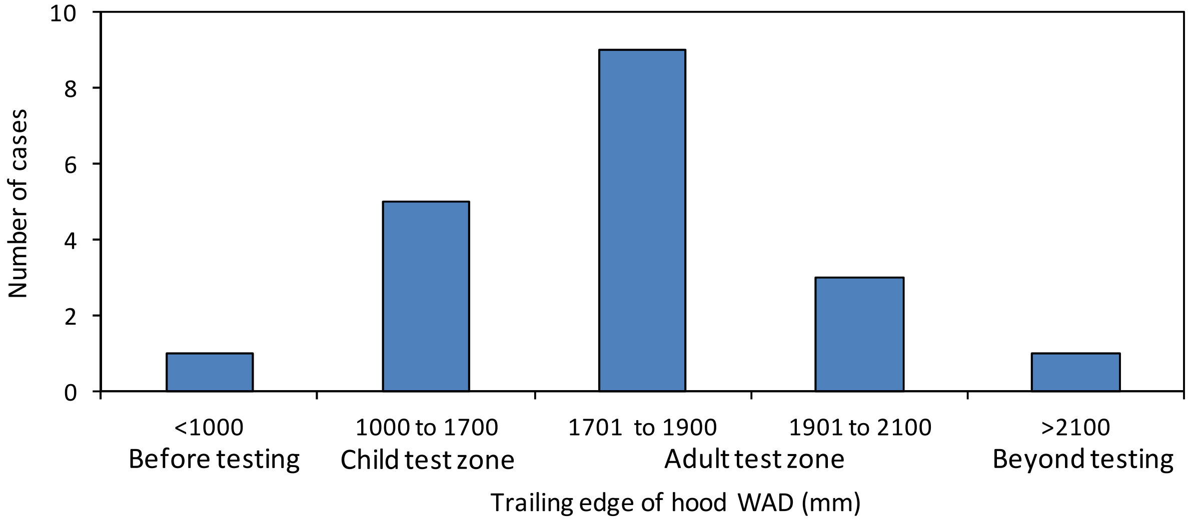

Fig. 5. Measured trailing edge of hood WAD for case vehicles

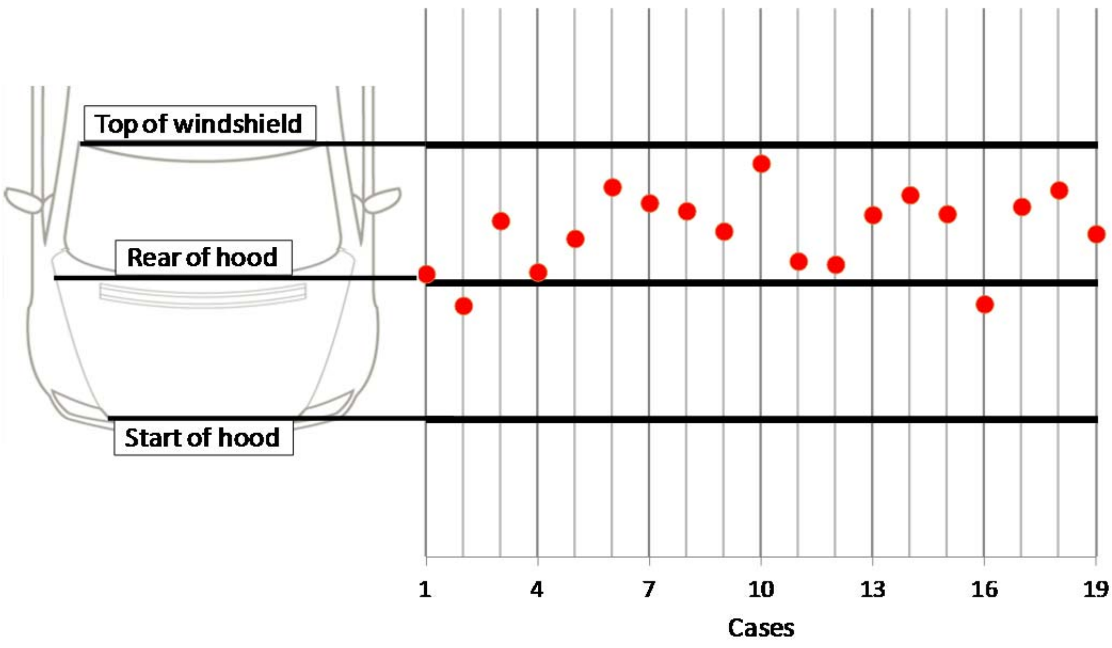

Fig. 6. Normalized head impact locations relative to vehicle landmarks for pedestrians with AIS 2+ head injuries

