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INITIAL ASSESSMENT OF TARGET POPULATION FOR POTENTIAL REDUCTION OF PEDESTRIAN HEAD INJURY IN THE UNITED STATES:

An Estimate Based on PCDS Cases

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Initial Assessment of Target Population for Potential Reduction of Pedestrian Head Injury in the United States:

An Estimate Based on PCDS Cases

Brief Summary of Method

- PCDS cases were sorted according to impact surface
- Impact surfaces were categorized by their scope for improvement, i.e. whether they could be improved to potentially reduce risk to pedestrians
- The number of people in the PCDS database who sustained head injuries against "improvable" surfaces was tallied resulting in an estimate of the "Target Population." The Target Population included pedestrians whose most serious injuries included a head injury that could potentially be reduced with improvements to vehicle design.
- A head injury case is included in our Target Population if a pedestrian's most severe head injury from an impact surface that is considered "improvable" is *at least as severe* as the pedestrian's most severe intractable injury.
- The Target Population derived from the PCDS data was adjusted based on changes in the vehicle fleet since the period during which the PCDS data was collected.
- The Target Population estimate was applied to pedestrian injury statistics for 2002, resulting in an estimated annual number of pedestrian injuries and deaths that could potentially be reduced or prevented by improvement to the structures considered.

Summary of Source Data

The analysis was based on the 550[1] cases in the Pedestrian Crash Data Study [PCDS][2] database. Of these cases, 540 had at least one injury of known severity, and 242[3] had at least one head injury. A total of 761 head injuries are listed in the database. PCDS records the vehicle impact surface for each injury. Table 1 contains a summary of the frequency of head injury from impacts to various surfaces. A large number of these real-world head injuries are a result of impacts to surfaces that are included in the head test procedures that were proposed by the International Harmonization Research Activity (IHRA) Pedestrian Safety Working Group to the UN/ECE/WP29 GRSP pedestrian safety ad hoc group[4] in 2003.

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[1] As per personal communication with Marv Stephens of NCSA, two duplicate cases were excluded from publicly available, 552-case version of database.

[2] Chidester A, Isenberg R. "Final Report on the Pedestrian Crash Data Study," Paper No. 248, ESV 2001.

[3] Head injury included all records coded as REGION90=1, therefore face injuries excluded.

[4] An informal working group within the Transport Division of the United Nations Economic Commission for Europe; WP29 is a world forum for the global harmonization of vehicle regulations

Table 1: Frequency of head injuries by impact surface

Contact Surface/Area	Number of injuries (N=761)	AIS 2-6 injuries (N=481)	AIS 3-6 injuries (N=393)
A-Pillar / Header	85	65	54
Front bumper/Valence	13	12	11
Environment (including ground)	134	61	45
Grille, headlamps, etc.	2	0	0
Hood surface	134	89	69
Areas adjacent to hood[5]	70	39	31
Non-contact	4	4	4
Side, roof, or rear component	22	12	9
Undercarriage	4	2	2
Windshield	293	197	168

Estimation of Target Population from PCDS

The Target Population among all PCDS cases was estimated. This population is the number of PCDS cases that included a head injury from hitting a vehicle component potentially covered by a proposed test procedure that was *at least as severe as* any other head injury, and *at least as severe* as any injury to any other body part. The Target Population, therefore, includes cases where the highest AIS head injury was sustained by striking a surface that could potentially be "improved" by appropriate countermeasures. The Target Population does not include pedestrian cases where the head injury was sustained in an impact not affected by any test procedures, such as with the ground or with the undercarriage of the vehicle. For example, the Target Population would include a pedestrian with an AIS 3 head injury from hood impact, only if the victim did not have any AIS 4-6 head injuries from impacts with the ground, etc. Furthermore, the Target Population would include a pedestrian with an AIS 3 head injury, only if the victim did not have any AIS 4-6 injuries to another body part. Although there is undoubtedly benefit to reducing this pedestrian's head injury severity, the pedestrian is not counted in the Target Population.

Since it is debatable which vehicle surfaces should be included in a test procedure, and which vehicle components could potentially be improved by design or material changes, the Target Population was estimated for a number of different scenarios. The first scenario assumes that only head injuries from impacts to the hood surface can potentially be mitigated. Each subsequent scenario is based on the assumption that additional vehicle components have scope for improvement, resulting in a larger Target Population.

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[5] Including front edge of hood, upper surface of fender, cowl, etc.

Table 2: Definition of each set of vehicle components considered

Scenario	Specific vehicle components included (with corresponding PCDS Injury Source code)
1 – Hood surface	• Hood surface (770) • Hood surface reinforced by under hood component (771)
2 – All the above, plus surfaces adjacent to the hood	• Hood edge and/or trim (703) • Hood ornament (704,705) • Front antenna (721, 741) • Front fender top surface (772) • Cowl area (773) • Wiper blade & mountings (774)
3 – All the above, plus bumper/grille area	• Front bumper (700) • Front lower valence/spoiler (701) • Front grille (702) • Headlight (706) • Retractable headlight door (open/closed) (707) • Turn signal/parking lights (708) • Other front or add on object (718) • Unknown front object (719)
4- All the above, plus A-pillar and Header	• A1 pillar, right (722) • A1 pillar, left (742) • Front header (776)
5 – All the above, plus Windshield	• Windshield glazing (775)

Tables 3-1 to 3-5 list the number of PCDS cases that would be part of the “Target Population” under each scenario. These numbers are also listed as a percentage of the total population of injured pedestrians in PCDS. Results are tabulated for all injuries (AIS 1-6), for moderate injuries (AIS 2-6) and for serious injuries (AIS 3-6), separated by light trucks and vans (LTV) and passenger cars.

Table 3: Target Population in PCDS given various improvement scenarios (Head injuries that could potentially be reduced by vehicle improvement, as a percentage of the total number of injury cases)

(3-1) Scenario one assumes potential injury reduction from impacts to ***HOOD*** only

	LTV (n=170)	Pass Car (n=370)	Total (n=540)
All	11 (6.5%)	23 (6.2%)	34 (6.3 %)
AIS 2-6	10 (10.1%)	16 (7.9%)	26 (8.6%)
AIS 3-6	6 (9.0%)	6 (4.7%)	12 (6.2%)

(3-2) Scenario two assumes potential injury reduction from impacts to ***HOOD AND ADJACENT STRUCTURES:***

Head Injuries	LTV	Pass Car	Total
All	19 (11.2 %)	32 (8.6%)	51 (9.4 %)
AIS 2-6	18 (18.2%)	20 (9.9%)	38 (12.6%)
AIS 3-6	11 (16.4%)	9 (7.1%)	20 (10.3%)

(3-3) Scenario three assumes potential injury reduction from impacts to ***HOOD, ADJACENT STRUCTURES, BUMPER, and GRILLE AREAS:***

Head Injuries	LTV	Pass Car	Total
All	20 (11.8%)	34 (9.2%)	54 (10.0%)
AIS 2-6	18 (18.2%)	22 (10.8%)	40 (13.3%)
AIS 3-6	11 (16.4%)	11 (8.7%)	22 (11.3%)

(3-4) Scenario four assumes potential injury reduction from impacts to ***HOOD, ADJACENT STRUCTURES, BUMPER, GRILLE, A-PILLAR and HEADER AREAS:***

Head Injuries	LTV	Pass Car	Total
All	25 (14.7%)	53 (14.3%)	78 (14.4%)
AIS 2-6	23 (23.2%)	40 (19.7%)	63 (20.9%)
AIS 3-6	15 (22.4%)	24 (18.9%)	39 (20.1%)

(3-5) Scenario five assumes potential injury reduction from impacts to ***HOOD, ADJACENT STRUCTURES, BUMPER, GRILLE, A-PILLAR, HEADER AREAS and WINDSHIELD:***

Head Injuries	LTV	Pass Car	Total
All	35 (20.6%)	106 (28.6%)	141 (26.1%)
AIS 2-6	30 (30.3%)	85 (41.9%)	115 (38.1%)
AIS 3-6	22 (32.8%)	59 (46.5%)	81 (41.8%)

Adjustment of PCDS Target Population to Account for Changing Fleet

PCDS cases include crashes that occurred from 1994 to 1998 (mean 1996.4, median 1996). Vehicle models ranged from 1988 to 1999 (mean 1993.2 and median 1993).

During the period of data collection (1994 to 1998), LTV registrations as a percentage of total registrations increased steadily from approximately 32% to approximately 36%[6] for an average of approximately 34%. By 2001, LTV registrations comprised approximately 38% of the fleet. Sales of LTV's had reached almost 50% by 2001. Given the steady annual increase in registrations and sales of LTV's, an estimate of *current* LTV registrations is 40% and rising. It is reasonable, given sales trends, to predict that *future* LTV registrations will reach 50%.

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[6] "Initiatives to Address Vehicle Compatibility", NHTSA report, June 2003, *www-nrd.nhtsa.dot.gov/departments/nrd-11/aggressivity/IPTVehicleCompatibilityReport/* . Percentages were estimated from bar-chart in this report.

For most scenarios, a higher percentage of the LTV cases in the PCDS database are in the Target Population (i.e. in more of the LTV cases, the most serious injury is a head injury that could potentially be reduced or prevented with vehicle improvements). This difference may, in part, be related to a higher incidence of head-to-hood impacts in LTV impacts than in passenger car impacts. Passenger cars generally have shorter vehicle fronts and hood lengths, and pedestrians impacted by passenger cars have a lower average head impact wrap around distance (WAD) than those impacted by LTV's (Table 4). This combination leads to a higher likelihood that pedestrian impacts on passenger cars will occur beyond the hood. Therefore, the increasing proportion of LTV's in the fleet will change the proportion of pedestrian head injuries that are potentially preventable. The estimates of the total Target Population in Tables 3.1 through 3.5 were adjusted to reflect the expected proportions of preventable injuries given changing LTV presence in the fleet. The resulting adjusted Target Populations are listed in Tables 5.1 through 5.5.

Table 4: PCDS cases with known WAD by vehicle type

Vehicle Type	N	Median (cm)	Mean (cm)
Passenger Car	170	205.5	199.4
Minivan	22	181.5	181.9
Pickup	20	160.5	171.5
SUV	16	152	155.6
Van	6	173	168.2

Table 5: Estimated Target Population - Percentage of injury cases where most serious injury is a head injury that could potentially be reduced or prevented (Given projected proportion of LTV's in vehicle fleet).

(5-1) Scenario one assumes potential injury reduction from impacts to ***HOOD*** only

Head Injuries	PCDS (34% LTV Fleet)	Projected Current (40% LTV Fleet)	Projected Future (50% LTV Fleet)
All	6.3%	6.3%	6.3%
AIS 2-6	8.6%	8.8%	9.0%
AIS 3-6	6.2%	6.4%	6.8%

(5-2) Scenario two assumes potential injury reduction from impacts to ***HOOD AND ADJACENT STRUCTURES:***

Head Injuries	PCDS (34% LTV Fleet)	Current (40% LTV Fleet)	Future (50% LTV Fleet)
All	9.4%	9.7%	9.9%
AIS 2-6	12.6%	13.2%	14.0%
AIS 3-6	10.3%	10.8%	11.8%

(5-3) Scenario three assumes potential injury reduction from impacts to ***HOOD, ADJACENT STRUCTURES, BUMPER, and GRILLE AREAS:***

Head Injuries	PCDS (34% LTV Fleet)	Current (40% LTV Fleet)	Future (50% LTV Fleet)
All	10.0%	10.2%	10.5%
AIS 2-6	13.2%	13.8%	14.5%
AIS 3-6	11.3%	11.8%	12.5%

(5-4) Scenario four assumes potential injury reduction from impacts to ***HOOD, ADJACENT STRUCTURES, BUMPER, GRILLE, A-PILLAR and HEADER AREAS:***

Head Injuries	PCDS (34% LTV Fleet)	Current (40% LTV Fleet)	Future (50% LTV Fleet)
All	14.4%	14.5%	14.5%
AIS 2-6	20.9%	21.1%	21.5%
AIS 3-6	20.1%	20.3%	20.6%

(5-5) Scenario five assumes potential injury reduction from impacts to ***HOOD, ADJACENT STRUCTURES, BUMPER, GRILLE, A-PILLAR, HEADER AREAS and WINDSHIELD:***

Head Injuries	PCDS (34% LTV Fleet)	Current (40% LTV Fleet)	Future (50% LTV Fleet)
All	26.1%	25.4%	24.6%
AIS 2-6	38.1%	37.2%	36.1%
AIS 3-6	41.8%	41.0%	39.6%

The percentages in the above tables represent the percent of injured pedestrians whose most serious injuries are head injuries that could potentially be mitigated. In summary, given the current proportion of LTV's in the US fleet (approximately 40%), the Target Population for head injury reduction as a result of vehicle improvements for pedestrian safety would be between 6.3% (Table 5-1, All Head Injuries) and 25.4% (Table 5-5, All Head Injuries) of all injured pedestrians, depending on the range of vehicle improvements assumed possible. Considering only moderate and worse injuries (AIS 2-6), the Target Population would range from approximately 9% (Table 5-1, AIS 2-6) to 37% (Table 5-5, AIS 2-6) of all injured pedestrians for the current vehicle fleet. This projected Target Population is not dramatically different than the Target Populations calculated based on earlier fleets with fewer LTV's or projected from a future fleet with more LTV's.

Application of Target Population Estimate To Annual Number of Pedestrians Injured

The number of pedestrians in the Target Population was estimated based on National Center for Statistics and Analysis (NCSA) data for 2002,[7] which listed 4,808 pedestrian fatalities and 71,000 pedestrians injured.

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[7] "Traffic Safety Facts 2002, Pedestrians", NCSA, NHTSA, DOT HS 809 614.

Assuming that LTV's comprised approximately 40% of the fleet in 2002, the projected *current* Target Population percentages from Tables 5-1 through 5-5 were applied to NCSA's 2002 injury statistics to estimate how many of the injured pedestrians could potentially have benefited from improved vehicle structures. In Table 6, the Target Population percentages calculated from all severities of injury from the PCDS database (AIS 1-6) were used to estimate the Target Population among all injured pedestrians in 2002, while the Target Population calculated from the serious PCDS injuries (AIS 3-6) were used to estimate the Target Population among the killed pedestrians.

For example, under Scenario 1 in Table 5-1, it was estimated that 6.3 % of pedestrian injuries (AIS1-6) would be within the Target Population given the current fleet of 40% LTV's. That is, 6.3 % of injured pedestrians sustained a head injury from hood contact that was at least as serious as any other injury sustained. This estimate was applied in Table 6 by multiplying the estimated number of pedestrians injured (71,000) by 6.3%, to estimate a Target Population of 4,473 pedestrians with head injuries due to hood contact in 2002.

Table 6: Target Population calculated by applying Target Population percentages from PCDS analysis to NCSA injury statistics from 2002.

	Pedestrians Injured	**Pedestrian Fatalities**
NCSA Statistics 2002	71,000	4,808
Target Population in 2002: *Based on projected fleet estimate of 40% LTV*	*Based on Target Population calculated from all PCDS injuries (AIS 1-6)*	*Based on Target Population calculated from serious PCDS injuries (AIS3-6)*
Scenario 1	4,473	308
Scenario 2	6,887	519
Scenario 3	7,242	567
Scenario 4	10,295	976
Scenario 5	18,034	1,971

This analysis shows the potential number of pedestrians that could be affected annually by improvements in vehicle structure. The magnitude of this Target Population depends on which vehicle components could potentially be improved by design or material changes. By the most conservative evaluation, assuming that only head injuries from direct impact to the hood can be mitigated, the Target Population is estimated to be 4,473 pedestrians, including 308 fatalities. Assuming that a test procedure could, in fact, result in improvements to a very wide variety of vehicle components, the benefits could potentially affect as many as 18,034 pedestrian head injuries including 1,971 fatalities.

Limitations of Method

This estimate of Target Population was intended as a "back-of-the-envelope" estimate. It is limited by the following assumptions and shortcuts:

- It is assumed that the PCDS cases are representative of the population of pedestrian injuries. In particular, it is assumed that the percentage of head impacts to "improvable" surfaces in all injury cases is the same as that in the US population, and that the percentage of impacts to "improvable" surfaces in the AIS 3-6 head injury cases are the same as in US pedestrian fatalities.

- Given the year range of the vehicles in the PCDS database, and the change in vehicle profiles since that time, it is likely that today's fleet has different percentages. Although this is partly accounted for by adjusting for SUV and Light truck fleet increases, even the shape of LTV's and SUV's have changed since that time.
- Although head injured pedestrians obviously benefit from head injury reduction even if they injure other body parts more seriously, this benefit is neglected in this Target Population analysis.
- It is customary in benefit calculations to only count 50% of an injury benefit if there is another "unsavable" injury of the same AIS level. Although this analysis does not count injury benefit if there is another injury of higher AIS level, this analysis did not account for cases where there was an injury of the same AIS level. That omission likely means the final estimate is probably more liberal than it would be if done in the customary way.

COMPONENT LEG TESTING OF VEHICLE FRONT STRUCTURES

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ABSTRACT

Current and proposed pedestrian test procedures in Europe and Japan evaluate lower extremity injury risk by using a projectile legform to impact the bumper of a stationary vehicle. Although there are no pedestrian regulations in North America, bumper design is affected in both the United States and Canada by regulations limiting damage in low-speed impact testing. The main objectives of this study were to (1) evaluate differences in instrumentation capability and kinematic response of two pedestrian legforms (FlexPLI 2004, TRL), and (2) determine if and to what extent vehicles designed to conform to North American bumper regulations are more aggressive toward pedestrians than similar vehicles designed to conform to European bumper impact requirements. The results indicated that none of the North American bumpers were able to achieve the level of pedestrian lower leg protection required by future European Union regulations. It was also found that both legforms have limitations in testing the North American bumpers. The bumpers damaged the FlexPLI legform in repeated tests and exceeded the measurement limits of the TRL legform.

INTRODUCTION

On average, 374 pedestrians and 55 cyclists are fatally injured in Canada every year, making up 14.9% of fatalities among all road users (5-year average 1999-2003) [1]. In the United States, 4,749 pedestrians and 622 cyclists were killed in 2003, comprising 12.6% of all motor vehicle-related fatalities [2]. Combined international statistics from the United States, Europe and Japan indicate that approximately 30% of moderate to catastrophic pedestrian injuries involve the lower extremities, with the front bumper identified as injury source for the majority of those injuries [3]. Transport Canada is investigating whether its bumper regulation is detrimental to the safety of pedestrians. Because bumper designs for the Canadian market are largely similar or identical to those sold in the United States, this research has potential implications for all vehicles in the North American fleet.

The Canadian Motor Vehicle Safety Standard (CMVSS) 215 for bumpers is based on a series of 8 km/h longitudinal impacts and 4 km/h corner impacts after which the safety systems of the vehicle have to function as intended [4]. The United States CFR 49 Part 581 standard and the United Nations Economic Commission for Europe Regulation No. 42 (ECE R42) have lower impact speeds, with longitudinal impacts conducted at only 4 km/h. Both regulations apply only to passenger cars. The U.S. criteria are for no cosmetic or safety system damage, whereas the European requirements are for no damage to safety systems only. Thus, Canada’s higher test speed and the broader U.S. damage limitations make the bumper damage criteria in both countries different from the European requirements. Research and testing was deemed necessary to determine if bumpers designed to meet the North American bumper regulations are more aggressive toward pedestrian lower extremities than their European counterparts designed to meet UN ECE Regulation No. 42.

The European New Car Assessment Program (EuroNCAP) includes pedestrian testing to assess aggressiveness of vehicle frontal areas [5]. The procedure calls for a free-flight bumper impact at 40 km/h with a legform developed by the Transport Research Laboratory (TRL Limited, Berkshire, UK). This legform is a simplified device that approximates human anthropometry while using frangible steel knee ligament surrogates designed to deform plastically during impact [6]. The legform’s instrumentation allows it to measure tibia acceleration, shear displacement, and bending angle at the knee.

European Union regulations specify tests relating to the protection of pedestrians and other vulnerable road users in Directive 2003/102/EC [7]. The procedure includes tests for legform to bumper evaluation, as well as for head impact testing and leg to bonnet edge testing. The lower legform to bumper test performed at 40-km/h limits maximum dynamic knee bending angle to 21 degrees, maximum dynamic knee shearing displacement to 6 mm and acceleration at the upper tibia to 200 g. Although the TRL legform is not explicitly named in the directive, the required injury measures correspond exactly to the values that the TRL legform is equipped to measure.

The FlexPLI 2004 has been more recently developed by the Japanese Automobile Research Institute (JARI). This legform has been described to have improved biofidelity over the TRL legform as well as increased instrumentation capabilities [8]. This device is more complex than the TRL legform, with 14 hollow cylindrical steel segments along its length that surround two surrogate bone cores representing the femur and the tibia. These cores are made of glass reinforced plastic (GRP) and are equipped with strain gauges mounted at defined locations. The FlexPLI is also equipped with four cabled surrogate ligaments at anthropometrically accurate locations within the knee structure. It is designed to be completely non-frangible, and it is able to measure bending moments in the upper and lower segments as well as knee ligament displacements and individual segment accelerations.

The objective of this study was to use the TRL and FlexPLI legforms to assess the pedestrian aggressiveness of a sample of North American model bumper systems and then compare those systems to their European counterparts.

METHODS

Pedestrian lower extremity testing was performed by impacting the front bumpers of five different passenger car models with projectile legforms. All bumpers in the test series were tested using a TRL legform impactor. Selected bumpers were also tested using the FlexPLI 2004.

Legforms were launched in this test series by a carriage mounted to a hydraulic linear ram. During acceleration, the legforms were suspended from a pin at the top of the carriage and supported horizontally by padded fixtures mounted on the carriage adjacent to the upper leg and the lower leg (Figure 1).

Figure 1. Test setup.

Legform acceleration to free-flight speed was achieved over a distance of approximately 24 cm for the TRL legform and 28 cm for the FlexPLI legform. Legform height at the time of impact with the bumper was such that the bottom of the legform was within ±10 mm of ground reference level, which is defined as the horizontal plane that passes through the lowest points of contact for the tires of the vehicle in normal ride attitude. As defined in the EuroNCAP procedure, the legform was vertical in the sagittal and coronal planes and aligned about the z-axis so that the lateral side of the legform contacted the bumper.

Target impact speed was 11.1 ± 0.2 m/s (40 ± 0.7 km/h) for all testing with the TRL legform. Target impact speed for the FlexPLI legform was initially the same as for the TRL legform but reduced in subsequent tests to 8.3 ± 0.2 m/s (30 ± 0.7 km/h). Velocity was measured by integrating upper tibia acceleration data.

The TRL legform was equipped with angular displacement transducers in the lower femur and upper tibia components that allowed calculation of shear displacement and bending angle in the knee [6]. Tibia acceleration was measured by a 500 g uniaxial accelerometer mounted on the non-impact side of the upper tibia. The FlexPLI's instrumentation consisted of 3 pairs of strain gages mounted on the thigh bone core, 4 pairs of strain gages mounted on the lower leg bone core, and three linear potentiometers across the knee joint. The strain gages were used to measure bending moments along the length of the femur and tibia, while the knee potentiometers measured stretch of the ACL, PCL, and MCL ligaments. In addition to this standard instrumentation, a uniaxial accelerometer was mounted on the non-impact side of the FlexPLI's upper tibia. All data was sampled at 20 kHz, pre-filtered at 3 kHz, then filtered using CFC 180 (300 Hz). Lateral and overhead high-speed video documented the tests at 1000 frames per second.

The five vehicles tested were the following North American models:

- 2000 Volvo S40
- 2001 Ford Focus
- 1999 Volkswagen Beetle
- 2001 Honda Civic
- 2002 Mazda Miata

All vehicles were purchased in the United States and selected because the corresponding European models of each one had been previously evaluated in EuroNCAP pedestrian testing. These vehicles have similar bumper systems in Canada and in the U.S.

In total, 28 impact tests (23 with TRL, 5 with FlexPLI) were conducted in this study (Table 1).

Table 1.
Test matrix (impacts at full speed unless noted otherwise)

Vehicles	TRL		FlexPLI	
	Center	Lateral	Center	Lateral
Volkswagen Beetle	2	3	--	--
Mazda Miata	2	3	--	1[A]
Ford Focus	2	3	--	--
Volvo S40	2	2	1[A]	2[A]
Honda Civic	2	2	--	1

[A] Tests were done at 30 km/h

Bumper impacts were targeted at the areas near the left and right side bumper supports and centrally at the bumper midline. Figure 2 illustrates the impact points on each vehicle bumper. The locations of the off-center (hereafter referred to as "lateral") impacts on each vehicle were symmetrical about the vehicle centerline. No impact points were within 65 mm of the bumper corner, as defined in the EuroNCAP procedure. Tire pressure was set according to manufacturer's instructions. The emergency brake was engaged. No additional ballast was added to the vehicle weight. Tests were performed at all three locations before replacing the entire bumper system.

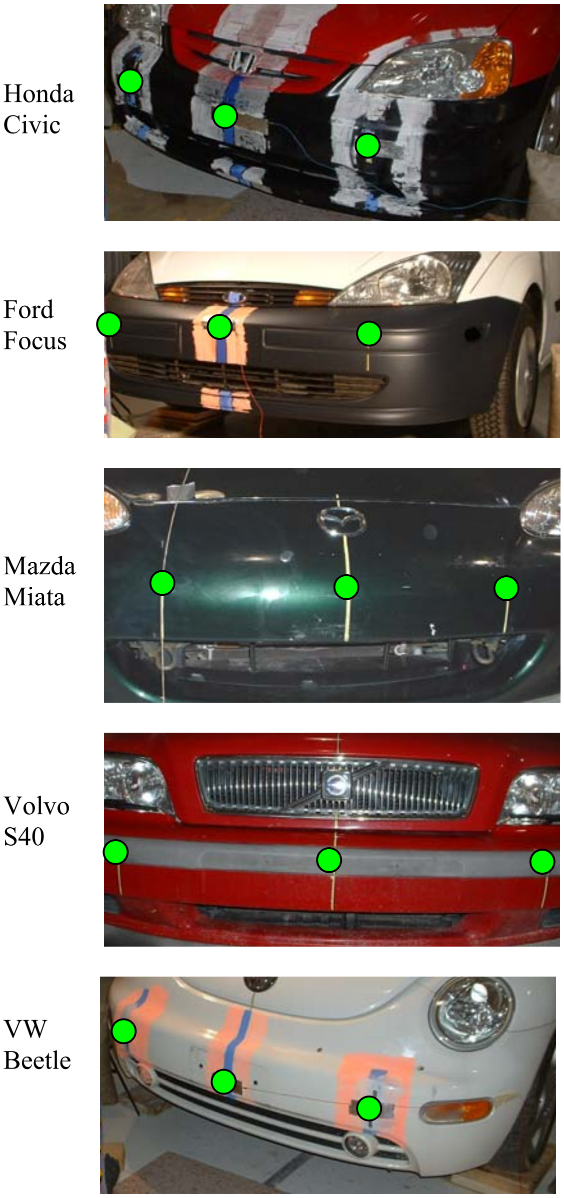

Figure 2. Impact points on each bumper system.

External inspection of the bumper systems for damage was done immediately following each test, and internal inspection was performed after bumper replacement. Post-test inspection of each legform was carried out according to manufacturer's instructions.

RESULTS

TRL Legform Impacts

Kinematics during the first 20 milliseconds after impact are shown in Figure 3. These video frames show the moment of initial contact between the lateral side of the legform and the bumper, followed by the legform's position 10, 15, and 20 milliseconds after impact. Initial interaction between the bumper and the legform is visible at 10 milliseconds when the legform tends to follow the contour of taller bumpers that are more rounded (such as the Ford Focus and Mazda Miata) while narrower or more angular bumpers (such as the Volkswagen Beetle or Volvo S40) tend to produce a more pronounced bend at the knee.

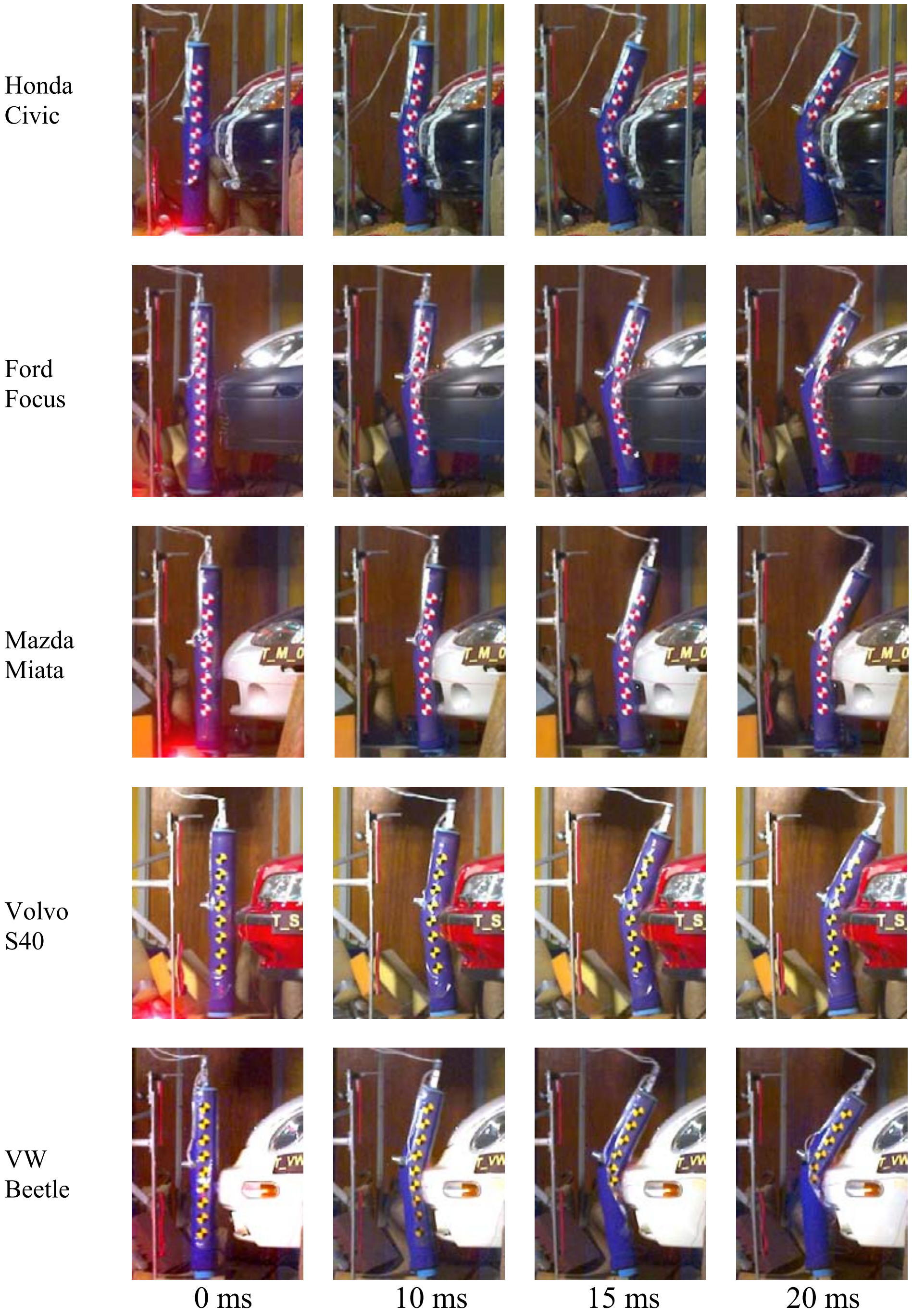

Figure 3. Kinematics of TRL legform for five vehicles.

At 15 milliseconds, the effect of lower bumper shape on lower leg motion is visible. By this time, the tibia component of the legform has reached its maximum forward angle against the inward slanted lower bumpers of the Ford Focus and the Honda Civic. The more vertical front face of the Mazda Miata bumper has limited the bending of the knee even more than the Ford Focus or Honda Civic bumpers. The legforms impacted into the Volvo S40 and Volkswagen Beetle bumpers have not yet impacted the lower bumper structures at 15 milliseconds and are still free to wrap under the bumper and increase knee bending angle. The frame at 20 milliseconds represents the approximate time of maximum bending for each legform as the femur component reaches the grille or hood area. The vehicles with more upright grille or hood structures appeared to limit forward femur movement the most, effectively limiting knee bending.

Post-test inspection of the TRL legform revealed no major structural damage after any of the tests. Instrumentation damage that required repair between tests was limited to a torn femur potentiometer wire and a displaced tibial potentiometer shaft that was press fit back in place. Neither affected the usable portion of data. Deformed frangible knee ligaments were replaced after each test.

In most tests, the vehicle and bumper systems showed either no damage or damage limited to fine scuffing, scratching, or cracking of the paint related to contact with the legform or instrumentation. No deformation was found to the internal bumper structures or energy absorbing elements.

Impact speed measured in the TRL legform tests was 10.9 ± 0.2 m/s, which was slightly slower than the nominal target range of 11.1 ± 0.2 m/s. Orientation of the legform at impact was as specified according to review of lateral and overhead high-speed video.

For each test, upper tibia acceleration, knee shear displacement, and knee bending angle were measured. In all tests, peak values of these measures were recorded in the first 30 milliseconds after bumper contact. Time histories for acceleration, shear displacement, and bending angle are shown for typical impacts with each vehicle in Figures 4 through 6.

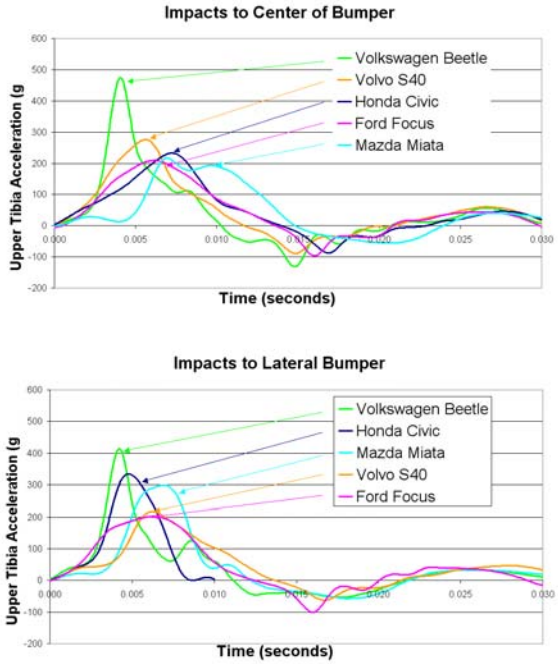

Figure 4. Upper tibia acceleration.

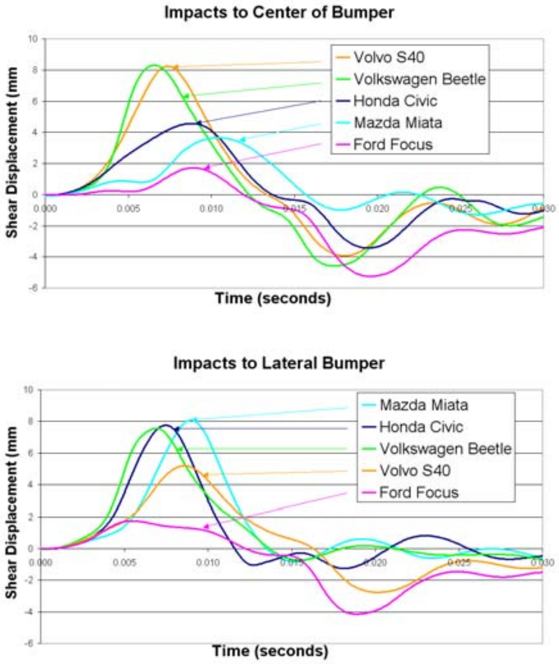

Figure 5. Knee shear displacement.

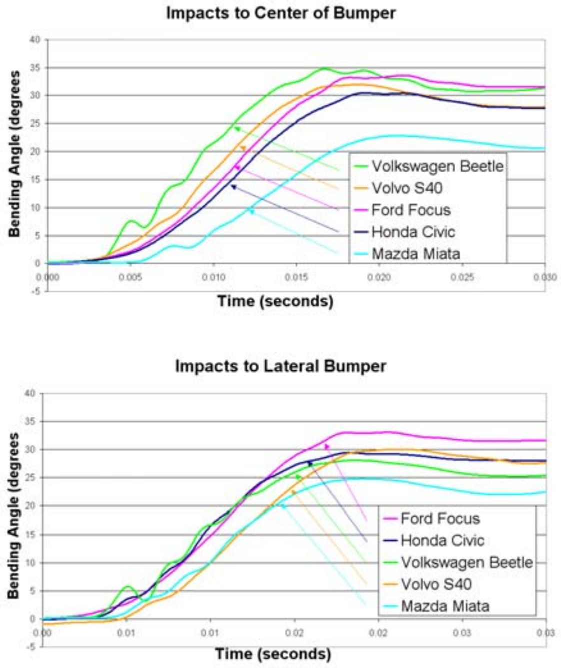

Figure 6. Knee bending angle.

Although the bending angle measurements shown in Figure 6 indicate peak bending angles in excess of 30 degrees, the limit of bending angle accuracy for the TRL legform is considered to be 30 degrees because of contact between the tibial and femoral components at this angle [9]. Subsequent to that contact at a knee bending angle of approximately 30 degrees, resistance to bending is expected to increase. Although measurements above 30 degrees are expected to correspond to progressively worse actual bending angles, the exact value of any peaks above 30 degrees is uncertain.

Two center-bumper impacts and two or three lateral-bumper impacts were performed for each vehicle. No significant variation was found between left-sided and right-sided impacts or between impacts performed on an untested bumper versus impacts into a bumper tested previously in a different location. Repeatability analysis of injury measures for testing on vehicles for which three lateral impacts were performed showed coefficients of variation ranging from 2% to 15%. Because of this range of test result variation, comparisons between bumpers were made using averaged values of peak injury measurements for all center impacts to each vehicle (Table 2) and for all lateral impacts for each vehicle (Table 3).

Table 2.
Average peak injury measures for all center-bumper impacts.

Vehicle	Average Peak Acceleration (g)	Average Peak Bending Angle (degrees)	Average Peak Shear Displ. (mm)
Ford Focus	195.0	33.4	-4.9
Honda Civic	221.4	31.0	4.7
Mazda Miata	208.8	24.7	3.4
VW Beetle	461.9	34.7	8.3
Volvo S40	262.9	31.1	8.2

Table 3.
Average peak injury measures for all lateral-bumper impacts.

Vehicle	Average Peak Acceleration (g)	Average Peak Bending Angle (degrees)	Average Peak Shear Displ. (mm)
Ford Focus	209.3	32.3	-3.8
Honda Civic	368.5	30.7	7.7
Mazda Miata	264.3	25.1	7.4
VW Beetle	464.2	29.1	8.2
Volvo S40	246.0	30.2	6.2

Figures 7 through 9 compare the averaged peak values for each vehicle and impact location to European Union requirements [7] and to the more stringent and less stringent performance limits used to rate vehicles in the EuroNCAP point system. In the EuroNCAP system, injury measurements meeting the more stringent limit receive 2 points, measurements between the two limits receive an interpolated point value, and measurements exceeding the less stringent limit earn 0 points [5]. The total point value awarded for an individual test is equal to the lowest of the calculated acceleration, bending and shear point values. The point values for three lower extremity tests are added to the point values earned in head impact and upper leg press tests to calculate the vehicle's overall pedestrian star rating.

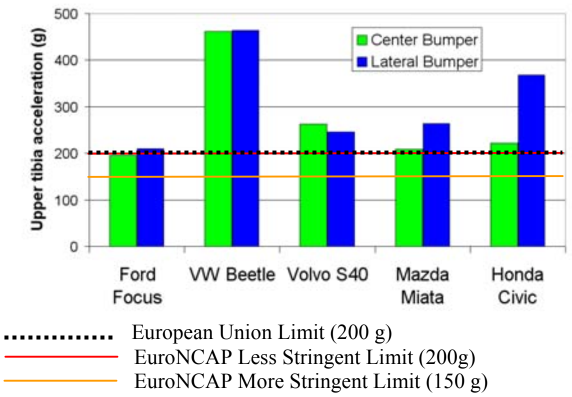

Figure 7. Peak upper tibia acceleration

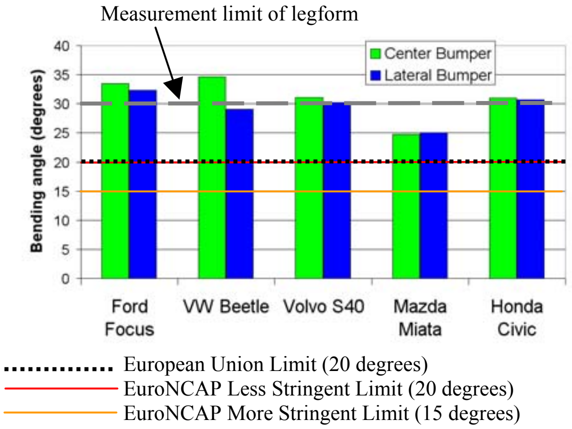

Figure 8. Peak knee bending angle averaged for all impacts at each location.

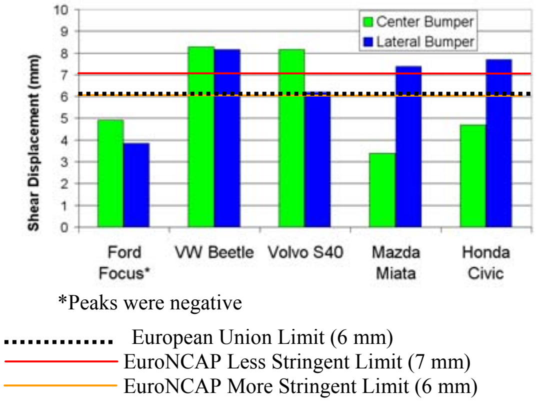

Figure 9. Peak knee shear displacement averaged for all impacts at each location.

Since no impacts in the current series produced a bending angle lower than the less stringent limit of 20 degrees, the bending angle point value for all tests would be zero. Therefore, all impacts in this series would result in overall EuroNCAP lower extremity point values of 0. In order to compare the performance of the tested vehicles in the current study to each other, rather than to vehicles previously tested under EuroNCAP procedures, a modified version of the EuroNCAP point system was used. Under the modified point system, point values were interpolated between 2 and 1 for injury measurements between the EuroNCAP less stringent and more stringent limits, and interpolated between 1 and 0 for injury measurements that exceeded the EuroNCAP less stringent limit but were less than double that limit. For example, an injury measurement that exceeded the less stringent limit by 50% earns 0.5 points while an injury measure that was two times that limit would earn 0 points. Modified point values calculated for the averaged results at each vehicle location are listed in Table 4.

Table 4 shows that by the modified EuroNCAP point system the Mazda Miata bumper (0.76 center and 0.68 lateral) was least aggressive toward pedestrian legforms. It was followed in order of increasing aggressivity by the Volvo S40 (0.49 lateral and 0.45 center), the Honda Civic center bumper (0.45), the Ford Focus (0.38 lateral bumper and 0.33 center bumper), the Honda Civic lateral bumper (0.16), and the Volkswagen Beetle (0.0 lateral and center).

Table 4.
Modified point values earned for each injury measurement, averaged for each vehicle/location (final overall modified score in *italic bold*)

Vehicle	Location	Upper Tibia Accel.	Bending Angle	Shear Displ.
Ford	Lateral	0.95	***0.38***	2
Focus	Center	1.90	***0.33***	2
Honda	Lateral	***0.16***	0.46	0.9
Civic	Center	0.89	***0.45***	2
Mazda	Lateral	***0.68***	0.75	0.95
Miata	Center	0.96	***0.76***	2
VW	Lateral	***0***	0.55	0.83
Beetle	Center	***0***	0.27	0.82
Volvo	Lateral	0.77	***0.49***	1.12
S40	Center	0.69	***0.45***	0.83

Of the three EuroNCAP injury criteria, shear displacement was the easiest for the vehicles to meet. The Ford Focus (both lateral and center), Honda Civic (center), and Mazda Miata (center) all met the more stringent shear displacement requirement of 6 mm and no other impact locations resulted in a modified score lower than 0.82.

Bending angle was the most difficult limit to meet, with no impact location achieving a modified score above 0.75. The widest range of modified scores was in tibia acceleration, from a score of 0 by the Volkswagen Beetle in both the center and lateral locations to 1.90 by the Ford Focus at the center location.

The impacts at each vehicle location were also evaluated against limits defined in the European Union directive 2003/102/EC. The maximum acceleration limit of 200 g was exceeded for all impact locations except the center bumper of the Ford Focus, which produced upper tibial acceleration of 195 g. The 21-degree bending angle limit was exceeded for center and lateral impact locations for all vehicles tested. The Ford Focus was the only vehicle tested to remain under the maximum shear displacement angle of 6 mm for both center and lateral impacts, while the Mazda Miata and Honda Civic were able to stay below that limit for the center bumper location only. The Volkswagen Beetle and Volvo S40 shear values were over the limit at both locations.

FlexPLI Legform Impacts

Five bumper impacts were performed with the FlexPLI legform: one impact to the Honda Civic at full speed (nominally 40 km/h or 11.1 m/s as in the TRL tests), one to the Mazda Miata at a reduced nominal target speed of 8.3 m/s (30 km/h) and three to the Volvo S40, also at a target speed of 8.3 m/s. The legform sustained damage in the Honda Civic test, necessitating the reduction in speed. It was also damaged in the Mazda Miata test and the third Volvo S40 test at the lower speed.

Kinematics of the FlexPLI are shown for tests into the lateral bumper of the Honda Civic, Mazda Miata, and Volvo S40 in Figure 10. The frames at 10 to 20 milliseconds show the knee end of the femur, and to a lesser extent the tibia, bending away from the bumper after contact in the knee area. The resulting convex curvature of the thigh and leg away from the bumper is followed by concave curvature toward the vehicle by 20 to 30 milliseconds after contact. As the knee flexes around the front of the vehicle, the upper and lower leg segments also bend, essentially wrapping under the bumper and around the hood leading edge. The lower leg bending appears greater for the Honda Civic and Volvo S40 bumpers where their recessed lower structures allow the lower leg to wrap under the bumper. The more flat-faced Mazda Miata bumper restricts tibial bending below the bumper structures. The upper leg bending appears most limited by the Volvo S40 bumper, which has a more upright grille area than the other vehicles.

Post-test inspection of the FlexPLI legform showed major damage following three tests. After the impact into the right lateral bumper of the Honda Civic at 40 km/h, routine inspection of the tibial bone core showed an anterior-posterior crack through the tibial bone core. Dismantling of the lower leg structures revealed that the linear crack started at the top of the tibia, but did not extend down to the bottom of the bone.

A replacement FlexPLI legform underwent two subsequent tests into the lateral and center bumper of a Volvo S40 at a reduced speed of 30 km/h without sustaining damage. A third impact into the lateral bumper of the Volvo S40 produced a small crack in the distal femoral bone core. A final impact into the lateral bumper of the Mazda Miata, also at reduced speed, resulted in an additional fracture of the tibial bone core.

Time histories of the moments measured at each level in the thigh and lower leg are shown for the first impact into the Volvo S40's lateral bumper impact location at reduced speed (Figures 11 and 12). Positive moment in the leg and thigh corresponds to moment that produces concave lateral bending, as when the femur wraps around the hood leading edge or the tibia wraps under the bumper. Negative moment corresponds to moment that produces convex lateral bending, as when the knee is initially pushed medially.