Lower Extremity Injuries

Tibia and fibula fractures comprised the vast majority of AIS 2+ lower extremity injuries, occurring in 42 pedestrians. Multiple fractures on the same leg were common, with 30 of 42 pedestrians sustaining 2 or more leg fractures. Fourteen pedestrians had fractures of both legs. Although not among the most severe lower extremity injuries sustained by any pedestrian, 5 pedestrians sustained knee ligament or meniscus injuries in addition to fractures. Figure 7 shows the locations of 38 tibia and fibula fractures sustained by 28 pedestrians for whom radiography was available.

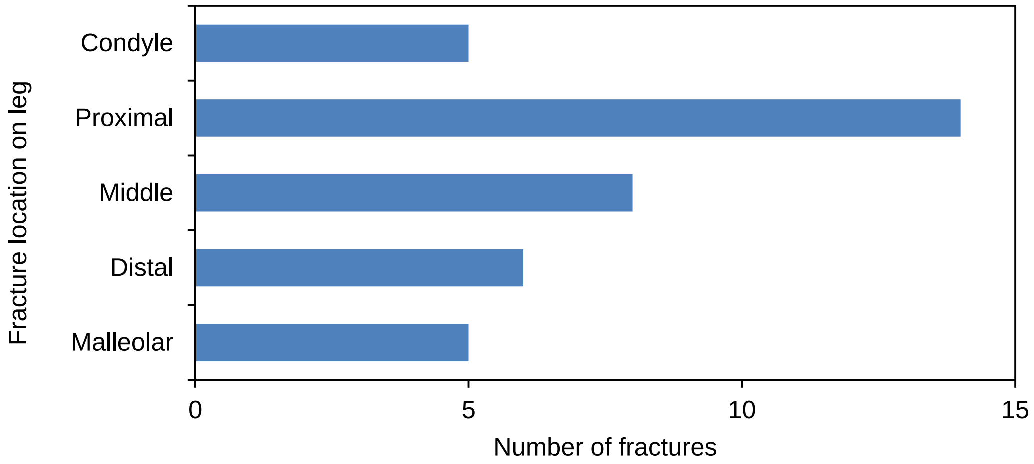

Fig. 7. Distribution of location of tibia and fibula fractures among pedestrians with radiography results

Seventy-seven percent of leg injuries were associated with bumper impacts. Bumper impact locations were recorded for the fractures sustained by the 28 pedestrians with radiography results. The distribution of impacts across the front of the striking vehicles is illustrated in Figure 8, with the impact locations scaled relative to the total width of the GTR 9 test zone. Only 4 pedestrians' leg fractures were associated with a part of the bumper that was outside the GTR 9 test zone.