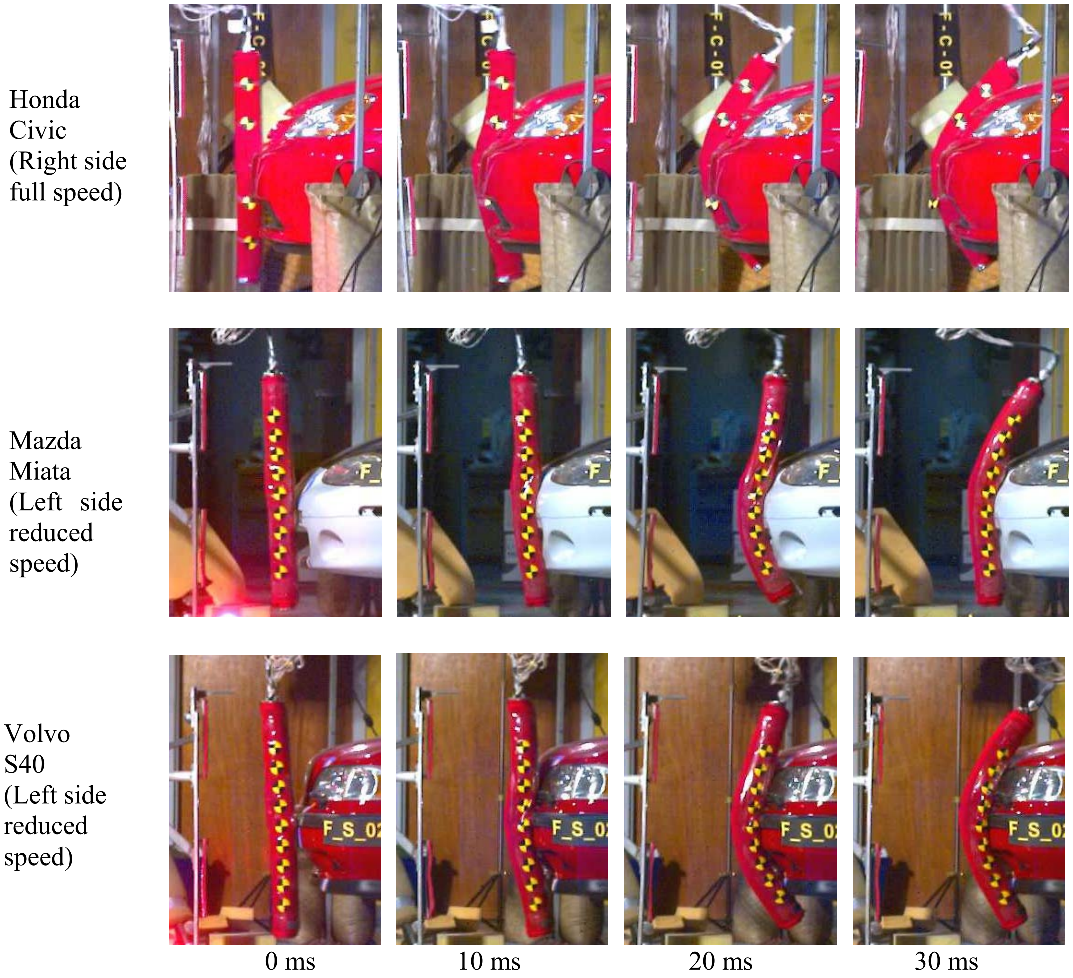

Figure 10. Kinematics of FlexPLI legform for three vehicles.

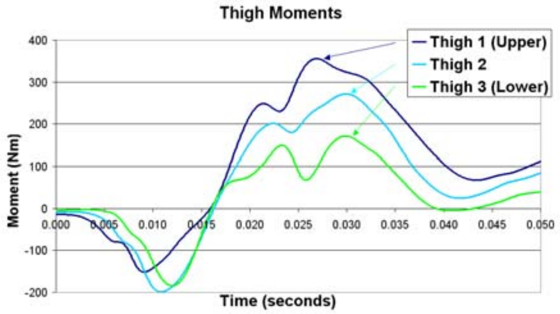

Figure 11. Thigh bending moments for right lateral impact into Volvo S40 bumper at reduced speed.

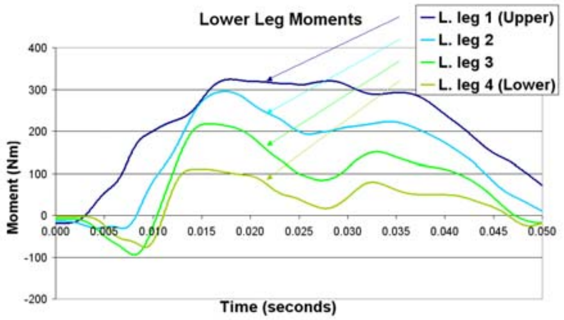

Figure 12. Lower leg moments for right lateral impact into Volvo S40 bumper at reduced speed.

Figures 13 and 14 compare the peak magnitude of moments measured in all tests performed with the FlexPLI. In all tests run with the FlexPLI, the peak positive moments were greater in magnitude than the peak negative moments in the leg and for the upper two moment sensors in the thigh. In the lowest moment sensor in the thigh, positioned closest to the knee, negative moment was greater in magnitude than positive moment. Peak bending moment in the thigh tended to be greatest for sensors further from the knee, while peak bending moment in the lower leg tended to be greatest for sensors closer to the knee. Values are compared to preliminary proposed injury limits for the FlexPLI legform [10]. The full-speed Honda Civic test and the reduced speed Volvo S40 tests all exceeded the moment limit at the upper thigh sensor, while the Mazda Miata was within moment injury limits in the thigh. In the lower leg, the only measurement to exceed the injury limit was the bending moment adjacent to the knee in the final Volvo S40 test.

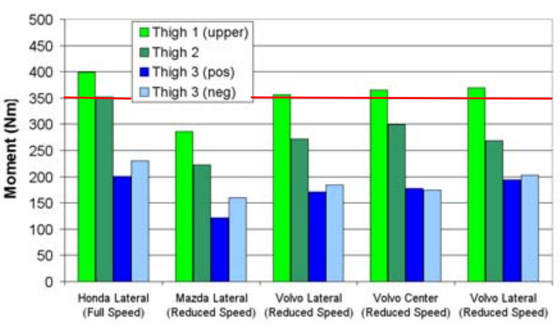

Figure 13. Thigh moments for all impacts with FlexPLI legform (proposed injury limit of 350 Nm).

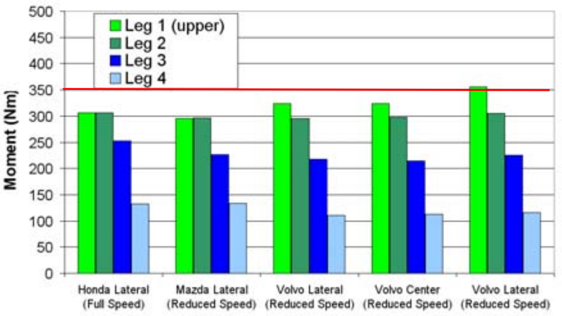

Figure 14. Lower leg moments for all impacts with FlexPLI legform (proposed injury limit of 350 Nm).

Displacements of the potentiometers representing knee ligament extension are shown for the example impact with the Volvo S40 bumper in Figure 15 and compared for all tests in Figure 16. The full-speed Honda Civic test exceeded the proposed injury limits for two of the three ligaments. Among the reduced speed tests, the Mazda Miata exceeded limits for the ACL, and the Volvo S40 exceeded the ACL and MCL limits on all tests.

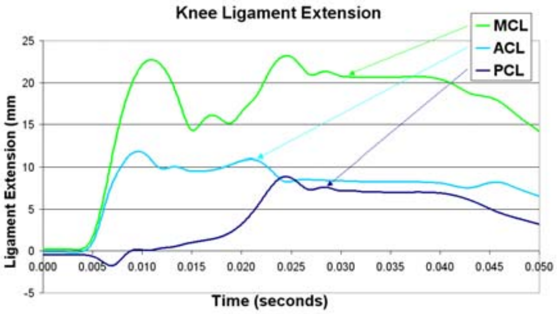

Figure 15. Ligament extension for right lateral impact into Volvo S40 bumper at reduced speed.

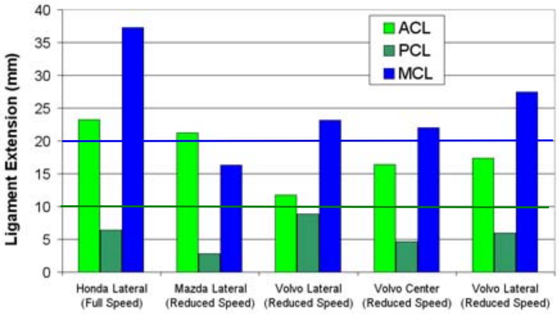

Figure 16. Ligament extensions for all impacts with FlexPLI legform (proposed injury limits of 20 mm for MCL and 10 mm for ACL and PCL).

Upper tibial acceleration is shown for the example impact with the Volvo S40 bumper in Figure 17, and compared for all tests in Figure 18. No injury limits have been proposed for acceleration of the FlexPLI legform.

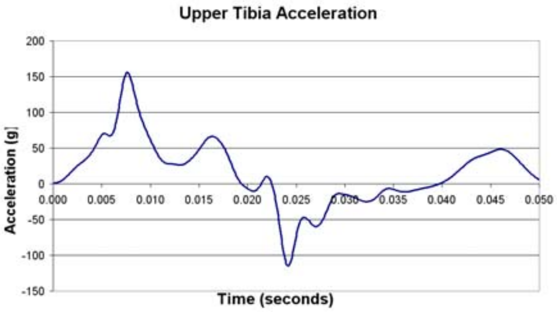

Figure 17. Upper tibia acceleration for right lateral impact into Volvo S40 bumper at reduced speed.

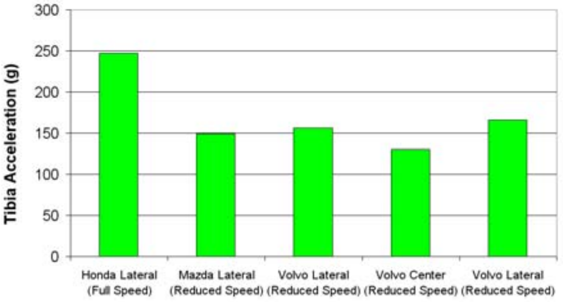

Figure 18. **Upper tibia acceleration for all impacts with FlexPLI legform (no injury limit proposed).**

DISCUSSION

Evaluation of TRL and FlexPLI Legforms

Figures 3 and 10 show the marked difference between how the TRL and FlexPLI legforms interact with the vehicles. The single-jointed TRL bent only at the knee while the FlexPLI's flexible femur and tibial elements allowed it to wrap around the front of the vehicle. This difference in how the legforms conform to the vehicle shape is likely to affect not only the magnitude of bending angle at the knee but all injury measures. Variations in the shape of the bumper, grille, and hood leading-edge structures may have a different effect on injury measures recorded by one legform than they do on the other legform.

The knee shear displacement and knee bending angle calculated using rotary potentiometers by the TRL legform relate directly to physiologic measurements for which known biofidelity corridors exist [11, 12]. These quantities, along with upper tibial acceleration, are the only measurements made by the TRL legform. The simplicity of the instrumentation system contributes to its reliability and the lightness of its wiring umbilical helps to maintain the leg's orientation during free flight.

The instrumentation in the FlexPLI 2004 includes moment measurements along the flexible femur and tibia components as well as injury measurements at the knee joint. This additional information may allow better understanding of how specific structures on the upper or lower vehicle front interact with a pedestrian lower extremity and also offer insight into injury potential of the long-bones rather than just the knee. Although the additional instrumentation in the FlexPLI increases the potential for damage to wiring and loss of data, the pairs of strain gauges mounted to the bone cores allow redundant data to be collected at each level, reducing the risk of lost data as a result of wiring damage. Unfortunately, this built-in redundancy further increases the number of wires in the legform's umbilical and makes it difficult to maintain perfect orientation during free-flight. An onboard data acquisition system may be a useful feature for any free-flight legform.

Both legforms tested in this study were designed outside of North America and had limitations for testing vehicles from the North American market. The FlexPLI legform fractured when used with North American vehicles at 40 km/h or even at a reduced speed of 30 km/h. The bone core elements fractured in three of five tests. The core fractured even before reaching the proposed injury limit for bending moment in two of those three tests that produced fracture.

Although the TRL legform withstood the testing without structural damage, its bending limits were exceeded, restricting measurement of peak values. Peak values of all injury measures were likely affected since this mechanical bending limitation affected the motion of the legform rather than simply its ability to measure the motion.

Comparison of North American and European Bumpers

Comparison of North American and European versions of the specific vehicles tested is possible because the North American vehicles selected for this study corresponded to European vehicles previously tested under EuroNCAP procedures. Although there were minor differences in the launch procedure for the current study from the EuroNCAP procedure, the tests are essentially comparable. The slightly slower than targeted impact speed in the current study makes the comparison conservative in that the current tests were slightly less demanding than the comparison EuroNCAP tests.

The bumpers tested in EuroNCAP procedures were subject to European bumper damage regulations while those tested in the current study were subject to North American bumper standards. However, EuroNCAP results for the European versions of the vehicles tested showed that lower leg pedestrian test performance was not consistently better for the European versions of these same five vehicles. In fact, only the European Honda Civic and Volvo S40 scored any EuroNCAP points in the legform to bumper tests. Table 5 contains peak measurements made for EuroNCAP data for vehicles in the same model year range as the vehicles in this test study

[13]. These peaks are compared to the corresponding peak measurements in the currently reported tests on the North American models in Figures 19 to 21.

Table 5.
Peak Measurements in EuroNCAP testing of European models of test vehicles.

	Test No.	Upper Tibia Accel	Bend Angle	Shear Displ.	Euro NCAP Points
1999	1	536.7	33.3	6.6	0
Ford	2	483.7	34.2	8.0	0
Focus	3	542.7	33.6	5.8	0
2001	1	116.4	7.1	1.9	2
Honda	2	97.7	7.0	2.3	2
Civic	3	189.6	20.7	2.1	1.01
2002	1*				0
Mazda	2	278.1	32.9	4.3	0
MX-5 / Miata	3	351.1	30.6	6.8	0
1999	1	416.0	31.4	7.0	0
VW	2	520.0	29.8	7.4	0
Beetle	3	470.0	27.7	7.0	0
1997	1	231.0	33.7	7.4	0
Volvo	2	220.0	30.5	7.5	1
S40	3	180.0	32.8	7.0	0

* No Mazda impact was performed at site 1 because identical to site 3.

The North American Ford Focus performed better than its European counterpart in terms of shear displacement and tibia acceleration, while the European and North American Ford Focus both exceeded the 30-degree bending angle limit of the TRL legform. The North American Mazda Miata's performance was better than the European model in both bending angle and upper tibial acceleration. Peak measurements made on the North American Volkswagen Beetle and Volvo S40 were comparable to those made in tests of their European models. The European version of the Honda Civic performed dramatically better in lower leg testing than the North American model. In fact, Honda peak injury measurements were lower in every test than in any of the other North American vehicles tested in this study.

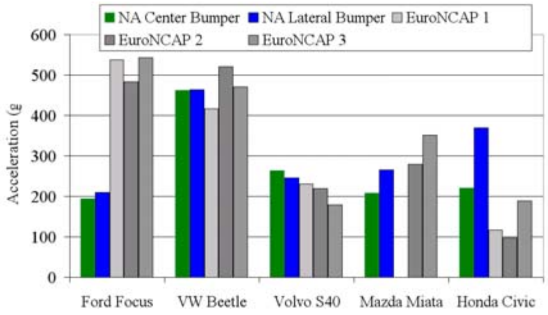

Figure 19. Peak average upper tibia acceleration for North American models compared to European models.

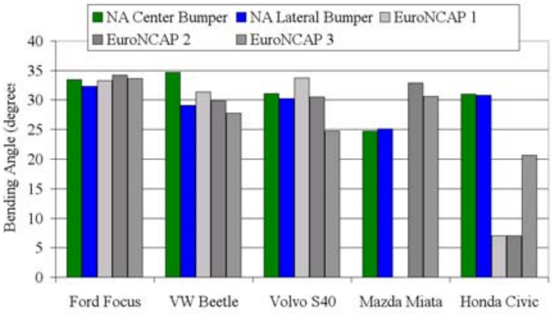

Figure 20. Peak average knee bending angle for North American models compared to European models.

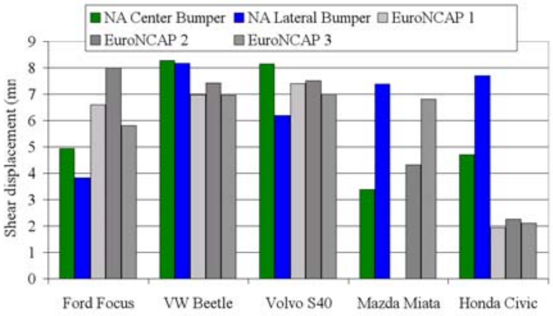

Figure 21. Peak average knee shear displacement for North American models compared to European models.

The similar performance of the Volkswagen and Volvo vehicles compared to European versions suggests that there may not have been significant differences in the international versions of their front bumper systems. The better performance of the North American Ford Focus and Mazda Miata over their European counterparts and the European Honda Civic over its North American counterpart suggests that bumper design differences exist between the international versions of these vehicles.

The European models of the Volvo S40, Volkswagen Beetle, Ford Focus, and Mazda Miata did not appear to offer better pedestrian leg protection than the North American models of those vehicles in spite of the fact that the European vehicles were required to meet different bumper damage requirements than the North American versions. In contrast, the European 2001 Honda Civic showed much improved pedestrian leg protection over the North American Honda Civic in the same year range. Given that the European vehicles tested were not yet required to meet the upcoming European Union pedestrian safety requirements, the better performance of the European 2001 Honda Civic may reflect a trend toward improvement to meet the upcoming pedestrian requirements.

Damageability and Bumper Performance

The relationship between bumper performance in pedestrian lower extremity impacts and bumper damageability was also considered. Damageability testing has been reported for 3 vehicles that are in the same model and year range as the vehicles tested in the current study [14]. Low-speed flat barrier, angled barrier and pole impact tests were performed at 7.96 ± 0.24 km/h [15] on vehicles including the 2000-2005 Ford Focus, 2001-2005 Honda Civic, and the 1998-2005 Volkswagen Beetle. By the IIHS qualitative rating scale, in which the vehicles that sustain the least damage in testing score highest, the Volkswagen Beetle scored Good, the Honda Civic Acceptable, and the Ford Focus Marginal. It was reported that the North American Volkswagen Beetle model tested had indeed been one of the best cars ever tested for bumper performance in the low-speed damage tests and that it performed better in damage tests than the European version of the Volkswagen Beetle [16].

In contrast, the North American Volkswagen Beetle was the worst performer in the current series of pedestrian lower extremity tests, using the modified EuroNCAP point calculation. Next worse of the three vehicles was the Honda Civic lateral bumper tests, both Ford Focus tests, then the Honda Civic center bumper tests. The contrary results of bumper damage tests and pedestrian lower extremity tests illustrate the incompatibility between bumper damage reduction and pedestrian lower extremity safety.

The fact that the more damage-resistant bumpers tended to perform worse in these pedestrian safety tests suggests that structural stiffness of bumper components influences the severity of pedestrian lower extremity injury. However, there were other design elements that appeared from video to have an effect on leg deformation, and therefore loading. These included the depth and angle of the bumper face and the shape of the grille and hood leading edge. Bumpers with a tall, flat face like the Mazda Miata's reduced bending at the knee and below by limiting wrapping of the tibia under the bumper. Similarly, vehicles like the Volvo S40 with upright hood structures above the bumper reduced bending of the knee and upper leg by reducing wraparound onto the hood in this free-flight test.

CONCLUSIONS

The single-jointed TRL legform and the flexible femur and tibia of the FlexPLI legform lead to marked differences in how the two legforms interact with vehicle front structures. Variations in bumper design may have different effects on the injury measures recorded by the two legforms.

Both legforms had limitations in testing North American vehicles in this test series. The FlexPLI 2004 fractured in three tests and the TRL legform was unable to produce reliable peak measurements when bending exceeded thirty degrees.

The North American bumpers tested in this series would not have met European limits set for pedestrian leg loading and repeatedly fractured or exceeded the measurement capabilities of the legforms developed for use in international pedestrian testing. Although four of the five European vehicles tested under comparable conditions also performed inadequately in similar tests, the European version of one vehicle tested showed dramatically improved pedestrian leg protection over its North American counterpart. Although these tests do not establish that the North American bumper standards are the reason for the aggressiveness of North American bumpers, IIHS testing suggests that bumpers that are more robust (i.e., those that score better in their bumper damage tests) may be more aggressive toward pedestrians.

Although this study suggests that less damageable bumpers may be more aggressive toward pedestrians, it does not establish that vehicles meeting North American bumper standards cannot achieve improved pedestrian leg safety. Further work should be done to determine if vehicle front design could be improved to better protect pedestrians while still conforming to current bumper regulations. This work may include both bumper and pedestrian testing of more recent models of the vehicles tested in this study to see how much each of them has changed with new pedestrian regulations on the horizon.

ACKNOWLEDGEMENTS

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AB NOTE

05-01

INITIAL ASSESSMENT OF TARGET POPULATION FOR POTENTIAL REDUCTION OF PEDESTRIAN HEAD INJURY IN HOOD AND WINDSHIELD IMPACTS:

An Estimate Based on PCDS Cases

A. MALLORY
J. STAMMEN

UPDATED JULY 2006

Background

In a previous study[1], the Vehicle Research and Test Center estimated the potential target population for injury reduction if a pedestrian head impact standard were introduced in the United States. Based on cases from the Pedestrian Crash Data Study (PCDS), that estimate considered several potential regulatory scenarios, where each scenario included different potential impact areas on the vehicle that could be included. The target population estimated for each scenario was then adjusted based on changes in the distribution of passenger cars and light trucks and vans (LTVs) in the vehicle fleet since the period during which the PCDS data was collected. These adjusted target populations were then applied to pedestrian injury and fatality statistics for 2002, resulting in an estimated annual number of pedestrian injury and deaths that could be potentially be reduced or prevented by improvement to the structures considered under each scenario.

This updated estimate of potential target population is based on the potential impact areas covered by the current proposed GTR (Global Technical Regulation) on pedestrian protection (TRANS/WP.29/GRSP/2005/3). Review of the proposed regulation has shown that its coverage area will be limited to areas of the hood and windshield for most US vehicles. Therefore, this updated target population estimate will address the scenario where only pedestrians with head impacts to the hood and windshield will be considered in the target population. Actual benefit for the target population will be calculated separately and should consider the areas of the hood and windshield that would actually be affected and the possible reduction in injury risk that would be achieved if current vehicles were improved to meet the proposed regulation. As in the previous estimate, the PCDS data will be adjusted based on changes in the US fleet since the period of PCDS data collection. Final estimates of target population are updated to reflect pedestrian injury and fatality statistics for 2003.

Brief Summary of Method

- PCDS cases were sorted according to impact surface, and windshield and hood impacts identified.
- The number of people in the PCDS database who sustained head injuries against the hood and windshield surfaces was tallied resulting in an estimate of the "Target Population." The Target Population included only pedestrians whose most serious injuries included a head injury from an impact against the hood or windshield.
- A head injury case is included in our Target Population if a pedestrian's most severe head injury from the hood or windshield is *at least as severe* as the pedestrian's most severe injury.
- The Target Population derived from the PCDS data was adjusted based on changes in the distribution of passenger cars and LTVs in the vehicle fleet since the period during which the PCDS data was collected.

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[1] Mallory A, Stammen J, "Initial Assessment of Target Population for Potential Reduction of Pedestrian Head Injury in the United States: An Estimate Based on PCDS Cases," PAB Note 04-01 (February 2004).

- The Target Population estimate was applied to pedestrian injury statistics for 2003, resulting in an estimated annual number of pedestrian injuries and deaths that could potentially be reduced or prevented by improvement to the hood or windshield.

Summary of Source Data

The analysis was based on the 550[2] cases in the Pedestrian Crash Data Study [PCDS][3] database collected between 1994 and 1998. These cases were collected by six of the zone centers already in place to conduct NASS/CDS investigations (NCSA, 1996). Each center investigated all pedestrian crashes of which they were aware in their region that met PCDS inclusion criteria. They were alerted to pedestrian crashes by monitoring police radio or other methods. Inclusion criteria were as follows:

- pedestrian impact was by forward-moving vehicle,
- vehicle must be CDS applicable (late model and vehicle VEH07 code between 01 and 49),
- pedestrian was not lying or sitting,
- striking portion of the vehicle was previously undamaged OEM parts,
- pedestrian impact was vehicle's only impact,
- first point of contact with pedestrian is forward of the top of the A-pillar.

All eligible cases were included in PCDS, without sampling or weighting and are therefore believed to be reasonably representative of pedestrian crashes in that time period.

Of these cases, 540 had at least one injury of known severity, and 242[4] had at least one head injury. A total of 761 head injuries are listed in the database. PCDS records the vehicle impact surface for each injury. Table 1 contains a summary of the frequency of head injury from impacts to the windshield and hood. Structures surrounding the windshield and hood (such as the header, pillars, cowl, and fenders) are not included in this data. Note that the GTR procedure applies primarily to the hood and limited surrounding structures. The windshield is not included in the 2006 draft of the GTR.

Table 1: Frequency of head injuries by impact surface

Contact Surface/Area	Number of injuries (N=761)	AIS 2-6 injuries (N=481)	AIS 3-6 injuries (N=393)
Hood surface	134	89	69
Windshield	293	197	168

Estimation of Target Population from PCDS

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[2] As per personal communication with Marv Stephens of NCSA, two duplicate cases were excluded from publicly available, 552-case version of database.

[3] Chidester A, Isenberg R. "Final Report on the Pedestrian Crash Data Study," Paper No. 248, ESV 2001.

[4] Head injury included all records coded as REGION90=1, therefore face injuries excluded.

The Target Population among all PCDS cases was estimated. This population is the number of PCDS cases that included a head injury from hitting the hood or windshield that was *at least as severe as* any other head injury, and *at least as severe* as any injury to any other body part. The Target Population, therefore, includes cases where the highest AIS head injury was sustained by striking a surface that could potentially be "improved" by appropriate countermeasures for hood or windshield impacts. The Target Population does not include pedestrian cases where the head injury was sustained in an impact not expected to be affected by the GTR procedures, such as with the ground or with the undercarriage of the vehicle or with vehicle structures such as the grille, fender, cowl, or A-pillars. For example, the Target Population would include a pedestrian with an AIS 3 head injury from hood impact, only if the victim did not have any AIS 4-6 head injuries from impacts with the ground, etc. Furthermore, the Target Population would include a pedestrian with an AIS 3 head injury only if the victim did not have any AIS 4-6 injuries to another body part. Although there is undoubtedly benefit to reducing this pedestrian's head injury severity, the pedestrian is not counted in the Target Population.

Table 2 lists the number of PCDS cases that would be part of the "Target Population" that considers hood and windshield impacts. These numbers are also listed as a percentage of the total population of injured pedestrians in PCDS. Results are tabulated for all injuries (AIS 1-6), for moderate injuries (AIS 2-6) and for serious injuries (AIS 3-6), and separated by light trucks and vans (LTV) and passenger cars. The number of PCDS cases that would be included in the target population under other regulatory scenarios, was included as Table 3 in VRTC's previous estimate of target population, and can be found in Appendix A.

Table 2: Target Population in PCDS for Hood and Windshield Impacts (Head injuries that could potentially be reduced by vehicle improvement, as a percentage of the total number of injury cases for each vehicle category)

Head injury from impacts to ***HOOD*** only

Injury Severity (n = total number of PCDS injury cases)	LTV (n=170)	Pass Car (n=370)	Total (n=540)
All (Total n=540)	11 (6.5%)	23 (6.2%)	34 (6.3%)
AIS 2-6 (Total n=302)	10 (10.1%)	16 (7.9%)	26 (8.6%)
AIS 3-6 (Total n=194)	6 (9.0%)	6 (4.7%)	12 (6.2%)

Head injury from impacts to ***WINDSHIELD*** only

Injury Severity (n = total number of PCDS injury cases)	LTV (n=170)	Pass Car (n=370)	Total (n=540)
All (n=540)	10 (5.9%)	53 (14.3%)	63 (11.7%)
AIS 2-6 (n=302)	7 (7.1%)	45 (22.2%)	52 (17.2%)
AIS 3-6 (n=194)	7 (10.4%)	35 (27.6%)	42 (21.6%)

Adjustment of PCDS Target Population to Account for Changing Fleet

PCDS cases include crashes that occurred from 1994 to 1998 (mean 1996.4, median 1996). Vehicle models ranged from 1988 to 1999 (mean 1993.2 and median 1993).

During the period of data collection (1994 to 1998), LTV registrations as a percentage of total registrations increased steadily from approximately 32% to approximately 36%[5] for an average of approximately 34%. By 2001, LTV registrations comprised approximately 38% of the fleet, while sales of LTV's had reached almost 50% of all sales by 2002[6]. Review of sales and registration trends since the mid-1980's shows that the fleet percentage of registered LTV's trails the percentage of sold LTV's by five to ten years. Given the steady annual increase in registrations and sales of LTV's, an estimate of *current* LTV registrations is 40% and rising. It is reasonable, assuming sales trends continue, to predict that *future* LTV registrations will reach 50% as registrations catch up to sales.

This increasing proportion of LTV's in the fleet will change the proportion of pedestrian head injuries that are potentially preventable. The estimates of the total Target Population in Table 2 were adjusted to reflect the expected proportions of preventable injuries given changing LTV presence in the fleet. The resulting adjusted Target Populations are listed in Table 3. The target populations calculated under other possible regulatory scenarios was included as Table 4 in VRTC's previous estimate and can be found in Appendix B in this report.

Table 3: Estimated Target Population - Percentage of injury cases where most serious injury is a head injury from hood or windshield impact (Given projected proportion of LTV's in vehicle fleet).

Impacts to ***HOOD*** only

Head Injuries	PCDS (34% LTV Fleet)	Projected Current (40% LTV Fleet)	Projected Future (50% LTV Fleet)
All	6.3%	6.3%	6.3%
AIS 2-6	8.6%	8.8%	9.0%
AIS 3-6	6.2%	6.4%	6.8%

Impacts to ***WINDSHIELD*** only

Head Injuries	PCDS (34% LTV Fleet)	Projected Current (40% LTV Fleet)	Projected Future (50% LTV Fleet)
All	11.7%	10.9%	10.1%
AIS 2-6	17.2%	16.1%	14.6%
AIS 3-6	21.6%	20.7%	19.0%

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[5] "Initiatives to Address Vehicle Compatibility", NHTSA report, June 2003, *www-nrd.nhtsa.dot.gov/departments/nrd-11/aggressivity/IPTVehicleCompatibilityReport/* . Percentages were estimated from bar-chart in this report.

[6] Kahane CJ. "Cost Per Life Saved by the Federal Motor Vehicle Safety Standards", NHTSA report, December 2004, DOT HS 809 835. (Percentages were drawn from Tables 1 and 3.)

Impacts to ***HOOD and WINDSHIELD***

Head Injuries	PCDS (34% LTV Fleet)	Projected Current (40% LTV Fleet)	Projected Future (50% LTV Fleet)
All	18.0%	17.3%	16.4%
AIS 2-6	25.8%	24.9%	23.6%
AIS 3-6	27.8%	27.1%	25.8%

The percentages in the above tables represent the percent of injured pedestrians whose most serious injuries are head injuries that could potentially be mitigated with improvement to the windshield or hood. In summary, given the current proportion of LTV's in the US fleet (approximately 40%), the Target Population for head injury reduction as a result of hood and windshield improvements for pedestrian safety would be up to 17.3% of all injured pedestrians. Considering only more severe injuries, the Target Population would be up to 24.9% for all moderately injured pedestrians (AIS 2-6) and up to 27.1% for all seriously injured pedestrians (AIS 3-6), as projected for the current vehicle fleet. This projected Target Population is not dramatically different than the Target Populations calculated based on earlier fleets with fewer LTV's or projected from a future fleet with more LTV's.

Application of Target Population Estimate To Annual Number of Pedestrians Injured

The number of pedestrians in the Target Population was estimated based on National Center for Statistics and Analysis (NCSA) data for 2003,[7] which listed 4,749 pedestrian fatalities and 70,000 pedestrians injured.

Assuming that LTVs comprised approximately 40% of the fleet in 2003, the projected current Target Population percentages from Table 3 were applied to NCSA's 2003 injury statistics to estimate how many of the injured pedestrians could potentially have benefited from improved vehicle structures. In Table 4, the Target Population percentages calculated from all severities of injury from the PCDS database (AIS 1-6) were used to estimate the Target Population among all injured pedestrians in 2003, while the Target Population calculated from the serious PCDS injuries (AIS 3-6) were used to estimate the Target Population among the killed pedestrians.

For example, from Table 3, it was estimated that 17.3% of injured pedestrians (AIS1-6) would be within the Target Population for hood and windshield impacts given the current fleet of 40% LTV's. That is, 17.3% of injured pedestrians sustained a head injury from hood or windshield contact that was at least as serious as any other injury sustained. This estimate was applied in Table 4 by multiplying the estimated number of pedestrians injured (70,000) by 17.3%, to estimate a Target Population of 12,110 pedestrians with head injuries due to hood or windshield contact in 2003.

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[7] "Traffic Safety Facts 2003: A Compilation of Motor Vehicle Crash Data from the Fatality Analysis Reporting System and the General Estimates System", NHTSA, DOT 809 705.

Table 4: Target Population calculated by applying Target Population percentages from PCDS analysis to NCSA injury statistics from 2003.

	Pedestrians Injured	Pedestrian Fatalities
NCSA Statistics 2003	70,000	4,749
Target Population in 2003: *Based on projected fleet estimate of 40% LTV*	*Based on Target Population calculated from all PCDS injuries (AIS 1-6)*	*Based on Target Population calculated from serious PCDS injuries (AIS3-6)*
Hood	4,410	304
Windshield	7,630	983
Hood & Windshield	12,110	1,287

These estimates are based on 2003 injury statistics, and estimate current fleet proportions. If the total number of pedestrians deaths and injuries decrease over time, so will the target population. If the proportion of LTVs in the fleet continues to rise, the target population may increase. It is possible that these trends may counteract one another.

Summary

This analysis shows the potential number of US pedestrians that could be affected annually by improvements in vehicle structure. It is an estimate of target population only, and does not include an assessment of practicability or cost of countermeasures. As many as 12,100 injured pedestrians, and 1,287 killed pedestrians are in the annual target population for the proposed pedestrian GTR. This target population can be used to calculate potential benefit of a proposed pedestrian head impact regulation by incorporating data to show the actual area of the hood and windshield that would likely be covered by the proposed standards and by determining the possible reduction in injury risk that would be achieved if current vehicles were improved to meet the proposed standards. This estimated target population was intended as an initial calculation, and is limited by the assumptions and limitations noted in VRTC's prior report.

An additional limitation to note is that the NCSA injury statistics for pedestrian injuries and deaths may include cases where pedestrians were lying or sitting at the time of the crash or cases where the first pedestrian impact was rearward of the top of the A-pillar, while these cases are excluded from the PCDS data set. Future target population estimates should attempt to account for this difference in the data sets.

Appendix A

The following tables (Tables 3-1 to Table 3-5) are excerpted from VRTC's previous report calculating target population under several different regulatory scenarios. The tables list the number of PCDS cases that would be part of the "Target Population" under each scenario. These numbers are also listed as a percentage of the total population of injured pedestrians in PCDS. Results are tabulated for all injuries at three severity levels (AIS1-7, AIS2-6 and AIS3-6), and are separated by vehicle type.

Table 3: Target Population in PCDS given various improvement scenarios (Head injuries that could potentially be reduced by vehicle improvement, as a percentage of the total number of injury cases)

(3-1) Scenario one assumes potential injury reduction from impacts to ***HOOD*** only

	LTV (n=170)	Pass Car (n=370)	Total (n=540)
All	11 (6.5%)	23 (6.2%)	34 (6.3 %)
AIS 2-6	10 (10.1%)	16 (7.9%)	26 (8.6%)
AIS 3-6	6 (9.0%)	6 (4.7%)	12 (6.2%)

(3-2) Scenario two assumes potential injury reduction from impacts to ***HOOD AND ADJACENT STRUCTURES:***

Head Injuries	LTV	Pass Car	Total
All	19 (11.2 %)	32 (8.6%)	51 (9.4 %)
AIS 2-6	18 (18.2%)	20 (9.9%)	38 (12.6%)
AIS 3-6	11 (16.4%)	9 (7.1%)	20 (10.3%)

(3-3) Scenario three assumes potential injury reduction from impacts to ***HOOD, ADJACENT STRUCTURES, BUMPER, and GRILLE AREAS:***

Head Injuries	LTV	Pass Car	Total
All	20 (11.8%)	34 (9.2%)	54 (10.0%)
AIS 2-6	18 (18.2%)	22 (10.8%)	40 (13.3%)
AIS 3-6	11 (16.4%)	11 (8.7%)	22 (11.3%)

(3-4) Scenario four assumes potential injury reduction from impacts to ***HOOD, ADJACENT STRUCTURES, BUMPER, GRILLE, A-PILLAR and HEADER AREAS:***

Head Injuries	LTV	Pass Car	Total
All	25 (14.7%)	53 (14.3%)	78 (14.4%)
AIS 2-6	23 (23.2%)	40 (19.7%)	63 (20.9%)
AIS 3-6	15 (22.4%)	24 (18.9%)	39 (20.1%)

(3-5) Scenario five assumes potential injury reduction from impacts to ***HOOD, ADJACENT STRUCTURES, BUMPER, GRILLE, A-PILLAR, HEADER AREAS and WINDSHIELD:***

Head Injuries	LTV	Pass Car	Total
All	35 (20.6%)	106 (28.6%)	141 (26.1%)
AIS 2-6	30 (30.3%)	85 (41.9%)	115 (38.1%)
AIS 3-6	22 (32.8%)	59 (46.5%)	81 (41.8%)

Appendix B

The following tables (Tables 4-1 to Table 4-5) are excerpted from VRTC's previous report calculating target population under several different regulatory scenarios. In these tables, the estimates of target population in Tables 3-1 to 3-5 (Appendix A) were adjusted to reflect the expected proportions of preventable injuries given changing LTV presence in the fleet.

Table 4: Estimated Target Population - Percentage of injury cases where most serious injury is a head injury that could potentially be reduced or prevented - Given projected proportion of LTV's in vehicle fleet.

(4-1) Scenario one assumes potential injury reduction from impacts to ***HOOD*** only

Head Injuries	PCDS (34% LTV Fleet)	Projected Current (40% LTV Fleet)	Projected Future (50% LTV Fleet)
All	6.3%	6.3%	6.3%
AIS 2-6	8.6%	8.8%	9.0%
AIS 3-6	6.2%	6.4%	6.8%

(4-2) Scenario two assumes potential injury reduction from impacts to ***HOOD AND ADJACENT STRUCTURES:***

Head Injuries	PCDS (34% LTV Fleet)	Current (40% LTV Fleet)	Future (50% LTV Fleet)
All	9.4%	9.7%	9.9%
AIS 2-6	12.6%	13.2%	14.0%
AIS 3-6	10.3%	10.8%	11.8%

(4-3) Scenario three assumes potential injury reduction from impacts to ***HOOD, ADJACENT STRUCTURES, BUMPER, and GRILLE AREAS:***

Head Injuries	PCDS (34% LTV Fleet)	Current (40% LTV Fleet)	Future (50% LTV Fleet)
All	10.0%	10.2%	10.5%
AIS 2-6	13.2%	13.8%	14.5%
AIS 3-6	11.3%	11.8%	12.5%

(4-4) Scenario four assumes potential injury reduction from impacts to ***HOOD, ADJACENT STRUCTURES, BUMPER, GRILLE, A-PILLAR and HEADER AREAS:***

Head Injuries	PCDS (34% LTV Fleet)	Current (40% LTV Fleet)	Future (50% LTV Fleet)
All	14.4%	14.5%	14.5%
AIS 2-6	20.9%	21.1%	21.5%
AIS 3-6	20.1%	20.3%	20.6%

(4-5) Scenario five assumes potential injury reduction from impacts to ***HOOD, ADJACENT STRUCTURES, BUMPER, GRILLE, A-PILLAR, HEADER AREAS and WINDSHIELD:***

Head Injuries	PCDS (34% LTV Fleet)	Current (40% LTV Fleet)	Future (50% LTV Fleet)
All	26.1%	25.4%	24.6%
AIS 2-6	38.1%	37.2%	36.1%
AIS 3-6	41.8%	41.0%	39.6%

Pedestrian Head Safety Survey of U.S. Vehicles
In Support of the Proposed Global Technical Regulation (GTR)

VRTC Technical Report

Jason Stammen
NHTSA Vehicle Research & Test Center

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July 2006

EXECUTIVE SUMMARY

A draft global technical regulation (GTR) for pedestrian safety has been generated by the WP29/GRSP ad hoc informal working group. In the spring of 2006, the U.S. is to vote on whether this GTR should be implemented to test vehicles in the U.S. and around the globe. To prepare for this vote, NHTSA needs to determine if this GTR can provide sufficient benefit to pedestrians in the U.S and at the same time know whether it is feasible to meet the performance requirements outlined in the document.

The objectives of this study are to (1) experimentally generate head impact data (HIC) from a representative sample of the current U.S. fleet using the draft GTR test conditions and (2) critique the procedural details to minimize ambiguity.

The following bullets summarize this study's findings:

- Twenty-seven out of 38 head impact tests (71%) to the hood and windshield of six late model (2001-2004) vehicles sold in the U.S. had HIC values below 1000.
- Only one of six vehicles had a pass rate of 100%; however, it is possible that the hardest structure on that vehicle's front end was not tested.
- The extreme edges and corners of the test zones almost exclusively resulted in the most severe impacts.
- Countermeasures such as deformable hood hinges, crush zones in the hood reinforcing structure above hard frame/engine components, and large underhood clearances were present in several of the vehicles.
- In the Civic, those countermeasures resulted in as much as a 70% decrease in HIC when comparing impact locations of a 2001 model with that of a 1994 model.
- Some GTR portions were left open to interpretation. These included test zone reference line details and test-to-test details such as how often impacted structures should be replaced.

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1. BACKGROUND

A draft global technical regulation (GTR) for pedestrian safety has been generated by the WP29/GRSP ad hoc informal working group. In the spring of 2006, the U.S. is to vote on whether this GTR should be implemented to test vehicles in the U.S. and around the globe. To prepare for this vote, NHTSA needs to determine if this GTR can provide sufficient benefit to pedestrians in the U.S and at the same time know whether it is feasible to meet the performance requirements outlined in the document.

The Pedestrian Crash Data Study (PCDS) data from 1994-1998 includes vehicles from the late 80's through the mid-1990's. This data includes pedestrian head injury information from 242 cases distributed between passenger cars, utility vehicles, pickup trucks, and vans. The main sources of vehicle-induced head injury were from the windshield (39%), hood (18%), A-pillar/header (11%), and windshield frame (9%). According to NHTSA Traffic Safety Facts (2003), children (ages 15 and under) accounted for 27% of pedestrian injuries and 9% of pedestrian fatalities. In addition, PCDS analysis showed that wrap around distances (WAD) for children and adults vary with GTR vehicle category.

Mallory, et al (2004)[1] estimated that the target population for head injury reduction as a result of vehicle improvements for pedestrian safety would range from approximately 9% to 37% of all injured pedestrians for the current vehicle fleet, depending upon the range of vehicle improvements assumed possible [considering only moderate and worse injuries (AIS 2-6)].

The agency would like to know if a significant portion of the injuries and fatalities for this target population could be reduced or eliminated by implementation of this GTR. The agency needs pedestrian head impact data from a sample of the current U.S. fleet to know where the fleet stands in relation to the GTR performance requirements. In addition, feedback on the procedural details of the proposed regulation is desired so that ambiguity is minimized.

The objectives of this study are to (1) experimentally generate head impact data (HIC) from a representative sample of the current U.S. fleet using the draft GTR test conditions and (2) critique the procedural details to minimize ambiguity.

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[1] Mallory A, Stammen J, "Initial Assessment of Target Population for Potential Reduction of Pedestrian Head Injury in the United States: An Estimate Based on PCDS Cases," PAB Note 04-01 (February 2004).

2. METHODS

2.1. Vehicle Selection

Seven U.S. vehicles were tested using the proposed global technical regulation procedure (TRANS/WP.29/GRSP/2005/3). Six of these vehicles were late model (2001 and later) while the seventh was an earlier model of one of the six late model vehicles. While the six late model vehicles were tested to gain insight into the current level of pedestrian head safety afforded by popular vehicle makes and types, the seventh was tested to determine the improvement in safety due to changes in the hood structure. The following vehicles were tested:

- 2004 Toyota Camry
- 2004 GMC Savana
- 2004 Toyota Sienna
- 2003 Dodge Ram
- 2001 Honda Civic
- 2001 Ford Escape
- 1994 Honda Civic

These vehicles comprise a wide range of vehicle types, including three passenger cars (Camry and two Civics), a sport utility vehicle (Escape), a pickup truck (Ram), a minivan (Sienna), and a full size van (Savana).

2.2. Pedestrian Headforms

Two pedestrian headforms were used in this study (Figure 1). A 4.5 kg headform simulating a 50^{th} percentile adult male head and 3.5 kg headform simulating a 6 year old child head were launched into specified impact locations on the vehicles. These headforms were both 165 mm in diameter and equipped with a damped triaxial accelerometer, with seismic masses within the maximum tolerated distance from their center of gravity. The x, y, and z component accelerations acquired by this accelerometer were used to calculate a resultant acceleration vs. time trace, which was then input into an algorithm to calculate head injury criterion (HIC) from the impact.

Figure 1. IHRA-specified child (left) and adult (right) headform devices

2.3. Test Conditions

The headforms were attached to a pneumatic fixture with height/angle adjustment capabilities (Figure 2). A preset pressure related to a specific speed at impact was determined using the fixture's history and verified by speed trials. A containment box was positioned to protect the headform from secondary, potentially damaging impacts.

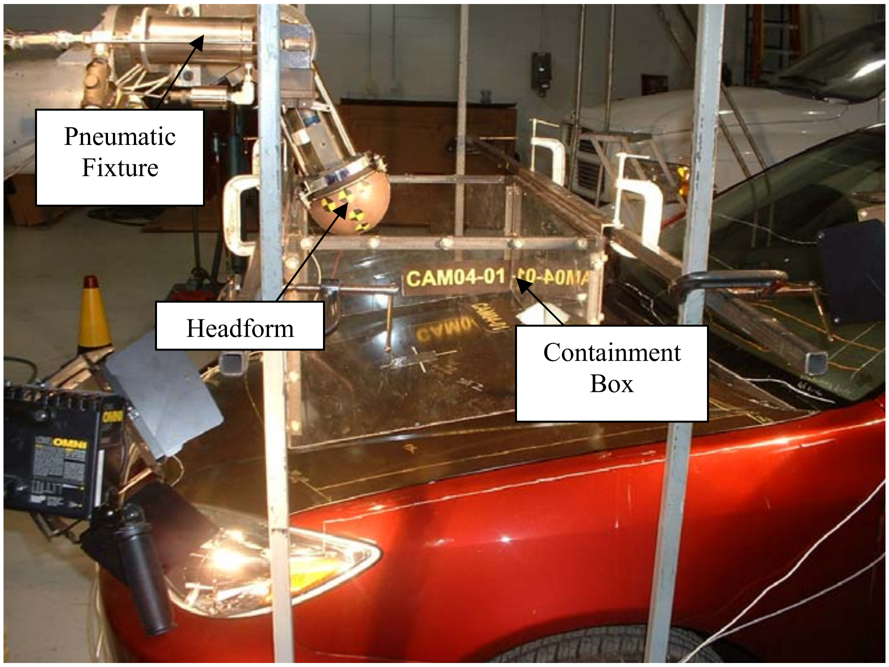


Figure 2. Test Configuration

The GTR states that the head velocity should be 8.9 ± 0.2 m/s (32 ± 0.72 km/hr) and also defines different incident angles relative to the horizontal depending on the three vehicle shape categories:

Table 1. Impact Angles by Vehicle Category

Category	Child Hood	Child WS	Adult Hood	Adult WS	Vehicles
Hood Angle > 30°	25°	25°	50°	50°	None
Hood Angle < 30° and Hood Leading Edge Height is:					
> 835 mm	60°	40°	90°	40°	2004 Savana, 2001 Escape, 2003 Ram, 2004 Sienna
< 835 mm	65°	40°	65°	40°	2001 Civic, 2004 Camry, 1994 Civic

All test locations were located in the GTR-defined test region applicable to that vehicle. The pedestrian GTR states that vehicle fronts should be tested in two zones, within vehicle-specific reference lines. For wrap-around-distances (WAD) of 1000 to 1700 mm, the 3.5 kg child headform should be used. For the areas between 1700 mm and 2100 mm, the 4.5 kg adult headform should be used. Figure 2 illustrates the test type distribution for a vehicle. The first types of tests were standard impacts based on 50th percentile WAD for each vehicle type, with two to the child zone and two to the adult zone (see Appendix B). When 50th percentile WAD locations fell within an exempted area of the vehicle, the impact point was moved to the closest testable WAD. The lateral locations of these tests were 1/6 and 4/6 of the total vehicle width. The rationale was to test at locations were the vehicle frame (1/6) and engine block (4/6) may have an influence, without specifically identifying or targeting these "worst-case" locations.