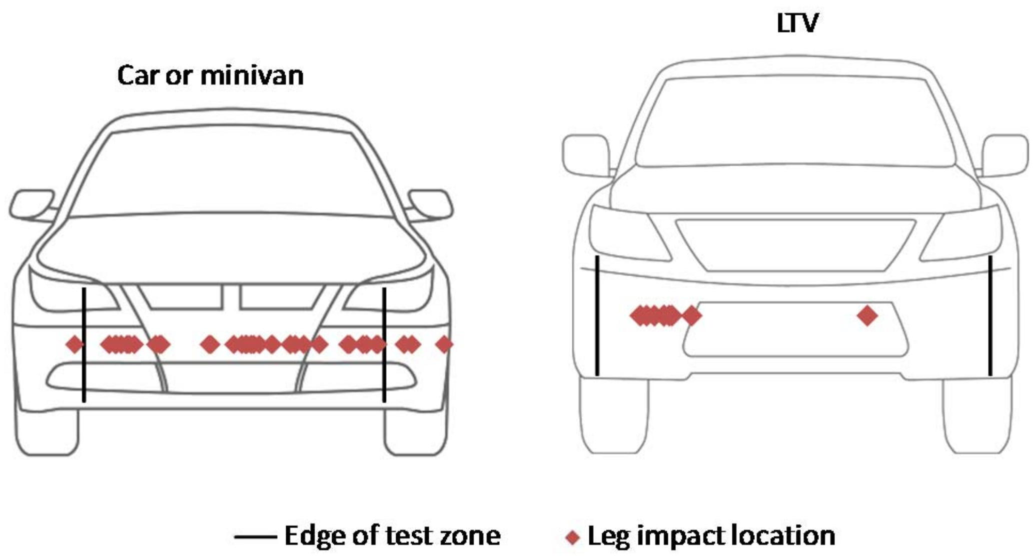

Fig. 8. Distribution of leg impact locations across striking vehicles width

The recorded tibia and fibula fracture locations from X-rays for each of the 28 pedestrians were compared with the height off the ground relative to the bumper zone specified in Federal Motor Vehicle Safety Standard 581, as shown in Figure 9. The 28 cases are grouped according to whether or not the report indicated vehicle braking. Braking affects vehicle pitch and the actual height of the bumper bar in these cases may be below the bumper zone limits illustrated in the figure.

Ten of the 28 pedestrians had leg fractures that aligned with the approximate height of the striking vehicle bumper. The other 18 had fractures below the height of typical bumpers. Four pedestrians were struck by a pickup or SUV (LTV), for which bumper heights may be greater than those mandated by FMVSS 581 for cars.

Twenty-two pedestrians had pelvis fractures and 6 had femur fractures. Ten of the pelvis/femur injured pedestrians sustained the injuries from impact with the hood leading edge. Among the remaining pedestrians with pelvis/femur injuries, fractures for 13 of them were caused by contact with a vehicle front component (e.g. hood, fender, grille or headlight).