The second types of tests were intended to find HIC values for the softest and hardest portions of both the hood and windshield regions. These tests were specific to the individual vehicle. The locations were selected at the engineer's discretion, and the data is intended to provide HIC values in both the "best" and "worst" case scenarios. The goal was to get two best and two worst case points for each vehicle, but the small size of the test zones usually allowed/required no more than two or three impacts. When these data sets were combined, it was hoped that a sample distribution of head impacts occurring in the field could be developed.

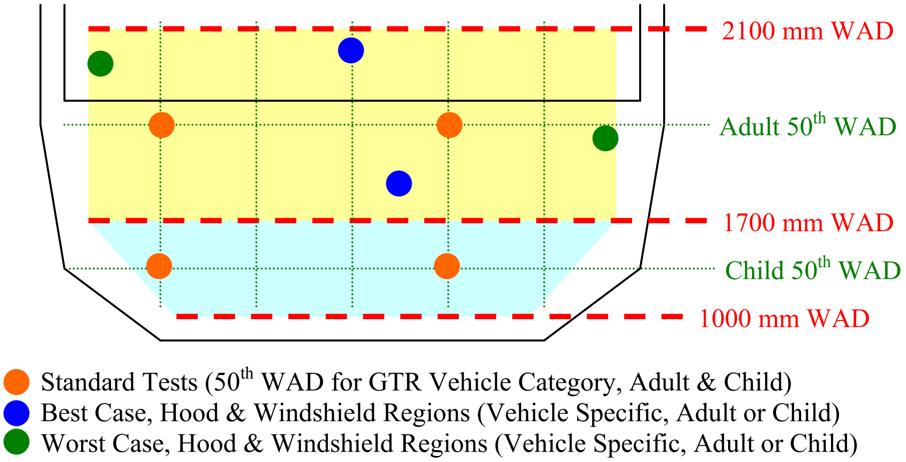


Figure 2. Test Locations (Vehicle Specific Locations are Examples Only)

2.4. Data Processing and Video

Component acceleration data was zeroed and then filtered with CFC 1000 (1650 Hz) prior to calculation of the resultant acceleration. A 15-millisecond window was used for the HIC algorithm as specified by the GTR. This window prevented HIC from being calculated from a secondary impact occurring during rebound of the headform. The impact velocity was integrated from the resultant acceleration. Pre and post-test photos of the impacted vehicle location were taken and high-speed video provided a side view of the head-vehicle kinematics.

3. RESULTS

A summary table of all head impact test results can be found in the Appendix.

3.1. Toyota Camry (2004)

Five out of the seven tests on the Camry were below HIC = 1000 (Figure 3). Three of the tests were standard WAD (two on hood with child head and one on windshield with adult head) and four were vehicle-specific. The stiffest point was in the rear passenger side corner of the child zone (HIC = 1759, peak resultant acceleration = 248 g).

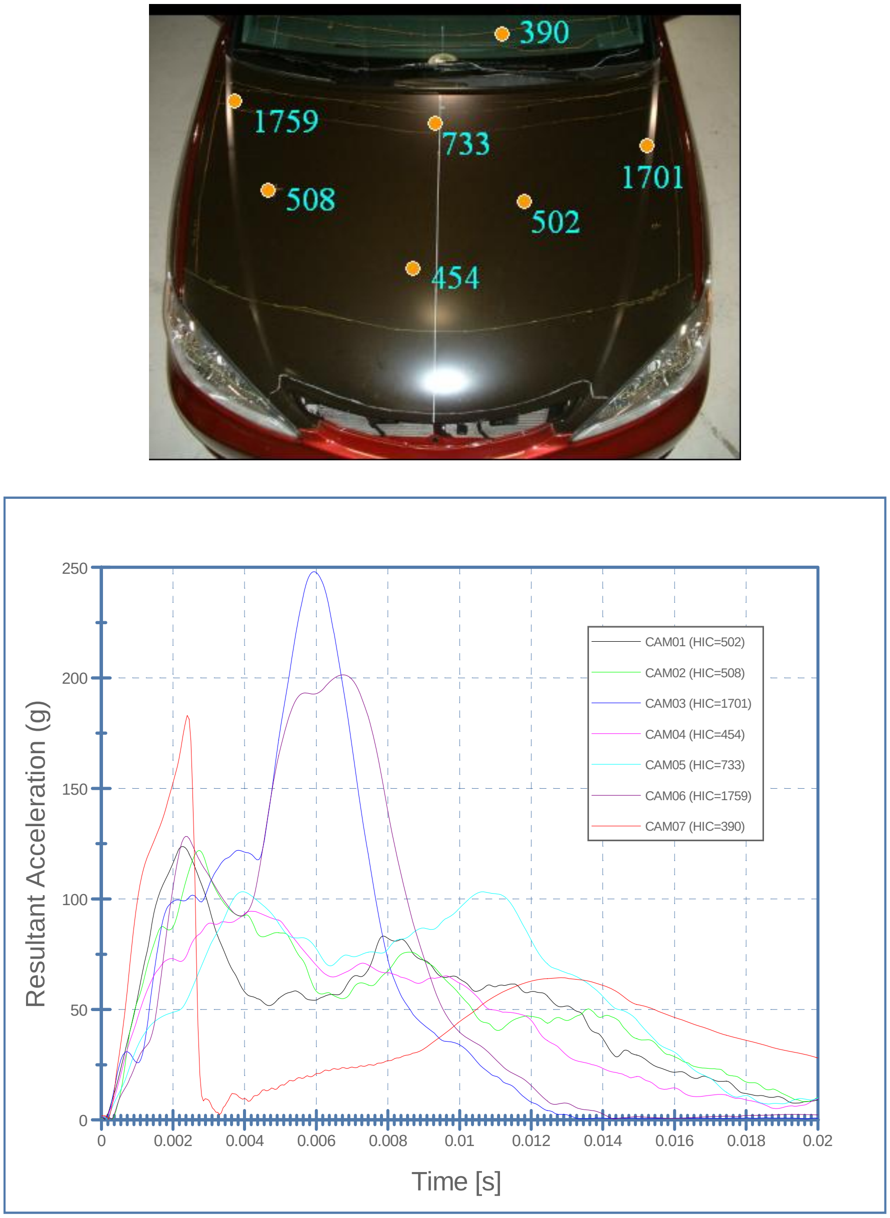


Figure 3. HIC and resultant accelerations for Toyota Camry test locations

3.2. GMC Savana (2004)

Five out of five tests on the Savana were below HIC = 1000 (Figure 4). Three of the tests were standard WAD (two on hood with child head and one on windshield with adult head) and two were vehicle-specific. It was a short hood and therefore the available test locations were somewhat limited. A large underhood clearance was observed over the majority of the hood surface. The stiffest point was in the rear driver side corner of the child zone (HIC = 984, peak resultant acceleration = 135 g) but it still passed the performance criterion.

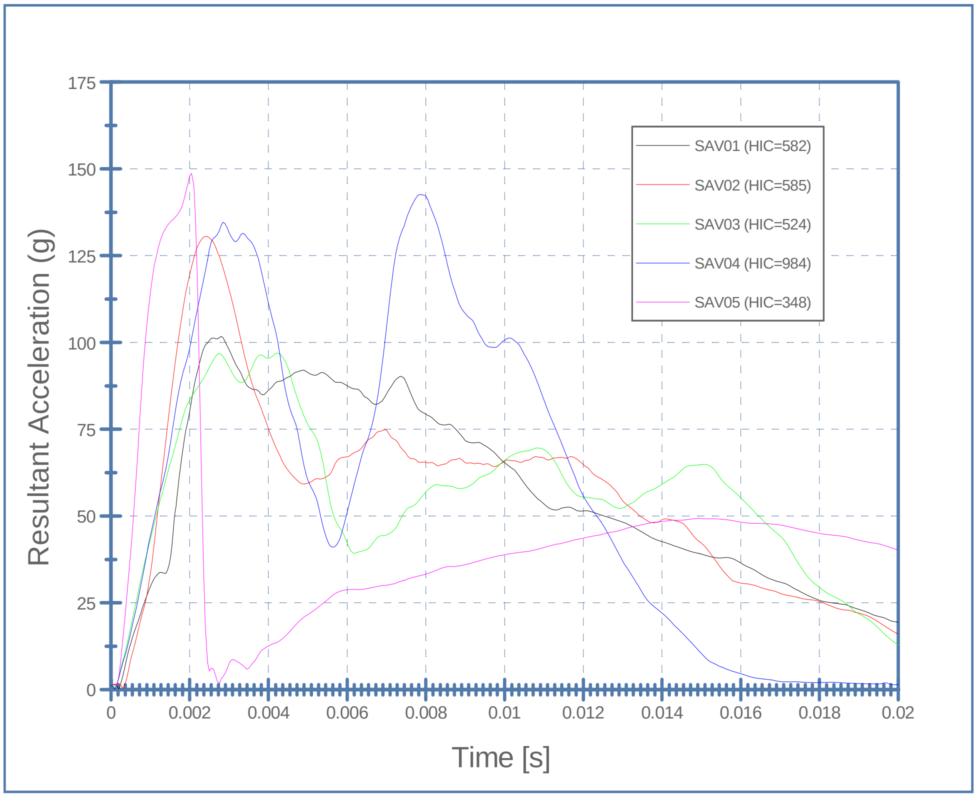
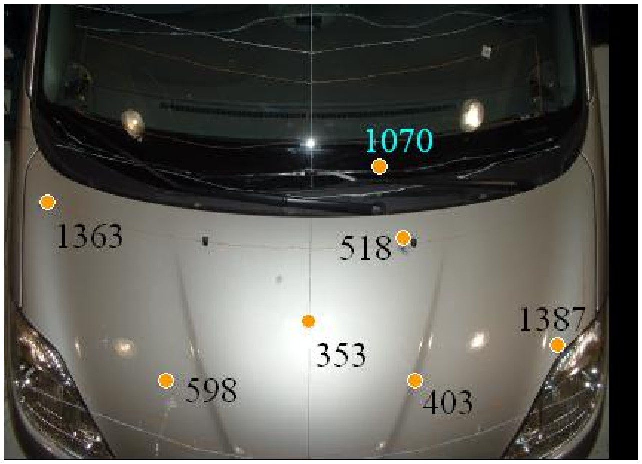


Figure 4. HIC and resultant accelerations for GMC Savana test locations

3.3. Toyota Sienna (2004)

Four of the seven Sienna tests passed the HIC requirement (Figure 5). Like the Camry and Savana, the extreme edges of the test zones resulted in the most severe impacts. An impact adjacent to the driver side headlight was the most severe (HIC = 1387, peak resultant acceleration = 160 g). The windshield test exceeded the HIC requirement because the deformation of the windshield was large enough to reach the dashboard below.



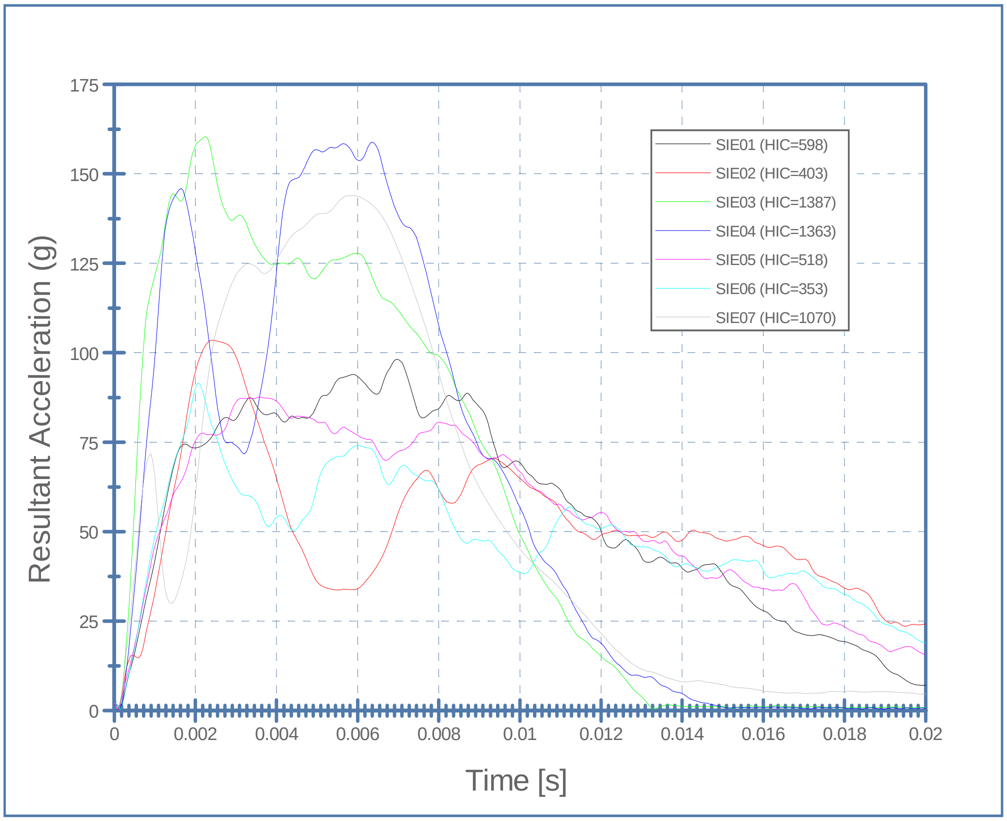
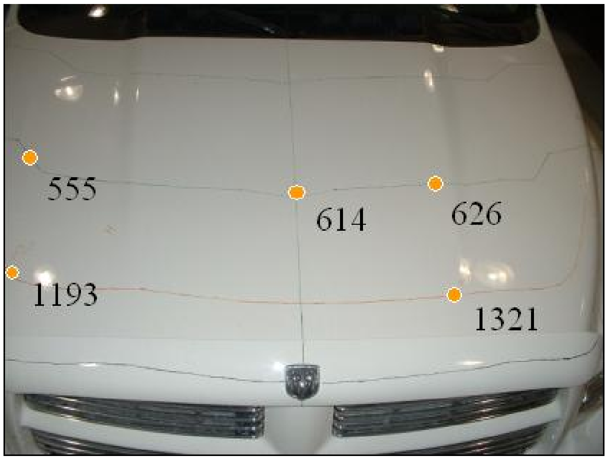


Figure 5. HIC and resultant accelerations for Toyota Sienna test locations

3.4. Dodge Ram (2003)

The Ram had the tallest and deepest front end of all the vehicles in this test series. Therefore, the impacts were concentrated toward the front of the vehicle (child zone, leading edge of adult zone). Three of the five tests passed the HIC requirement (Figure 6), with the standard child WAD test resulting in the most severe impact (HIC = 1321, peak resultant acceleration = 168 g).



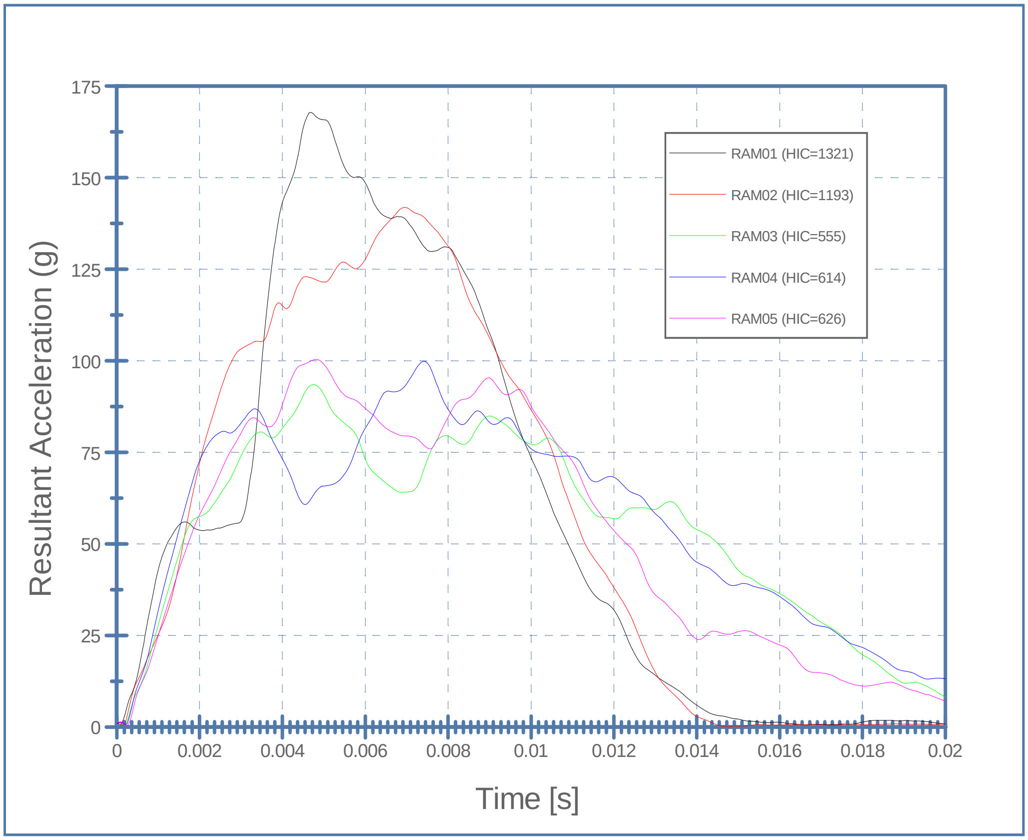


Figure 6. HIC and resultant accelerations for Dodge Ram test locations

3.5. Honda Civic (2001)

Six of the seven 2001 Civic tests passed the HIC requirement (Figure 7). The extreme edges of the child test zone resulted in the most severe impacts. An impact in the rearward, most outboard driver side portion of the zone was the most severe (HIC = 1005, peak resultant acceleration = 153 g).

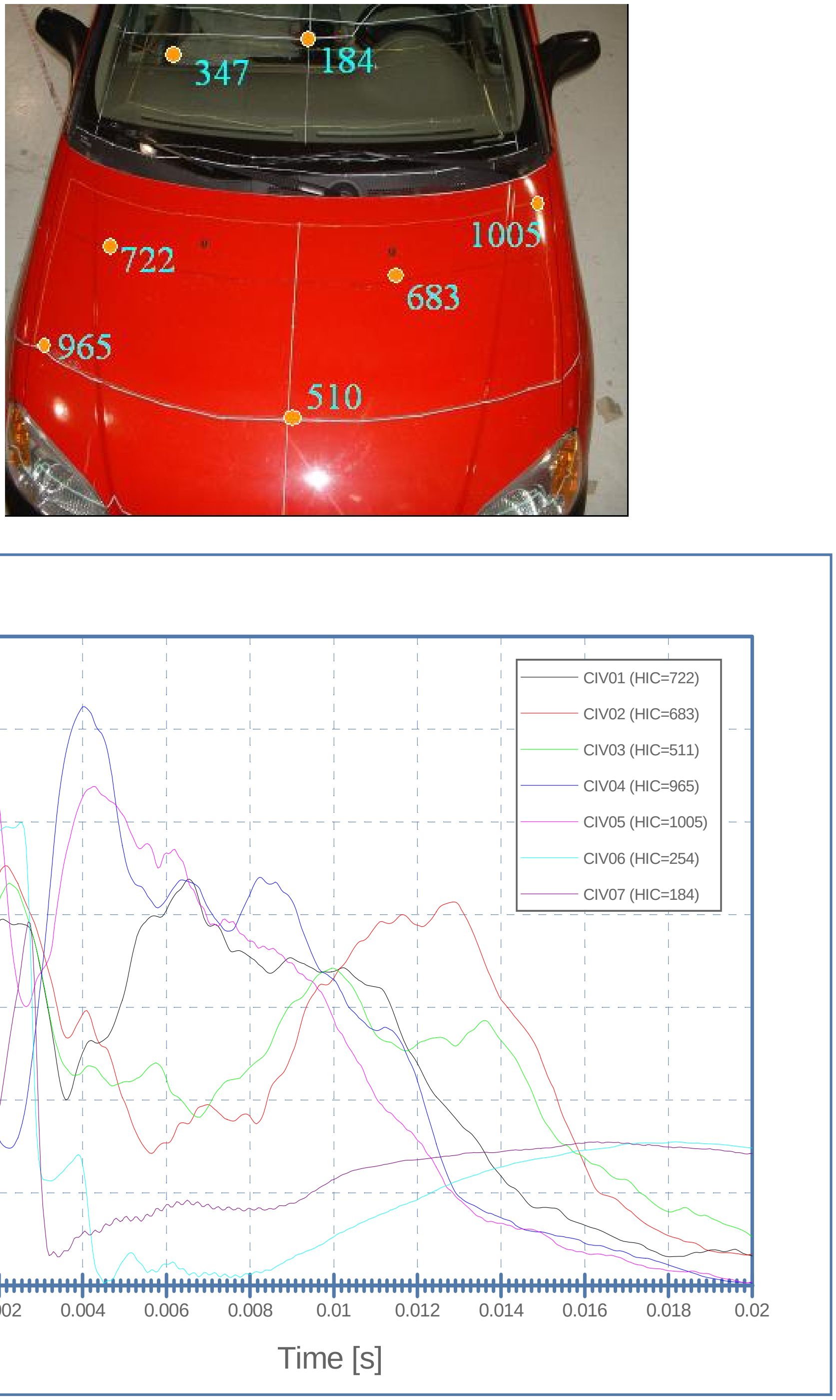


Figure 7. HIC and resultant accelerations for 2001 Honda Civic test locations

3.6. Ford Escape (2001)

Four of seven Escape tests passed the HIC requirement (Figure 8). The most severe impact was on the rearmost corner of the adult zone on the driver side (HIC = 2292, peak resultant acceleration = 248 g).

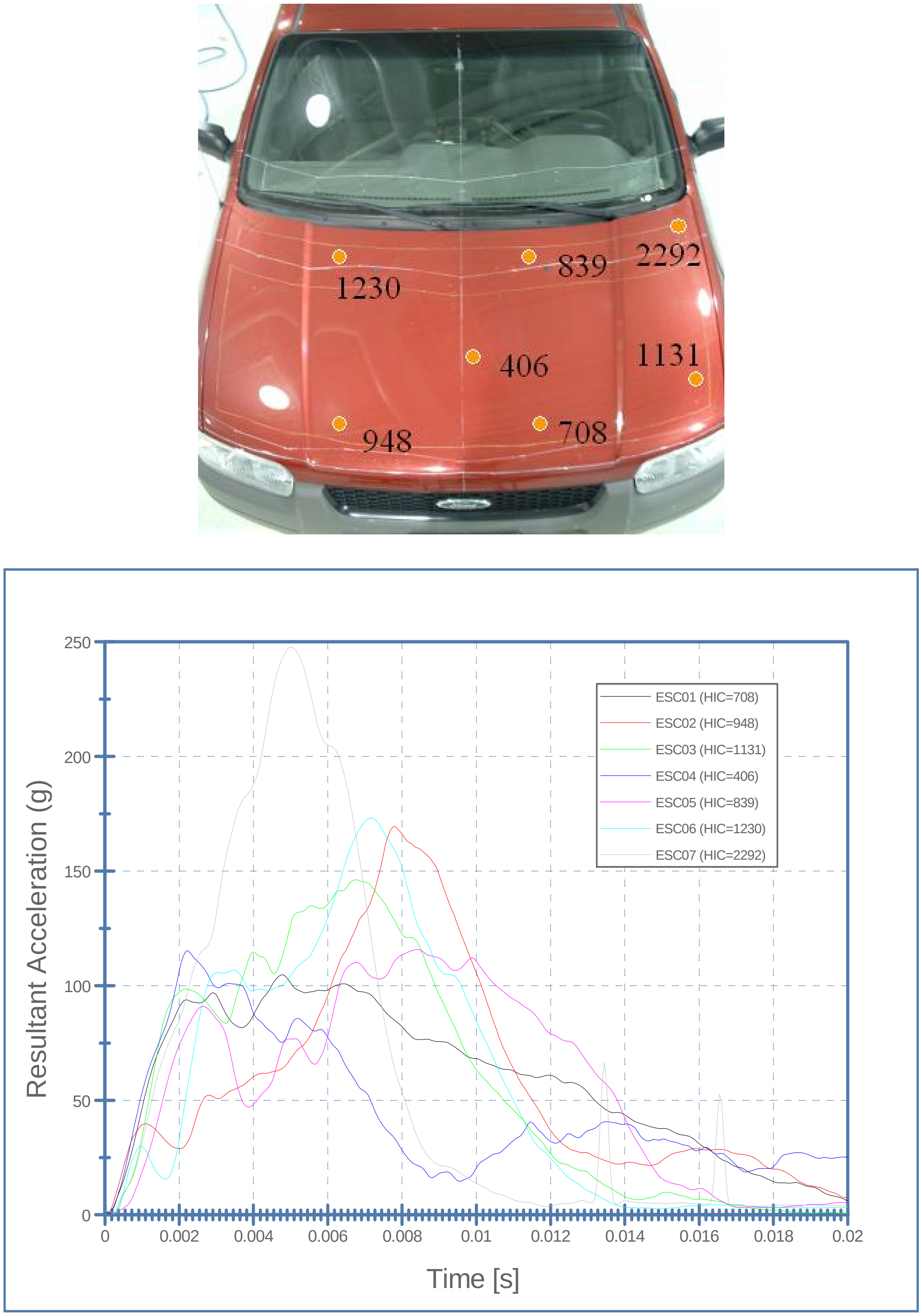


Figure 8. HIC and resultant accelerations for Ford Escape test locations

3.7. Honda Civic (1994)

Five hood locations consistent with those of the 2001 Civic were selected and tested to evaluate the effect of countermeasures on HIC. Some minor differences in the coordinates were necessary due to position modifications to the underhood components, but these differences were not suspected to influence HIC. Two of the five tests passed the HIC requirement, and all three of the high HIC values exceeded the highest HIC measured in any of the tests from the 2001-2004 vehicles (Figure 9).

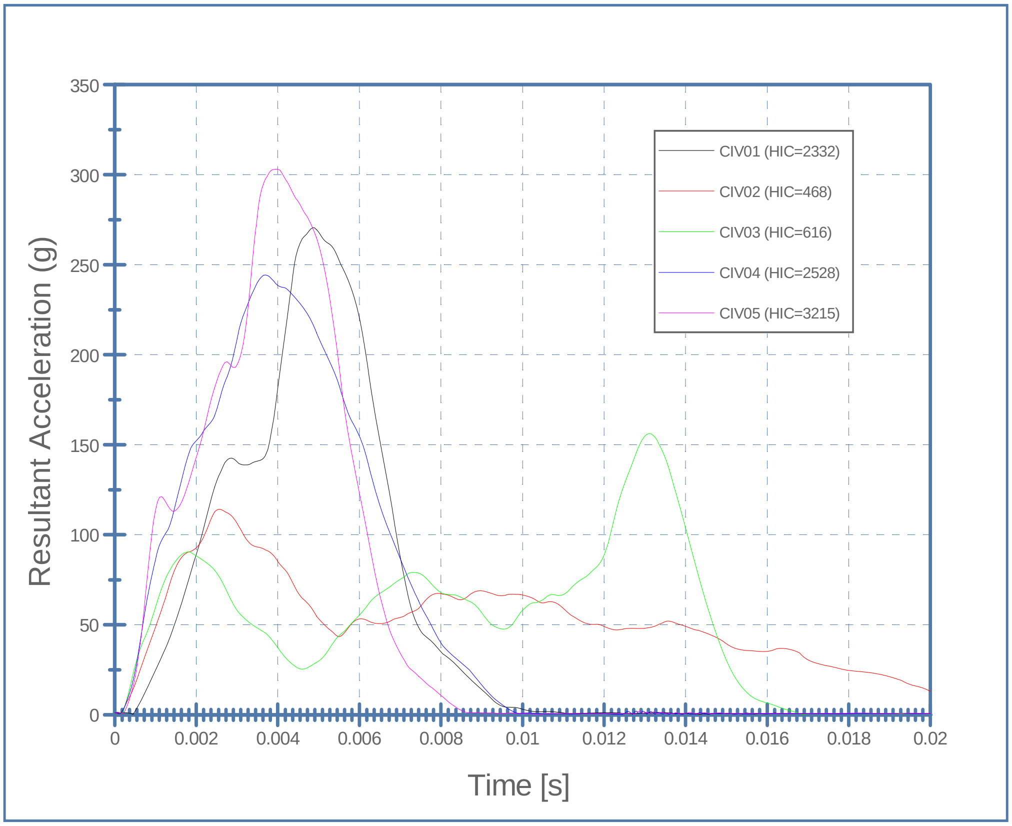


Figure 9. HIC and resultant accelerations for 1994 Honda Civic test locations

4. DISCUSSION

The thirty-eight tests to evaluate current U.S. vehicle performance are broken down by vehicle model, headform, and impacted structure versus test zone & targeted WAD in Figures 10 and 11. Note that the 1994 Civic results are not included because the model year is earlier than the four-year window used to illustrate the current situation in the U.S.

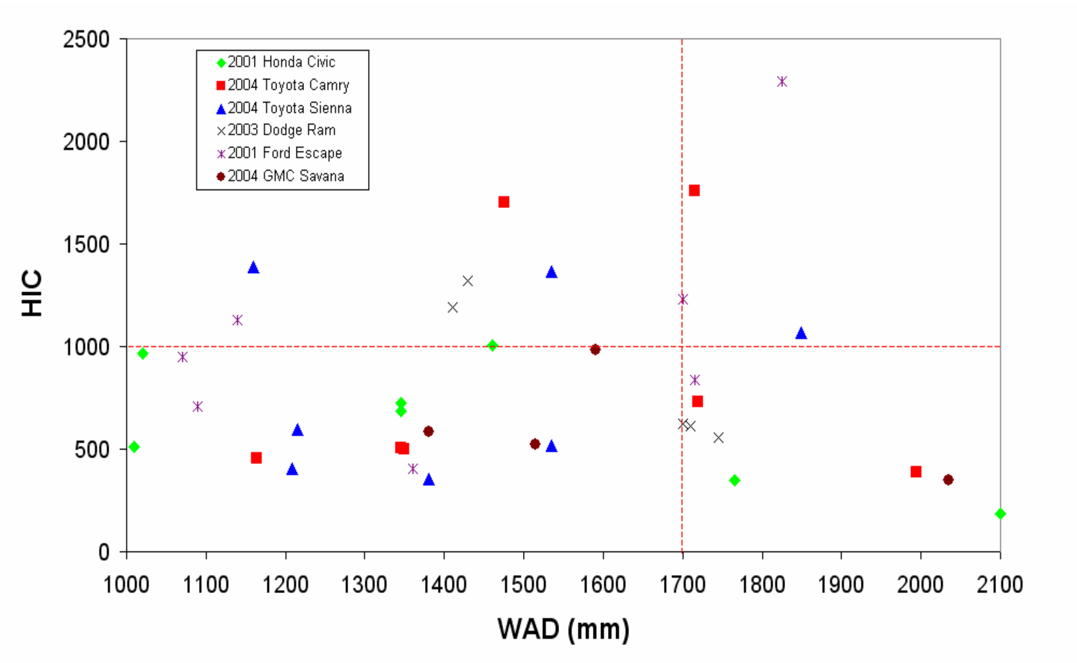


Figure 10. HIC by vehicle

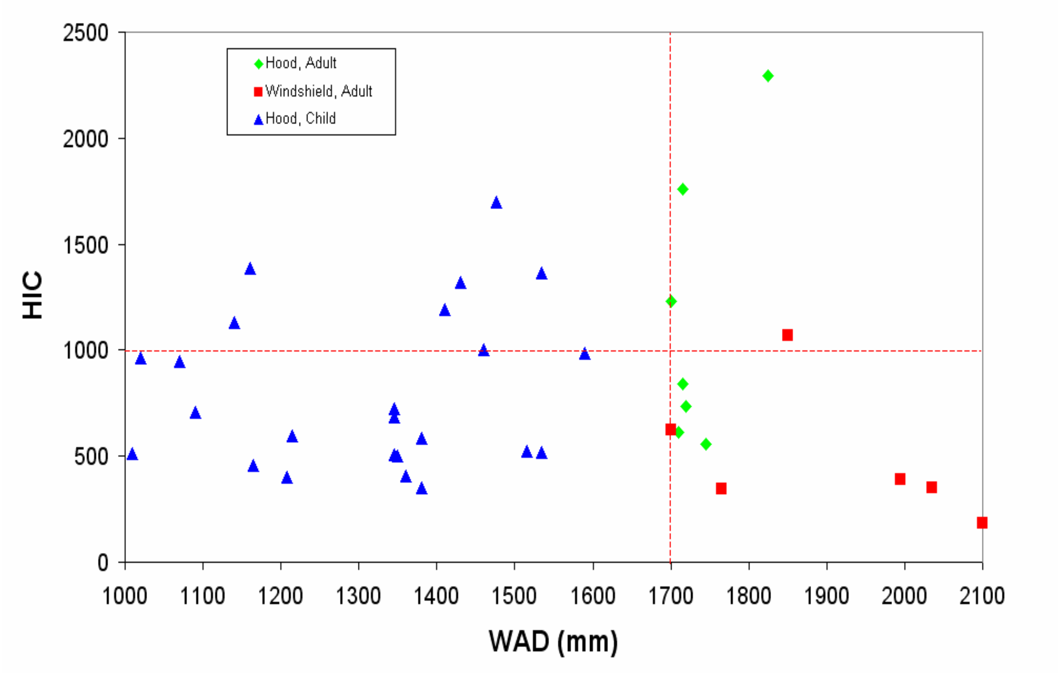


Figure 11. HIC by headform and impacted structure

In all, twenty-seven of the 38 tests resulted in a HIC value below 1000 (71%). Because the child test zone was always larger than the adult test zone, twenty-five of the 38 tests were child headform to hood (66%). Seventy-two percent (18 out of 25) passed the HIC requirement. Of the remaining 13 adult head tests, seven were to the hood and six were to the windshield. Four of the seven (57%) adult headform to hood tests resulted in HIC values below 1000, while five of six (83%) windshield tests passed the requirement.

The lowest HIC values typically occurred on the windshield and in areas of the hood where there were no underhood components or the clearance to those components was large. The highest HIC values were in hood edge areas. These areas included the hood/fender edge, dashboard, hood/windshield edge, and headlight. There were very few instances where mid-hood or mid-windshield locations had high HIC values due to contact with the underlying structure.

Only one of the six vehicles had all tests pass the requirement (Savana). However, this could have resulted because the hardest spots on the hood were not tested. Overall, it seems that a performance level requiring that all locations within the specified test zone need to be HIC = 1000 or below may be difficult to attain. On the other hand, this is test data from current vehicles not regulated for pedestrian safety. It is unknown if the GTR would change this trend for future vehicles if it were implemented in the U.S.

A possible feasibility compromise could be modification of the HIC requirement. For instance, if the HIC 15 ms requirement was 1500 instead of 1000, the pass rate would be 92% (35 of 38) and four of the six vehicles would be at 100% conformance in this test series. Figure 12 shows the relationship between conformance rate and HIC level for the sample of vehicles in this study. It should be noted that this relationship is just a snapshot; if tests were conducted at other locations or on different vehicles, this trend could very well change.

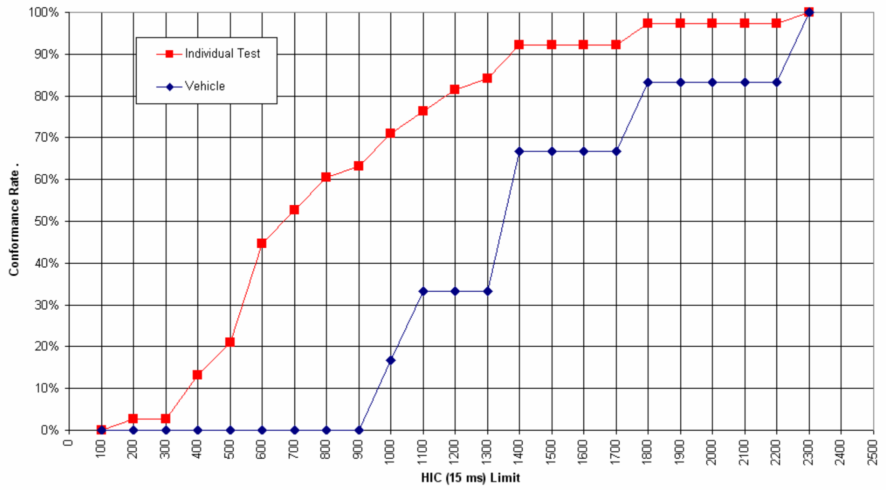
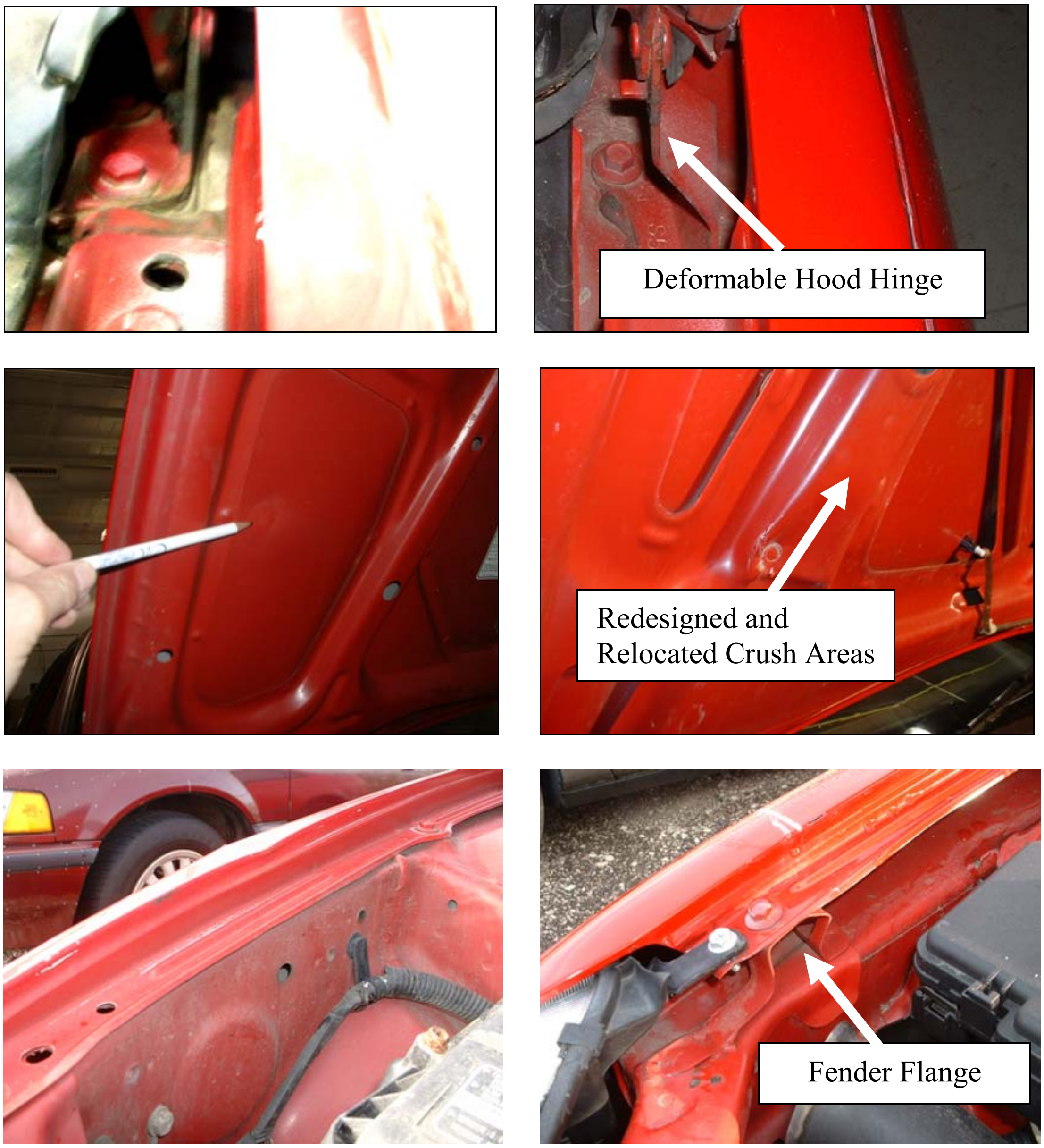


Figure 12. Relationship between HIC requirement and GTR conformity

The second part of this study dealt with two versions of a vehicle model, one eight years older than the other, to investigate the effect of countermeasures built into the newer model. The 2001 Honda Civic contained three countermeasures that did not exist in the 1994 version. These were deformable hood hinges, fender flanges, and areas of hood reinforcement re-positioned to areas of low underhood clearance (Figure 13).



1994 2001

Figure 13. Pedestrian safety countermeasures present in 2001 Civic

The deformable hinges (impact point #5) and fender flanges (impact point #4) allowed the hood to absorb more of the impact energy, including a portion of the energy normally absorbed by the nearby fender. The redesigned and relocated hood reinforcement (impact point #1) absorbed the energy associated with contact to the underhood structure by allowing a crush distance between the internal surface of the reinforcing structure and hood when the headform contacted the hood surface. These changes reduced HIC by nearly 70% (Figure 14). These types of changes were not unique to the Civic; similar structural countermeasures, especially well-placed crush structures in hood reinforcement, were present in some of the other vehicles.

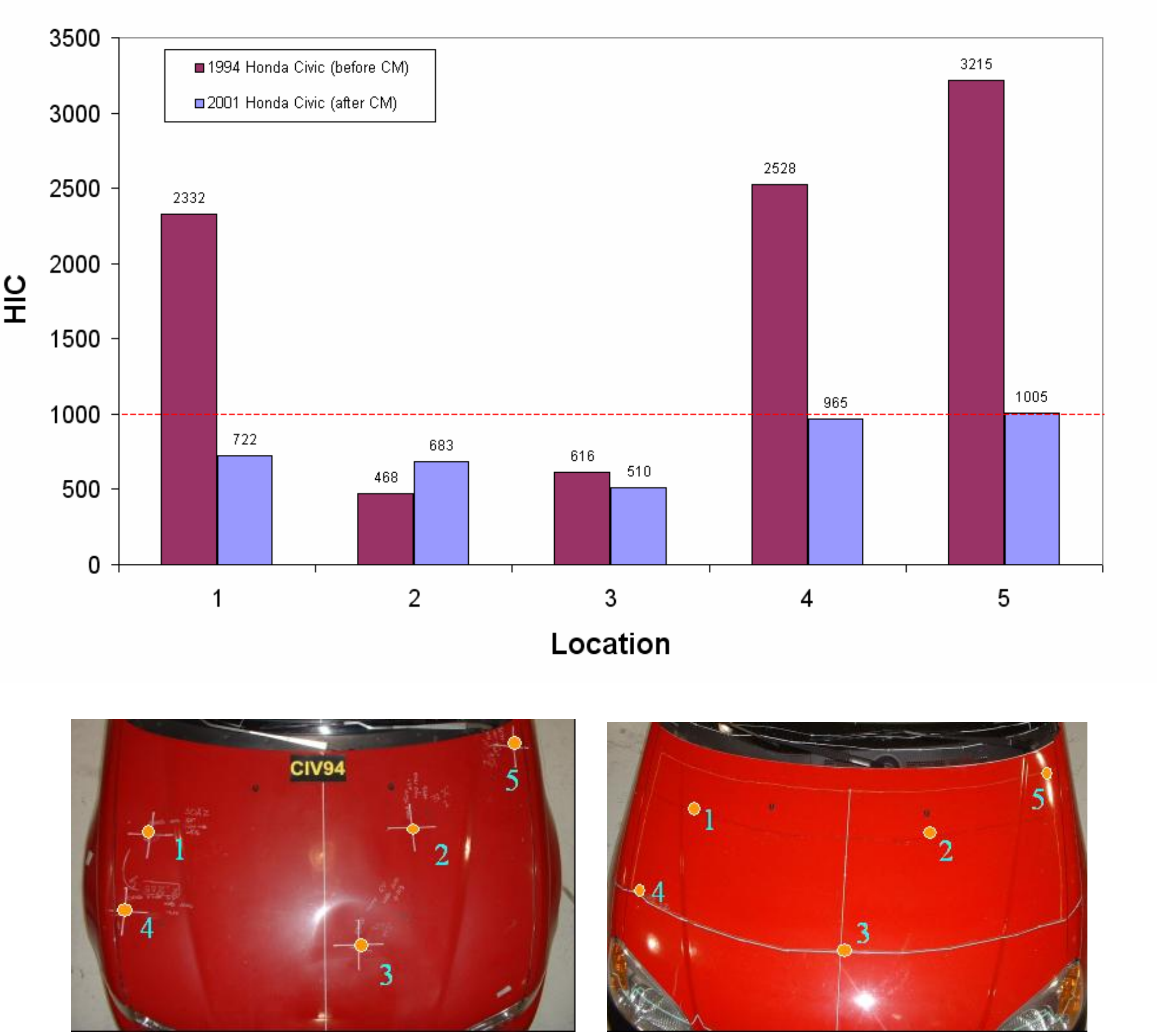


Figure 14. Effect of pedestrian safety improvements on Honda Civic from 1994-2001

There were some items in the GTR procedure that had to be interpreted. Most of these were related to test zone determination. The side reference lines often encompassed parts of the vehicle outside the hood edge, especially on the larger vehicles such as the Ram. It is not known if the GTR was intended for such areas. An offset of 82.5 mm was sometimes unnecessary, especially when it fell between child and adult zones on larger vehicles where the hood surface allowed for this transition area. The adult test zone is often very small and is sometimes subject to jagged edges due to the GTR method of determining the adult zone's rear edge reference lines. The method uses points of first contact between a headform and the vehicle. Structures such as windshield wipers and wiper fluid nozzles occasionally disrupt the linearity of the zone edge, much like vehicle leading edge geometry variations disrupt the child zone front reference line. Given the limited timeframe allowed for this study, VRTC opted to conduct multiple tests on a single hood, being careful to place impact points outside the deformation area of a previous impact. In preliminary testing, consistent HIC values resulted from primary (first impact to the hood) and secondary (after other impacts) tests at the same hood location, as long as they were outside the area of deformation caused by earlier tests. Also, critical areas of hood attachment such as a hood hinge were left until the end for each vehicle.

5. SUMMARY

The following bullets summarize this study's findings:

- Twenty-seven out of 38 head impact tests (71%) to the hood and windshield of six late model (2001-2004) vehicles sold in the U.S. had HIC values below 1000.

- Only one of six vehicles had a pass rate of 100%; however, it is possible that the hardest structure on that vehicle's front end was not tested.

- The extreme edges and corners of the test zones almost exclusively resulted in the most severe impacts.

- Countermeasures such as deformable hood hinges, fender flanges, crush zones in the hood reinforcing structure above hard frame/engine components, and large underhood clearances resulted in significant HIC reductions in the Civic.

- Some GTR portions had to be interpreted during this test series. These included test zone reference line details.