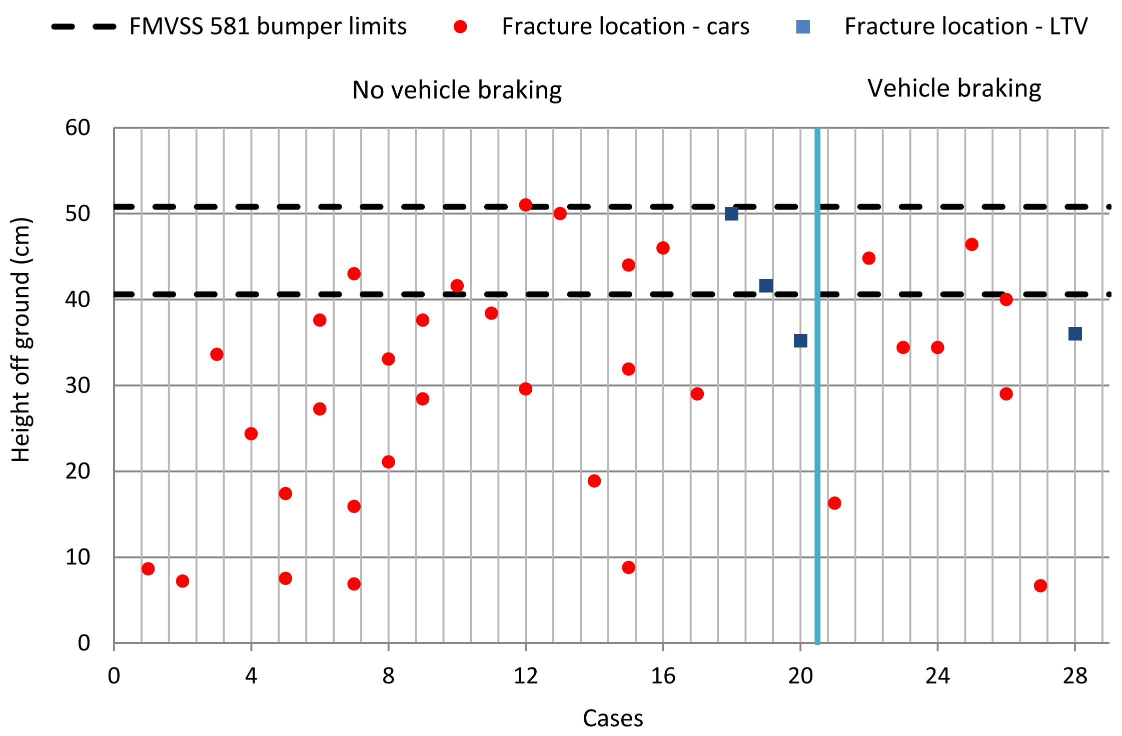

Fig. 9. Leg fracture locations relative to average bumper bar height

IV. DISCUSSION

GTR 9 is intended to encourage vehicle front-end designs that mitigate the risk and severity of injuries sustained by pedestrians in crashes. GTR 9 specifies test procedures and performance limits for simulated head-to-hood and leg-to-bumper impacts. Although serious head injuries account for the majority of permanently disabling or fatal injuries, many serious leg injuries also result in long-term impairment [20]. Although the head and leg are the most frequently injured body regions, more than two-thirds of the pedestrians in the study sample sustained injuries to body regions not directly addressed by the GTR 9 tests. Eight of the 67 pedestrians had injuries only to the head, leg or both, which are the only body regions addressed by GTR 9. However, several of the thorax, spine, abdomen, upper extremity and pelvis injuries were attributed by investigators to impacts with vehicle hoods. To the extent that the GTR 9 head impact tests encourage more forgiving hood structures that can crush when impacted, injuries to these body regions may be mitigated.

Only 5 of the 45 head-injured pedestrians sustained head injuries as a result of hitting the hood. The small number of head-to-hood impacts is consistent with other studies involving larger databases of pedestrian crashes, the U.S. Pedestrian Crash Data System (PCDS) and the German In-Depth Accident Survey (GIDAS) [21]-[22]-[23]. The cowl, A-pillar and windshield, which are not addressed by GTR 9, were far more common sources of head injuries, accounting for 27 of the 45 head-injured pedestrians. Extending the GTR 9 head testing zone to a WAD of 2100 mm (which encompasses the cowl, windshield and A-pillars) instead of ending it at the rear of the hood would address considerably more of the head injuries in the study sample. Nearly half of the injurious head impacts for which a WAD was known were located at WADs less than 2100 mm.

The International Harmonized Research Activities Pedestrian Safety (IHRA/PS) working group for GTR 9 initially proposed head testing to the windshield and A-pillar due to the frequency of head injuries from these sources. The group excluded these regions in the final report because the A-pillar and windshield are important structural load paths in front and side crashes that cannot be softened and no feasible countermeasures were currently available to provide sufficient pedestrian protection while maintaining compliance with the other relevant regulations [12]. New technologies such as inflatable windshield and A-pillar airbag countermeasures could be employed to address the challenges identified by the IHRA/PS by providing pedestrian protection behind the hood's rear edge without compromising windshield and A-pillar integrity. Volvo is the first automaker to introduce such a system on its V40 cars sold in Europe [24]. Concerns over steep costs, false activations, and repairability have largely deterred automakers from implementing these technologies. However, forward-looking sensors could alleviate problems typically associated with contact triggers located in bumpers; many forward collision warning systems have such sensors.

A large majority of leg injuries in this study were associated with bumper impacts. However, nearly two-thirds of pedestrians with leg fractures caused by bumper contact were injured below the height of typical bumpers. Factors such as vehicle braking, pedestrian footwear and pedestrian stance at impact also may influence where direct contact is made between the leg and the bumper. Half of all the leg fractures sustained by a subsample of 28 pedestrians for which radiography was available were midshaft or lower. These observations are consistent with those reported by Otte [25], as well as the biomechanical reality that the distal portions of these bones have smaller cross sections than the proximal portions. Thus, the bones fracture where they are weakest rather than where they are hit. It is not clear whether the TRL leg form specified in GTR 9, which does not include sensors in the distal leg, will be sensitive to these injury risks. The FLEX-PLI, which is being evaluated by several regulatory agencies, may be an alternative that could address more of the pedestrian leg injury problem, as additional sensors along the entirety of the leg have the potential to identify fracture risk on the distal portion of the leg and promote relevant countermeasures [26]-[27]. One countermeasure design includes an additional energy absorbing lower bumper beam to both control the bending motion of the leg and distribute the loading across the length of the leg.

Although the large majority of leg injuries in the study sample were associated with impacts in the GTR 9 test zone for the striking vehicle design, recent design trends may reduce the efficacy of the GTR 9 leg protection requirements. Figure 10 shows the plan view of typical bumpers for the study vehicles. The GTR 9 test zone covers 74 to 98 percent of the vehicle's overall width. In contrast, Figure 11 shows the same view of a bumper shape becoming more common among new vehicle designs. Due to the protrusions near the center of the bumper in these designs, the GTR 9 test zone is reduced to 39 to 60 percent of the vehicle overall width. Appendix B includes pictures and bumper zone measurements for specific examples of such designs. EuroNCAP recognizes that the test zone defined in GTR 9 may not always capture the bumper zone of modern vehicles due to bumper styling contours. Consequently, EuroNCAP [28], with test procedures similar to those of GTR 9, includes testing outside of the specified test zone if components in these areas appear injurious. A similar exception for GTR may increase relevance of bumper testing with modern vehicles.