APPENDIX A: Test Result Summary

Test	Vehicle	Head	Hood/WS	Angle (deg)	WAD (mm)	Lat * (mm)	Type	HIC	Peak Acc (g)	Imp Vel (m/s)	Pass?
CIV01	2001 Honda Civic	C	H	65	1345	-460	50th %	722	109.6	8.95	Yes
CIV02	2001 Honda Civic	C	H	65	1345	+230	50th %	683	113.2	8.95	Yes
CIV03	2001 Honda Civic	C	H	65	1010	0	Best	510	108.6	8.95	Yes
CIV04	2001 Honda Civic	C	H	65	1020	-680	Worst	965	156.1	8.97	Yes
CIV05	2001 Honda Civic	C	H	65	1460	+680	Worst	1005	153.1	8.92	No
CIV06	2001 Honda Civic	A	WS	40	1765	-335	50th %	347	124.9	8.86	Yes
CIV07	2001 Honda Civic	A	WS	40	2100	0	Best	184	124.9	8.85	Yes
SAV01	2004 GMC Savana	C	H	60	1380	-560	50th %	582	101.8	8.94	Yes
SAV02	2004 GMC Savana	C	H	60	1380	+270	50th %	585	130.6	8.94	Yes
SAV03	2004 GMC Savana	C	H	60	1515	0	Best	524	100.6	8.98	Yes
SAV04	2004 GMC Savana	C	H	60	1590	+760	Worst	984	134.6	8.90	Yes
SAV05	2004 GMC Savana	A	WS	40	2035	-500	50th %	348	148.7	8.89	Yes
ESC01	2001 Ford Escape	C	H	60	1090	+225	50th %	708	104.8	8.88	Yes
ESC02	2001 Ford Escape	C	H	60	1070	-450	50th %	948	169.6	8.87	Yes
ESC03	2001 Ford Escape	C	H	60	1140	+670	Worst	1131	146.2	8.86	No
ESC04	2001 Ford Escape	C	H	60	1360	+115	Best	406	115.2	8.88	Yes
ESC05	2001 Ford Escape	A	H	90	1715	+230	50th %	839	115.8	8.97	Yes
ESC06	2001 Ford Escape	A	H	90	1700	-465	50th %	1230	173.1	8.90	No
ESC07	2001 Ford Escape	A	H	90	1825	+685	Worst	2292	247.8	8.94	No
RAM01	2003 Dodge Ram	C	H	60	1430	+310	50th %	1321	167.8	8.93	No
RAM02	2003 Dodge Ram	C	H	60	1410	-620	50th %	1193	141.9	8.92	No
RAM03	2003 Dodge Ram	A	H	90	1745	-620	50th %	555	104.1	8.87	Yes
RAM04	2003 Dodge Ram	A	H	90	1710	0	Worst	614	100.0	8.86	Yes
RAM05	2003 Dodge Ram	A	H	90	1700	+603	Best	626	106.0	8.88	Yes
CAM01	2004 Toyota Camry	C	H	65	1350	+230	50th %	502	123.6	8.95	Yes
CAM02	2004 Toyota Camry	C	H	65	1346	-480	50th %	508	121.8	8.95	Yes
CAM03	2004 Toyota Camry	C	H	65	1476	+640	Worst	1701	248.0	8.92	No
CAM04	2004 Toyota Camry	C	H	65	1164	-74	Best	454	99.0	8.90	Yes
CAM05	2004 Toyota Camry	A	H	65	1720	0	Medium	733	103.3	8.95	Yes
CAM06	2004 Toyota Camry	A	H	65	1715	-712	Worst	1759	201.4	8.88	No
CAM07	2004 Toyota Camry	A	WS	40	1995	+193	50th %	390	183.0	8.88	Yes
SIE01	2004 Toyota Sienna	C	H	60	1215	-550	50th %	598	100.9	8.91	Yes
SIE02	2004 Toyota Sienna	C	H	60	1208	+255	50th %	403	103.5	8.92	Yes
SIE03	2004 Toyota Sienna	C	H	60	1160	+680	Worst	1387	160.4	8.91	No
SIE04	2004 Toyota Sienna	C	H	60	1535	-755	Worst	1363	158.9	8.88	No
SIE05	2004 Toyota Sienna	C	H	60	1535	+250	Medium	518	100.4	8.92	Yes
SIE06	2004 Toyota Sienna	C	H	60	1380	0	Best	353	102.1	8.87	Yes
SIE07	2004 Toyota Sienna	A	WS	40	1850	+170	50th %	1070	143.9	8.87	No
CIV9401	1994 Honda Civic	C	H	65	1300	-570	CIV01	2332	270.5	8.97	No
CIV9402	1994 Honda Civic	C	H	65	1363	+283	CIV02	468	114.2	8.97	Yes
CIV9403	1994 Honda Civic	C	H	65	1010	+103	CIV03	616	156.3	8.96	Yes
CIV9404	1994 Honda Civic	C	H	65	1020	-655	CIV04	2528	244.3	8.97	No
CIV9405	1994 Honda Civic	C	H	40	1563	+675	CIV05	3215	303.0	8.96	No

*Lat is defined as the lateral distance from the vehicle longitudinal centerline. A negative value indicates passenger side and positive is driver side.

APPENDIX B: Determination of 50th percentile WAD estimates

Median wrap-around distance (WAD) for children and adults was calculated based on PCDS data (Table B1 and Table B2). Only cases under 40 km/h were considered because these are the cases targeted by the GTR. Including cases over 40 km/h (as in Table B3) increases the median wrap-around distances such that they are less applicable to the targeted cases.

There are an insufficient number of child cases at or under the age of 12 to assess typical wrap-around distance for different vehicle types (Table B1). Increasing the age limit for children would have increased the number of available cases, but would have lead to an overlap in the standing heights of pedestrians in the adult and child groups, such that some pedestrians over 152 cm (5 feet) would be classified as adults while some pedestrians over 152 cm would be classified as children.

Since WAD is assumed to be function primarily of standing height, the ratio of WAD to standing height was calculated for all cases with known WAD and standing height in cases with impact speeds of 40 km/h or lower (Table B2). Typical or median WAD for an child or adult was then calculated for each vehicle type by multiplying the median WAD-to-Height ratio by the median height for an adult and child respectively. The heights used were from the Center for Disease Control growth charts:

- the child height was based on the 50th percentile standing height for 6 year-olds which was 115 cm (45.3 inches) for both girls and boys
- the adult height was based on the 50th percentile standing height for 20 year-old males (177 cm) and females (163 cm) for an average 50th percentile standing height of 170 cm (66.9 inches).

Table B1. PCDS cases <=40 km/h with known WAD by Age Group & Vehicle Type

Average WAD

	Child (<= 12 years)			Adult (>12 years)			All		
	N	Median (cm)	μ (cm)	N	Median (cm)	μ (cm)	N	Median (cm)	μ (cm)
Minivan	1	125	125	14	185.5	185.0	*15*	*185*	*181.0*
Pass Car	19	145	146.0	64	201.5	197.9	*83*	*188*	*186.0*
Pickup	0	--	--	10	157.5	169.1	*10*	*157.5*	*169.1*
SUV	2	116	116.0	6	162.5	154.7	*8*	*146*	*145.0*
Van	0	--	--	3	144	160.3	*3*	*144*	*160.3*
All	*22*	*139.5*	*142.3*	*97*	*190*	*189.3*	*119*	*182*	*180.6*

Table B2. PCDS cases <=40 km/h (All ages) with known WAD by Vehicle Type

Average WAD to Height Ratio (WAD/Height)

				Estimated Median WAD for Adult/Child	
	N	Median (Ratio)	μ (Ratio)	Median WAD/Height x Height of 50th %ile Adult (170 cm)	Median WAD/Height x 50th %ile Child (115 cm)
Minivan	13	1.04	1.05	**176.8 cm**	**119.6 cm**
Pass Car	77	1.17	1.16	**198.9 cm**	**134.55 cm**
Pickup	8	0.96	1.00	**163.2 cm**	**110.4 cm**
SUV	8	0.94	0.92	**159.8 cm**	**108.1 cm**
Van	3	0.86	0.90	**146.2 cm**	**98.9 cm**
All	*109*	*1.07*	*1.11*	181.9 cm	123.05 cm

Table B3. PCDS cases with known WAD by Age Group & Vehicle Type: All speeds

Average WAD

	Child (<= 12 years)			Adult (>12 years)			All		
	N	Median	μ (cm)	N	Median	μ (cm)	N	Median	μ (cm)
Minivan	2	153	153.0	20	183.5	184.8	*22*	*181.5*	*181.9*
Pass Car	25	163	156.2	145	213	206.8	*170*	*205.5*	*199.4*
Pickup	1	108	108.0	19	163	174.8	*20*	*160.5*	*171.5*
SUV	2	116	116.0	14	156	161.2	*16*	*152*	*155.6*
Van	0	--	--	6	173	168.2	*6*	*173*	*168.2*
All	*30*		*151.7*	*204*		*197.4*			

Lower Extremity Pedestrian Injury in the U.S.: A Summary of PCDS Data

AB NOTE
06-01

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July 2006

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Executive Summary

This Applied Biomechanics (AB) Note summarizes a series of database searches performed regarding lower extremity injuries in US pedestrian crashes. US injury data is uniquely useful in understanding the effect of vehicle type on lower extremity injury because of the large number of light trucks and vans in the US fleet.

These studies are based on data from NHTSA's Pedestrian Crash Data Study, a database of 550 pedestrian crashes that occurred between 1994 and 1998. Variables considered included injury location, injury severity, vehicle type, vehicle dimensions, impact speed, and injury source. Case data was used to understand questions related to the need for pedestrian lower extremity regulation and the parameters necessary for such a regulation to be effective for US pedestrians.

US pedestrian case data shows the importance of lower extremity injuries, including above-the-knee injuries:

- Lower extremity injuries accounted for approximately one third of all AIS 2-6 pedestrian injuries and one quarter of AIS 3-6 injuries, which supports the need for improvement of pedestrian lower extremity protection.
- Above-the-knee injuries to the lower extremity (thigh, hip, and pelvis injuries) make up almost half of the AIS 3-6 lower extremity injuries reported in US pedestrian crashes. The incidence of above-the-knee injuries is even higher among children.
- Light trucks and vans caused a disproportionately high number of above-the-knee injuries.
- Even when injuries from potentially intractable vehicle sources and speeds are removed from the analysis, and results are projected to a current or future fleet, above-the-knee injuries are expected to continue to account for approximately half of lower extremity injuries. The frequency of these injuries supports consideration of thigh, hip, and pelvis evaluation in test procedures for the US fleet.

Light trucks and vans have higher bumpers on average than passenger cars. **Based on proposed bumper height limits in the current draft of the GTR, different leg test procedures apply to different vehicles in the US fleet.** The percentage of US vehicles subjected to each test procedure depends on these defined limits.

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1 Introduction

During the development of a pedestrian leg test procedure by the International Harmonized Research Activities (IHRA) Pedestrian Safety Working Group (PSWG), many questions have arisen regarding the nature and frequency of lower extremity injuries in the United States. Because of the large presence of sport utility vehicles and other large vehicles on the road in the US, American injury data is uniquely useful in understanding the effects of vehicle type and size on lower extremity injury. It has been reported in previous studies of US data that the risk and nature of lower extremity injuries is affected by vehicle type (Ballesteros 2004, Matsui 2005).

This summary is intended to compile the results of a series of database searches performed by VRTC in support of the development of a lower extremity test procedure, and to understand the applicability of such a procedure to US vehicles.

The analyses presented here were based on the 550[1] cases in NHTSA's Pedestrian Crash Data Study (PCDS) database collected between 1994 and 1998. These cases were collected by six of the zone centers already in place to conduct NASS/CDS investigations (NCSA, 1996). Each center investigated all pedestrian crashes of which they were aware in their region that met PCDS inclusion criteria. They were alerted to pedestrian crashes by monitoring police radio or other methods. Inclusion criteria were as follows:

- pedestrian impact was by forward-moving vehicle,
- vehicle must be CDS applicable (late model and vehicle VEH07 code between 01 and 49),
- pedestrian was not lying or sitting,
- striking portion of the vehicle was previously undamaged OEM parts,
- pedestrian impact was vehicle's only impact,
- first point of contact with pedestrian is forward of the top of the A-pillar.

All eligible cases were included in PCDS, without sampling or weighting and are therefore believed to be reasonably representative of pedestrian crashes in that time period. Of those 550 cases, 540 had at least one injury of known severity, and 346 had a lower extremity injury attributed to impact by vehicle front structures. Bumper impacts resulted in lower extremity injury to 287 pedestrians.

For the purpose of this study, lower extremity injuries were defined as all injuries coded with the abbreviated injury scale (AIS) in the lower extremity body region. Under that coding system, pelvic fractures are included as lower extremity injuries, while injury to pelvic contents are coded with abdominal injuries. A list of injuries included as lower extremity injuries is in Appendix A.

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[1] As per personal communication with Marv Stephens of NCSA, two duplicate cases were excluded from publicly available, 552-case version of database.

Searching by vehicle type was based on the PCDS classification of vehicle type by passenger car (PC) or light truck or van (LTV). Sub-categories of LTV are minivans (MV), pickup trucks (PU), sport utility vehicles (SUV), and full-size vans (VAN). PCDS codes used to classify vehicles by body type are listed in Appendix B.

While the majority of lower extremity injuries are sustained in a direct impact by the striking vehicle, injuries such as those incurred when the pedestrian is thrown to the ground or run over by the tires may not be affected by improvements to the front structures of vehicles. Such injuries can be separated from those caused by parts of the vehicle which might be improved. In UMTRI's prior study of PCDS data (Klinich 2003), lower extremity injuries were considered "relevant" if the injury source was determined to be a vehicle component that "might be affected by regulation (such as bumpers and hood)". In an effort to make the current analysis comparable to the UMTRI analysis, "relevant" injury sources in this report are the front bumper, valence, spoiler, grille, hood edge/trim, headlamps and signal lamps, other front objects, front fenders, A-pillar, front antenna, hood surface, cowl, wiper blades and mountings, and windshield glazing. "Not relevant" sources are the side door, mirror, other side object, front header, roof surface, wheels/tires, ground, or other object in the environment. Among all lower extremity injuries in the PCDS dataset, 76% were from "relevant" sources. Among AIS 2-6 or AIS 3-6 lower extremity injuries, 89% were from "relevant" sources.

2 Frequency of Lower Extremity Injury

An analysis of the frequency of lower extremity injury in US pedestrian impacts was performed to determine the relative importance of lower extremity injury among US pedestrians.

During the five-year period of the PCDS data collection, there were an average of 5,395 pedestrians killed and 78,000 pedestrians injured annually in the US[2]. Of these pedestrian crashes, 550 were included in the PCDS database. From the 550 cases investigated, 460 cases included at least one known lower extremity injury. A total of 1464 lower extremity (LE) injuries were documented. Based on the PCDS analysis, injuries to the lower extremities are more frequent than any other body region, comprising approximately one third of the injuries documented in the PCDS database (Figure 2.1). Neglecting minor injuries, lower extremity injuries make up approximately one third of AIS 2-6 injuries in the database, and one quarter of AIS 3-6 injuries (Figure 2.2, Figure 2.3). At the AIS 3-6 level, lower extremity injuries are second in frequency to head injuries.

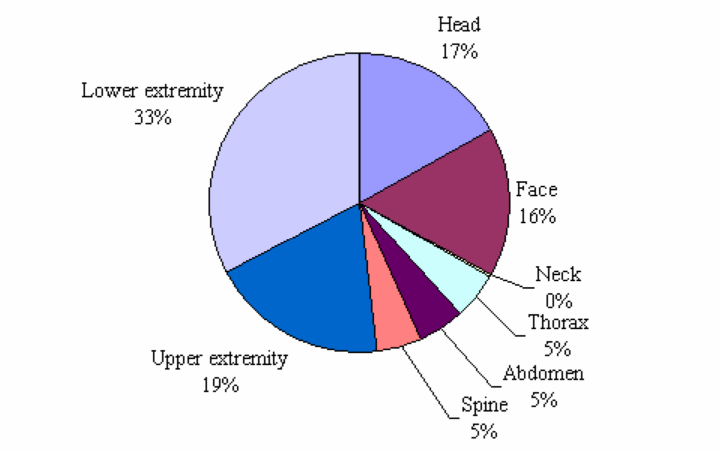

Figure 2.1. Distribution of injuries in PCDS (all injury severities)

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[2] These counts are rounded averages drawn from NHTSA's Traffic Safety Facts publications from 1994 to 1998, available from http://www-nrd.nhtsa.dot.gov/departments/nrd-30/ncsa/AvailInf.html . The number of pedestrians injured in 1994 was not available from the Traffic Safety Facts publication for that year; injury estimates are therefore based on data for 1995 to 1998.

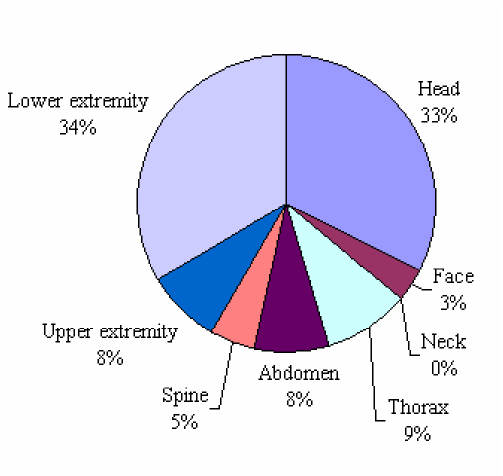


Figure 2.2. Distribution of moderate or worse injuries (AIS 2-6)

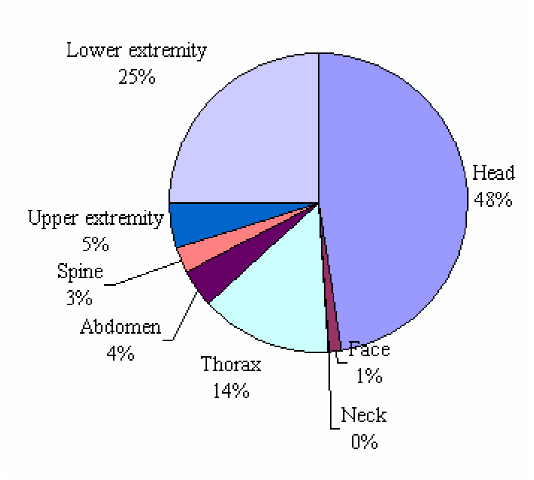


Figure 2.3. Distribution of serious or worse injuries (AIS 3-6)

The number of pedestrians with lower extremity injuries at the moderate or worse level (AIS 2-6) and the serious or worse level (AIS 3-6) are listed in Table 2.1.

Table 2.1. Total number of lower extremity (LE) injuries in the PCDS database (N=550)

	Total LE Injuries	Total Pedestrians with LE Injury
All injuries	1464	460
AIS 2-6	497	202
AIS 3-6	206	121

The high incidence of AIS 2-6 and AIS 3-6 lower extremity injuries among pedestrians in US accident data supports efforts to improve pedestrian lower extremity protection offered by US vehicles. Although less frequent than head injuries at the AIS 3-6 severity level (Figure 2.3), serious lower extremity injuries are more frequent than any other serious injury type in pedestrian crashes.

3 Distribution of Upper and Lower Leg Injuries

The current version of the GTR proposes different test procedures for high-bumper vehicles. The following analysis was performed to evaluate the prevalence of above-the-knee injuries among US pedestrians, in order to ultimately determine the benefit and target population of a test procedure for high-bumper vehicles.. It was important to perform this analysis on US data because it was assumed that the larger vehicles in the US fleet tend to produce more upper leg injuries than are seen in other countries.

The lower extremity injuries sustained by pedestrians are sorted here by the level of the injury. Using the full AIS injury code, each lower extremity injury was categorized as one of the following: hip/pelvis, thigh, knee, lower leg, ankle/foot, and skin. A listing of specific injuries included in each injury category is included in Appendix A.

As shown in Figure 3.1 to Figure 3.3, the distribution of injuries over the sub-regions of the lower extremity vary depending on the injury severities considered. Skin injuries are predominant if all injuries are considered. At the AIS 2-6 level, lower leg injuries are most common, with injuries at or below the knee accounting for almost 70% of injuries to the lower extremity. Among injuries that were serious or worse (AIS 3-6), thigh, hip and pelvis injuries gain importance, comprising almost half of the serious lower extremity injuries in the PCDS database.

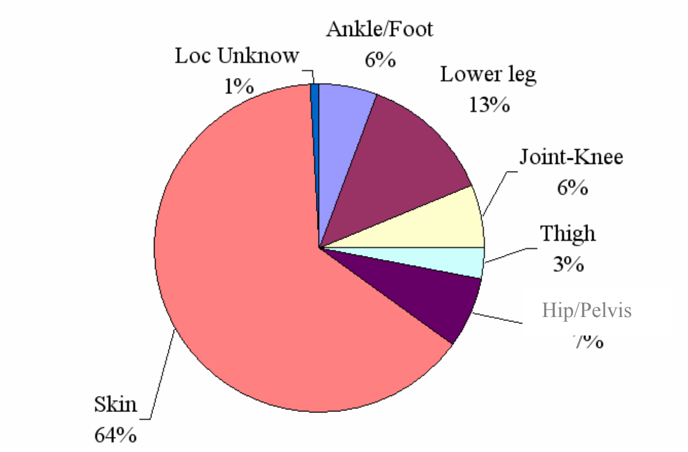


Figure 3.1. Location of lower extremity injuries (AIS 1-6)

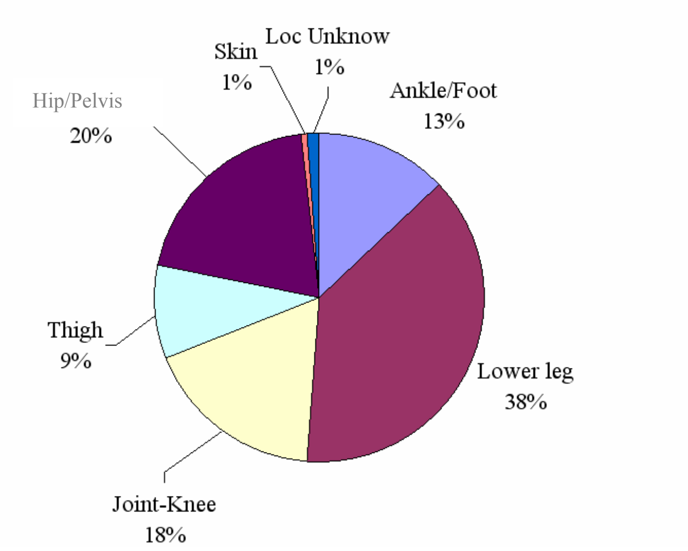


Figure 3.2. Location of moderate and worse lower extremity injuries (AIS 2-6)

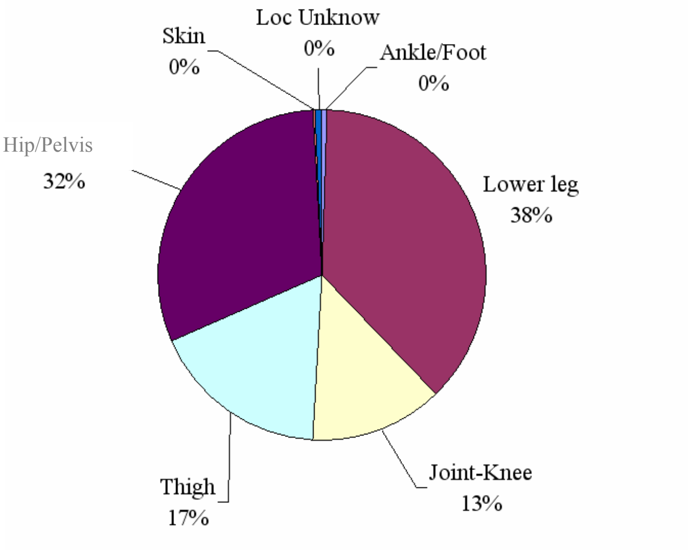
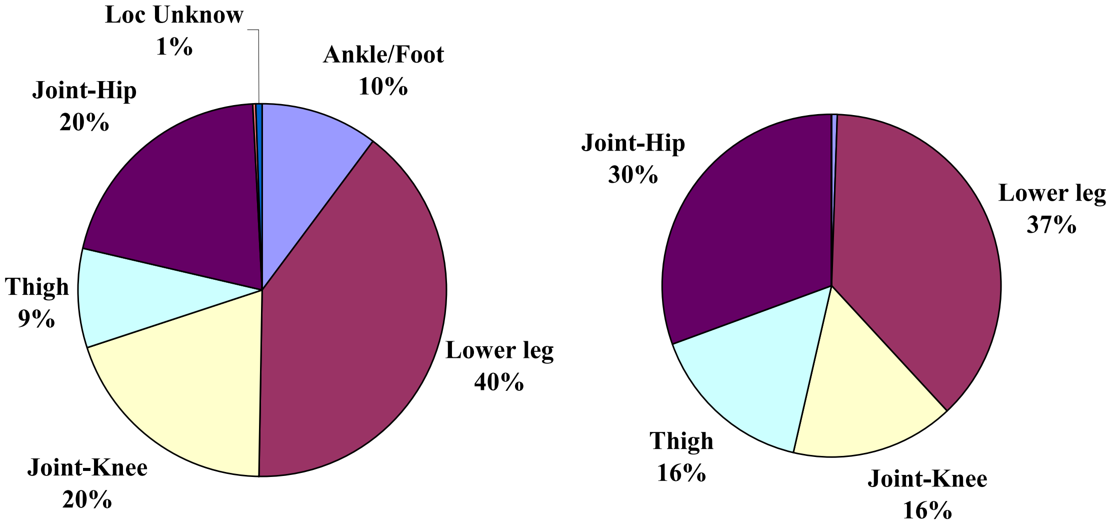


Figure 3.3. Location of serious and worse lower extremity injuries (AIS 3-6)

The distribution of injuries between structures at and below the knee versus structures above the knee has implications for regulating pedestrian protection. The fact that hip, pelvis, and thigh injuries make up 29% of AIS 2-6 lower extremity injuries and almost half of AIS 3-6 lower extremity injuries suggests that test procedures measuring risk to the upper leg may be useful.