Fig. 10. Representative GTR 9 bumper test zone for case vehicle designs

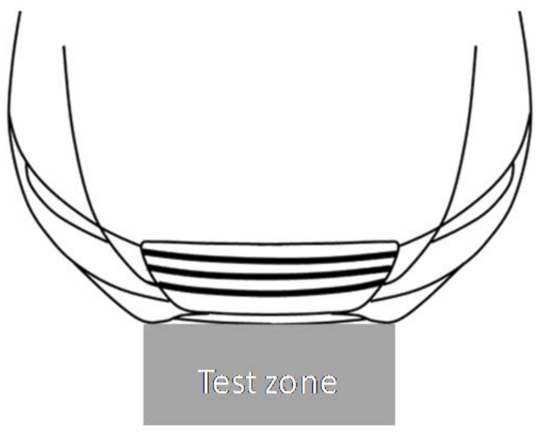

Fig. 11. Representative GTR 9 bumper test zone for new vehicle designs, which have bumper styling contours

Pelvis and thigh injuries were present in about one-third of the pedestrians in the sample of crashes, and nearly half of these injuries were attributed to impact with the HLE. This is similar to the PCDS evaluation of U.S. crashes reported by Mallory and Stammen [21]. Thus, the addition of an HLE test to GTR 9 could be beneficial.

Such a test is part of the European regulation and EuroNCAP, but was dropped from consideration in discussions leading to GTR 9 due to concerns about impactor biofidelity. The final report of the IHRA/PS working group recommended the adoption of an HLE test when a better impactor became available [12].

V. LIMITATIONS

The pedestrian injuries studied were from a convenience sample of pedestrians admitted to a suburban trauma center in Virginia and may not be representative of pedestrian injuries in other geographic areas or in a wider range of pedestrian crashes.

The estimated speeds for many of these crashes were higher than the target crashes for GTR 9. It is possible that people struck at slower speeds have different injury source patterns. In general, the pedestrians in this sample may have been more severely injured than the average pedestrian stuck by a motor vehicle in the United States, because all of these pedestrians' injuries required admittance to the trauma center. Still, these pedestrians sustained injuries intended to be addressed by GTR 9, and the fact that many of the injuries are not associated with parts of vehicles that will be affected by implementation of the regulation raises questions about its efficacy.

The preceding analysis of leg injury vertical locations may overestimate the number of below-bumper fractures because it does not take vehicle pitching due to braking into account. However, braking was reported in only about one-third of crashes and for only 7 of the 28 pedestrians with vertical fracture location measurements. Furthermore, even assuming that some of the fractures higher on the leg were caused by direct contact with the bumper, many were clearly too low to be caused by direct impact.

VI. CONCLUSIONS

GTR 9 aims to reduce the risk and severity of injuries sustained by pedestrians struck by motor vehicles. Its focus on head and leg injuries is supported by the analysis of this sample of pedestrians treated at a trauma center in northern Virginia. However, the sources and patterns of injuries sustained by these pedestrians raise questions about the ultimate effectiveness of adopting GTR 9 in the United States. Extending the head impact testing zone to include portions of the windshield and A-pillars likely would address more head injuries. Also, it is possible that using a legform that includes instrumentation in the distal portions instead of the one specified in GTR 9 would better address the types of leg injuries sustained by pedestrians in this sample. This analysis suggests that pedestrians sustain many injuries that are not directly addressed by either of the test procedures specified in the regulation.

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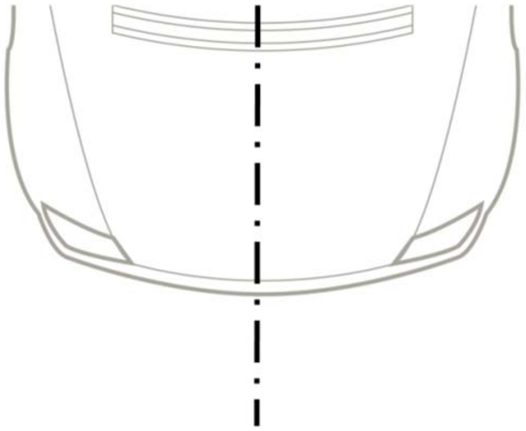
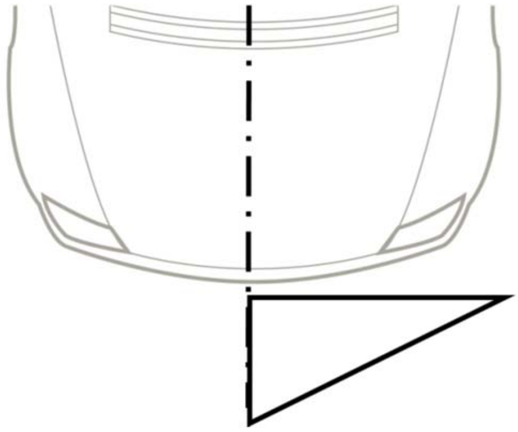
VIII. APPENDIX

Appendix A. Bumper test measuring protocol

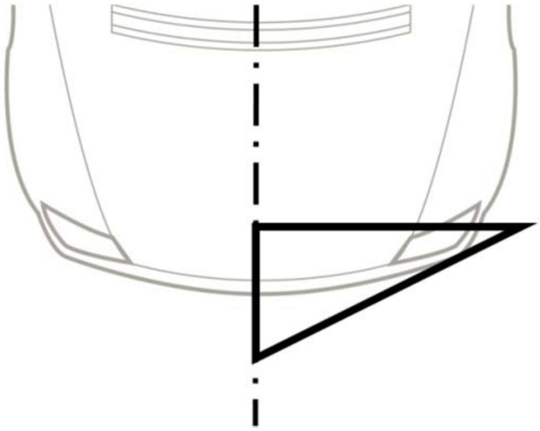
The bumper measuring device was designed to measure the edge of the bumper test zone as defined in GTR 9.



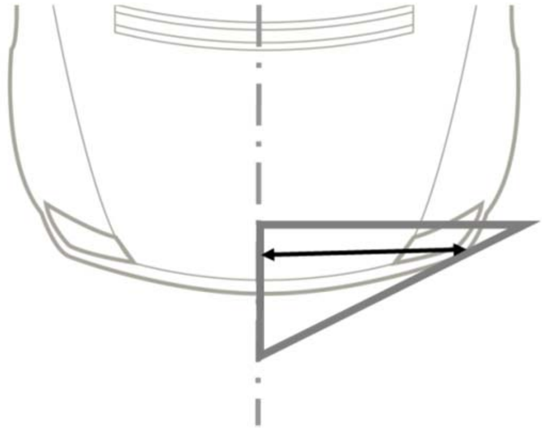
Step 1. Locate longitudinal centerline of vehicle using landmarks on vehicle.



Step 2. Align triangular measuring device with hypotenuse at 60-degree angle to the longitudinal centerline of vehicle.



Step 3. Slide triangle measuring device rearward until first contact is made with bumper.



Step 4. Most outboard location of first contact between measuring device and vehicle is bumper limit; measure and record distance from longitudinal centerline to point of first contact.

Appendix B. Example vehicle shapes and GTR test zone measurements

TABLE B1

SAMPLE OF MEASURED GTR 9 BUMPER TEST ZONES AND VEHICLE WIDTHS FOR NEW VEHICLE STYLES

Vehicle	GTR 9 test zone (cm)	Vehicle width (cm)	GTR zone coverage of vehicle width (%)
2012 Acura TSX	90	184	49
2012 Audi A4	90	182	49
2012 Audi A6	96	187	51
2012 Buick Regal	74	182	41
2013 Chevrolet Malibu	72	185	39
2012 Ford Focus	78	175	45
2012 Honda Accord	86	182	47
2012 Honda CRZ	86	171	50
2013 Lexus GS350	86	184	47
2012 Nissan Leaf	102	174	59
2012 Subaru Impreza	92	173	53
2012 Toyota Camry LE	108	180	60
2012 Volkswagen CC	78	185	42
2012 Volkswagen Jetta	84	173	49
2012 Volkswagen Beetle	90	180	50
2012 Volkswagen Passat	106	180	59
2012 Volvo C30	88	173	51
2011 Volvo S80	100	182	55