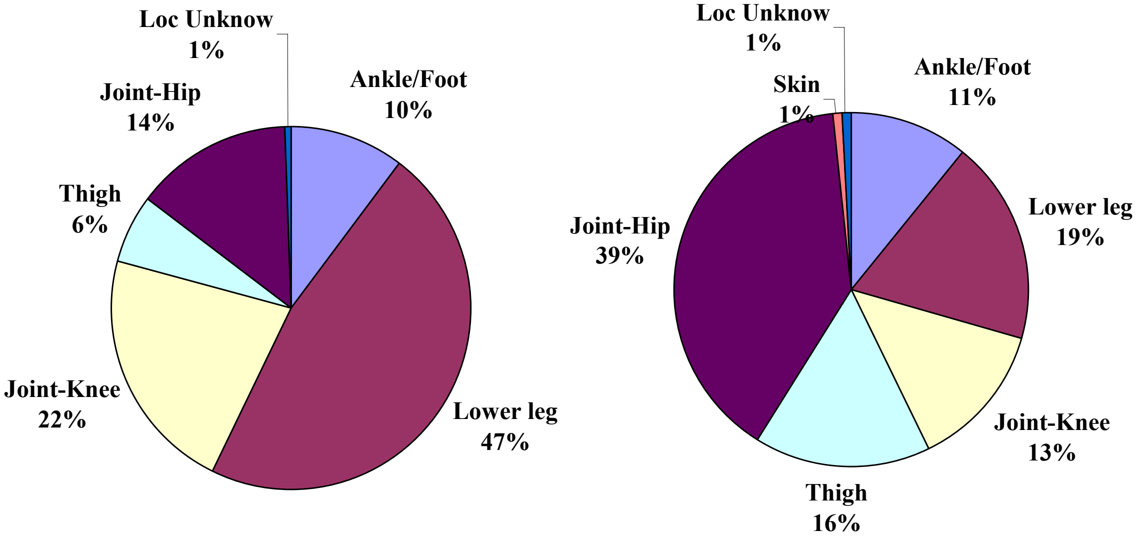
Figure 3.4 shows that when only injuries from "relevant" sources are considered, hip, pelvis, and thigh injuries make up 29% of the total number of moderate and worse injuries (AIS 2-6) and 46% of the total number of serious and worse injuries (AIS 3-6). Even if injuries from intractable sources are ignored, serious upper leg injury is still frequent in the PCDS database.



AIS 2-6 AIS 3-6

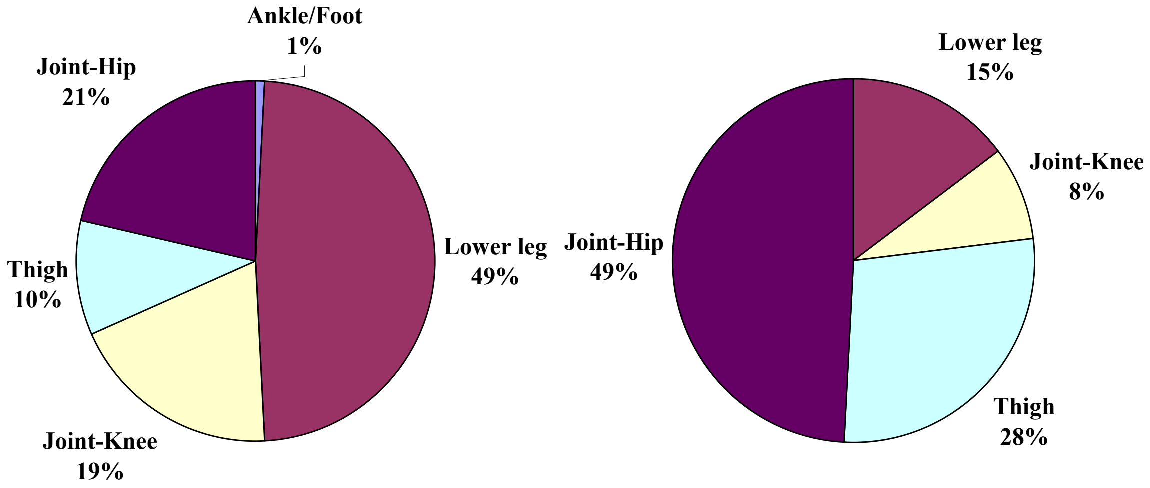
Figure 3.4. Location of injuries from "relevant" sources only

As shown in Figure 3.5 and Figure 3.6, a disproportionately large number of the above-the-knee injuries (thigh, hip, and pelvis) are a result of LTV impacts, while a disproportionately large number of the knee and lower leg injuries are a result of passenger car impacts.



Passenger Cars Light Trucks and Vans

Figure 3.5. Location of AIS 2-6 lower extremity injuries from "relevant" sources by vehicle type



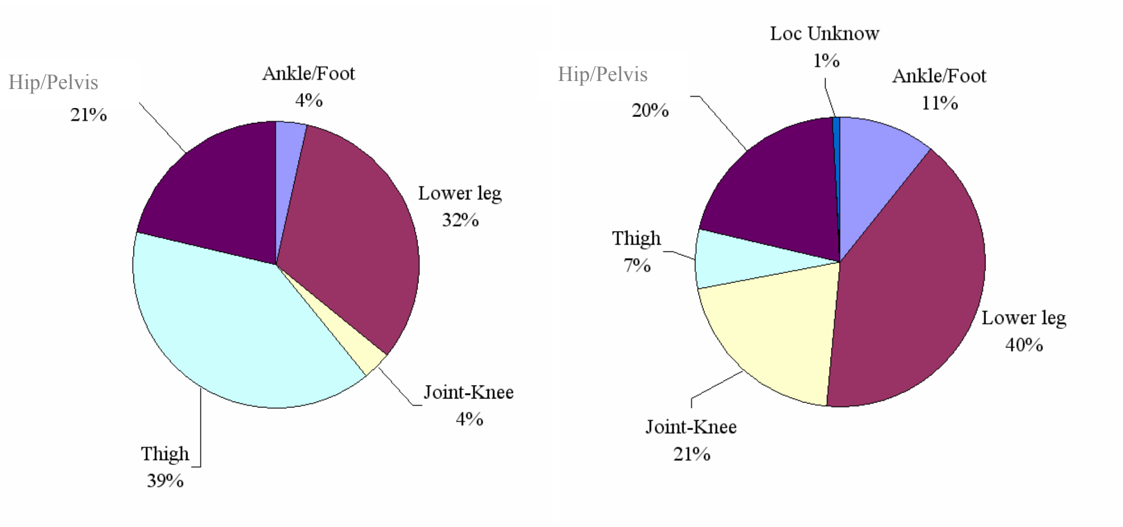
Passenger Cars

Light Trucks and Vans

Figure 3.6. Location of AIS 3-6 lower extremity injuries from "relevant" sources by vehicle type

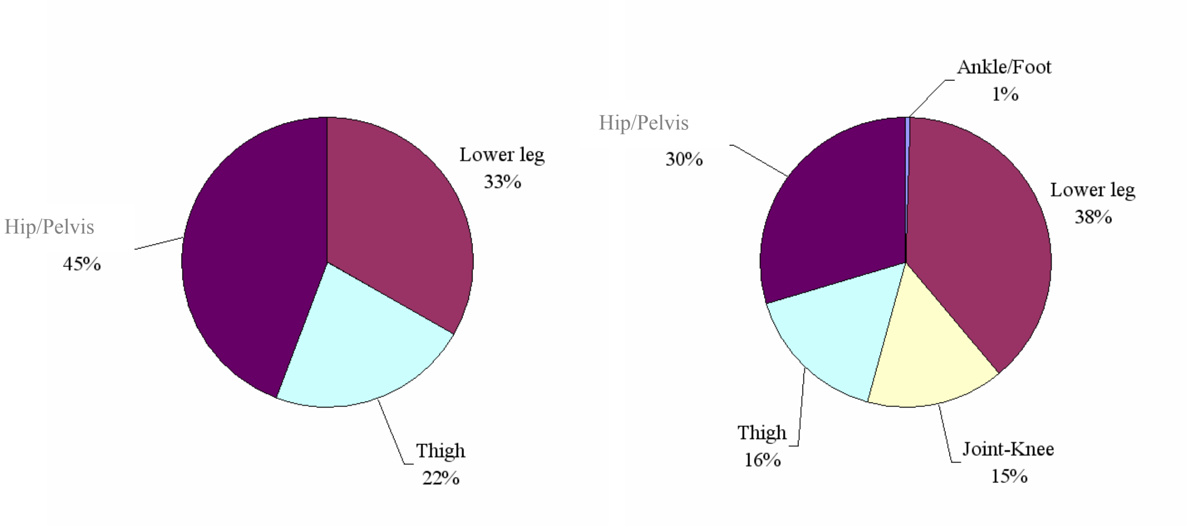
The distribution of upper and lower leg injuries found in the current study are consistent with the findings of a prior study of 2942 injured pedestrians (including 1,261 with "non-superficial" lower extremity injuries) in Maryland from 1995 to 1999 (Ballesteros 2004). Those results showed that sport utility vehicles and pickups resulted in a higher percentage of traumatic brain injuries (TBI), thoracic, abdominal, and spinal injuries, and injuries to the lower extremities *above* the knee, but a lower percentage of injuries *below* the knee. Ballesteros et al. attributed the higher percentage of below-knee injuries in passenger car impacts to their lower bumper height, as well as more dramatic downward pitching of the bumper during braking than in larger trucks or vans.

In order to determine if children are sustaining a higher percentage of upper leg injuries as a result of their short stature, injury location was compared for pedestrian lower extremity injuries among pedestrians age 12 and under ("children") and pedestrians older than age 12 ("adults"). Figure 3.7 and Figure 3.8 show that children sustain a higher percentage of hip, pelvis, and thigh injuries, and a lower percentage of lower leg and knee injuries than do adults.



“Children” (age 12 and under) Adults (over age 12)

Figure 3.7. Location of AIS 2-6 injuries from “relevant” sources, by age group



“Children” (age 12 and under) Adults (over age 12)

Figure 3.8. Location of AIS 3-6 injuries from “relevant” sources, by age group

Although IHRA PSWG discussion has focused on evaluation of lower leg injuries, analysis of US pedestrian injury data shows that above-the-knee injuries account for a significant portion of lower extremity injuries. The frequency of above-the-knee injuries in the PCDS database supports consideration of upper leg injury evaluation in test procedures for the US fleet for both adults and children.

4 Upper Leg Injury Sources

If upper leg, pelvis, hip injuries are occurring at such a frequency in US pedestrian crashes that a pedestrian regulation should be considered, it is important to know what type of impacts are producing these injuries. A PCDS database search was performed to understand which injuries are caused most frequently by which vehicle components in order to better understand which vehicle components and body regions should be included in a pedestrian test procedure. Table 4.1 shows the injury source distribution for relevant AIS 2-6 injuries in the PCDS database. For all injury types at thigh level and below, the front bumper was the most common injury source. At hip and pelvis level however, bumper impact was responsible for only 1% of the relevant injuries. In order of frequency, the most common injury sources for hip and pelvis injuries were the hood edge/trim, the hood surface, and the grille.

Table 4.1. Injury sources for lower extremity injuries by sub-region for AIS 2-6 relevant injuries with known injury source only

	Ankle/foot n=46	Lower leg n=176	Knee n=86	Thigh n=39	Hip/Pelvis n=90	Skin/Unknown n=4
Front bumper	74%	80%	85%	64%	1%	75%
Front lower valence	7%	4%				
Grille		3%		13%	11%	1%
Hood edge/trim		3%		10%	52%	
Headlight/signals		1%	3%	3%	1%	
Other front object	15%	5%	8%			
Fender	4%	5%	5%	8%	6%	
A-Pillar					1%	
Hood surface				3%	24%	
Cowl area					1%	
Windshield					2%	

Currently, proposed lower extremity test procedures involve front bumper testing with one of two possible test tools, depending on the height of the bumper. Since thigh injuries are occurring most frequently in bumper impacts while hip and pelvis injuries appear to be occurring more often in hood and grille impacts, it may not be possible to evaluate thigh, hip and pelvis injuries with bumper testing alone. A pelvis test to the hood, hood edge or grille may be required to evaluate the risk of hip and pelvis injuries, while it may be possible to evaluate the risk of thigh injury in bumper tests.

5 Lower Extremity Injury: Future Projections

The total number of pedestrian fatalities and injuries has been declining in the years since the PCDS was conducted. From an approximate average total of 5,398 deaths and 78,000 injuries during the PCDS period of collection, the total fell to 4,749 deaths and 70,000 injuries by 2003 (NCSA, 2004). These total fatalities and injuries have been collected via NHTSA's FARS and NASS/GES databases, which do not document injury details. In order to estimate how the proportions of different injury types have changed and how they will continue to change, PCDS case data was used to project how lower extremity injuries are changing, even as the total number of injuries is falling.

As discussed in the previous section, the frequency of upper leg impacts varies with the vehicle type. LTV bumpers tend to be higher (as discussed in section 7), and are therefore expected to result in more upper leg injuries than those of passenger cars. As the composition of the US fleet changes, an increase in the number of LTV's on the road might be expected to change the proportion of upper and lower leg injuries among pedestrians. Estimates of growing LTV representation in the US driving fleet were used to extrapolate the distribution in upper and lower leg injuries in the PCDS study to current and future timeframes.

PCDS cases include crashes that occurred from 1994 to 1998 (mean 1996.4, median 1996). Vehicle models ranged from 1988 to 1999 (mean 1993.2 and median 1993).

During the period of data collection (1994 to 1998), LTV registrations as a percentage of total registrations increased steadily from approximately 32% to approximately 36%[3] for an average of approximately 34%. LTV sales increased from approximately 41% to 47% during the same period. By 2001, LTV registrations comprised approximately 38% of the fleet[3], while sales of LTV's had reached almost 50% of all sales by 2002[4]. Review of sales and registration trends since the mid-1980's shows that the fleet percentage of registered LTV's trails the percentage of sold LTV's by five to ten years. Given the steady annual increase in registrations and sales of LTV's, an estimate of *current* LTV registrations is at least 40% and rising. It is reasonable, assuming sales trends continue, to predict that *future* LTV registrations will reach 50% as registrations catch up to sales.

Given the projections of at least 40% LTV's in the current fleet and 50% in the near future, the distribution of injury location by vehicle type for the PCDS data can be extrapolated to project how leg injury distribution might change with the changing fleet. This analysis is repeated in Table 5.1 and Table 5.2 for all lower extremity injuries at the AIS 2-6 and AIS 3-6 levels. For example, the estimated future distribution of AIS 2-6 knee injuries in passenger car and LTV impacts was calculated by multiplying the

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[3] "Initiatives to Address Vehicle Compatibility", NHTSA report, June 2003, *www-nrd.nhtsa.dot.gov/departments/nrd-11/aggressivity/IPTVehicleCompatibilityReport/*. (Percentages were estimated from bar-chart in this report).

[4] Kahane CJ. "Cost Per Life Saved by the Federal Motor Vehicle Safety Standards", NHTSA report, December 2004, DOT HS 809 835. (Percentages were drawn from Tables 1 and 3.)

number of PCDS knee injuries in LTV impacts (73) by 0.50/0.34 to reflect the growing percentage of LTV in the fleet and multiplying the number of PCDS knee injuries by passenger cars (16) by 0.50/0.66 to reflect the shrinking percentage of passenger cars in the fleet. The resulting total number of knee injuries dropped from 89, which was 18% of the total AIS 2-6 lower extremity injuries in PCDS to an expected 79 injuries, which was 17% of the expected total AIS 2-6 lower extremity injuries in the projected future fleet.

Table 5.1. Projected distribution of lower extremity injury based on growing percentage of LTVs in US fleet – all AIS 2-6 injuries

	PCDS 1994-98 34% LTV Fleet				Projected Current 40% LTV Fleet		Projected Future 50% LTV Fleet	
	PC	LTV	Total%		Total%		Total%	
Ankle/Foot	44	21	13%	69%	13%	67%	14%	65%
Lower leg	162	27	38%		37%		34%	
Knee	73	16	18%		17%		17%	
Thigh	25	20	9%	29%	9%	31%	10%	34%
Hip/Pelvis	51	50	20%		22%		24%	
Skin	1	2	1%		1%		1%	
Loc Unknown	4	1	1%		1%		1%	
Total			100%		100%		100%	

Table 5.2. Projected distribution of lower extremity injury based on growing percentage of LTVs in US fleet – all AIS 3-6 injuries

	PCDS 1994-98 34% LTV Fleet				Projected Current 40% LTV Fleet		Projected Future 50% LTV Fleet	
	PC	LTV	Total%		Total%		Total%	
Ankle/Foot	1	0	0%	50%	0%	49%	0%	44%
Lower leg	65	12	37%		36%		32%	
Knee	22	5	13%		13%		12%	
Thigh	17	19	17%	48%	18%	50%	20%	55%
Hip/Pelvis	29	34	31%		32%		35%	
Skin	1	0	0%		0%		0%	
Loc Unknown	1	0	0%		0%		0%	
Total			100%		100%		100%	

This extrapolation is based on the assumption that vehicle shapes for passenger cars and LTV's remain relatively constant over the period extrapolated. This assumption is supported by data presented to NHTSA by the Alliance for Automobile Manufacturers in 2004 showing that vehicle front-end dimensions for current models were not outside of the range of dimensions for vehicles included in the PCDS database. No data was available to determine how pedestrian-friendly design improvements to supporting structures change current or future extrapolations. Other possible shifts in pedestrian crash conditions since the 1990's, such as pedestrian demographics, vehicle speeds, and road design, were unknown and were not accounted for in this analysis. It is expected, however, that changes in these conditions would have less effect on lower extremity injuries than the dramatic increase in LTV's in the fleet, and would not be expected to negate the rise in upper leg injuries projected as the LTV's become more common.

In spite of the reported drop in the total number of pedestrian injuries since the timeframe of the PCDS data collection, there were still 4,641 pedestrians killed and 68,000 pedestrians injured in 2004.[5]. This analysis shows that the ratio of injuries to the upper leg versus the lower leg among US pedestrians is expected to increase as the number of LTV in the fleet increases. Considering only injuries at the AIS 3-6 severity level, upper leg injuries would be expected to become more frequent than lower leg injuries given the projected increases in LTV presence in the fleet. If the analysis is repeated for only "relevant" injuries, the resulting relative percentages of lower leg and upper leg injuries change only minimally. As a result, a pedestrian test procedure that evaluates only lower leg injuries may be less effective than one that also evaluates the risk of upper leg injuries.

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[5] NCSA, "Traffic Safety Facts 2004", available from http://www-nrd.nhtsa.dot.gov/pdf/nrd-30/NCSA/TSFAnn/TSF2004.pdf.

6 Vehicle Impact Speed and Lower Extremity Injury

The effects of vehicle speed on the frequency and distribution of lower extremity injuries were also explored in the current analysis of PCDS. The relationship between vehicle speed and injury source was considered. The purpose of this comparison was to determine if injuries to particular regions of the leg or by particular vehicle types or vehicle structures were occurring predominantly at higher speeds. If, for example, upper leg injuries tended to occur at high-speed, improvements to vehicle front structures may not be sufficient to prevent these high-speed injuries, thereby reducing the potential benefit of vehicle regulations.

Mean impact speed in PCDS was 29.4 km/h for passenger cars and 26.3 km/h for light trucks and vans, although this difference was not statistically significant (p=0.13) (Figure 6.1) A study of Maryland pedestrians showed an opposite relationship, with sport utility vehicles and pickup trucks involved, on average, in higher-speed pedestrian impacts (Ballesteros 2004). It was noted, however, that speed estimates were based on police reported speed limits rather than accident reconstructions. The PCDS cases were reconstructed using data including skid marks, point of impact, and point of rest to calculate stopping distance and estimated speed at the time of the collision.

For both passenger cars and LTV's, mean impact speed was only very slightly higher in PCDS cases with a lower extremity injury than when compared to all PCDS cases. Mean impact speed was higher when only cases with more severe lower extremity injuries were considered.

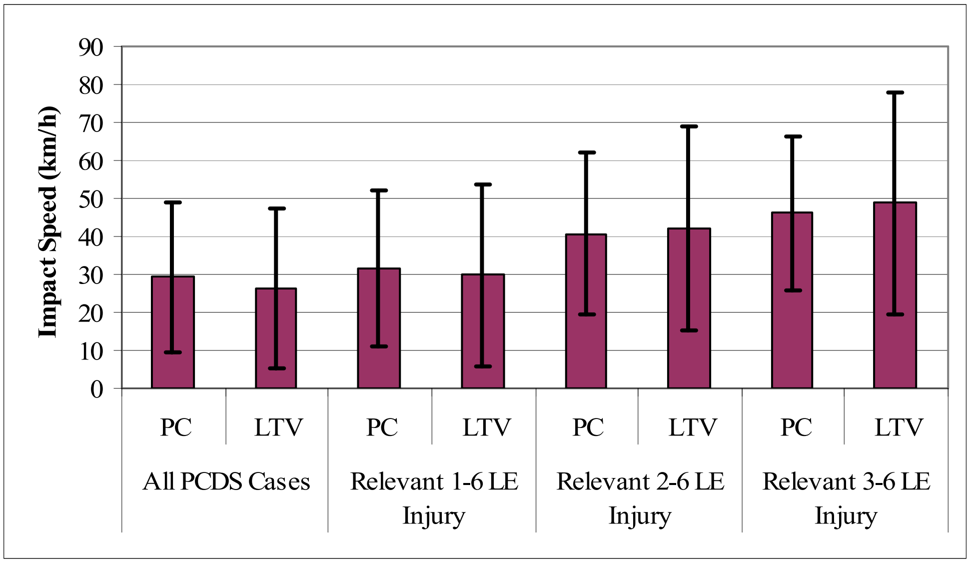


Figure 6.1. Mean impact speed (+/- 1 std dev) for all pedestrians in the PCDS database, compared to pedestrians with "relevant" lower extremity injuries at severity levels of AIS 1-6, AIS 2-6, and AIS 3-6, for all cases with known speed.

Figure 6.2 shows the variation of mean impact speed by different injury types. At both injury severity levels shown, knee injuries occurred at the lowest mean impact speed (26.8 km/h for AIS 2-6 injuries and 35.7 km/h for AIS 3-6 injuries). This difference suggests that the knee is more susceptible to injury at lower speeds, while hip/pelvis, thigh, and lower leg injuries are more likely in higher energy impacts.

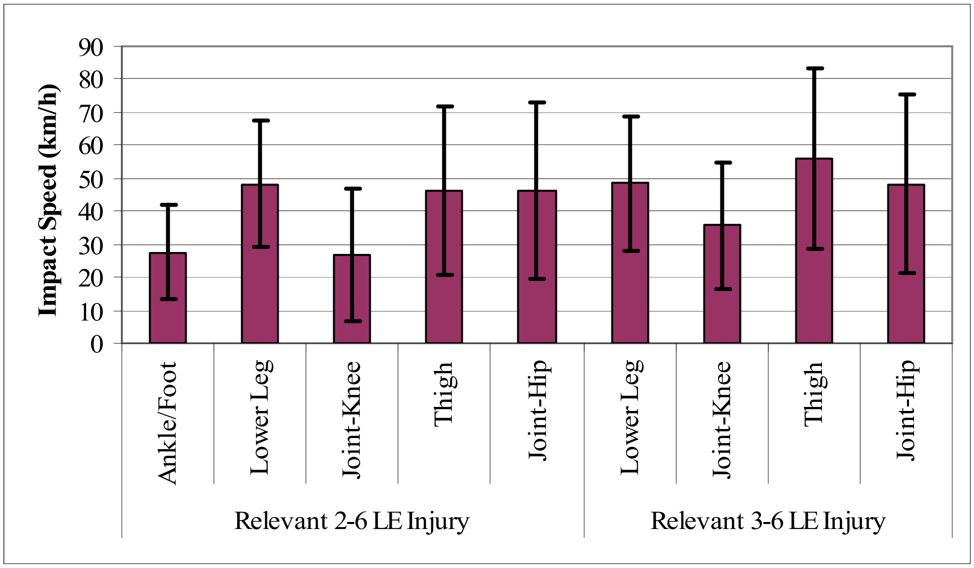


Figure 6.2. Mean impact speed (+/- 1 std dev) for "relevant" AIS 2-6 and AIS 3-6 injuries to different parts of the lower extremity for all cases with known speed.

These speed results are consistent with those reported by Matsui, whose PCDS search was limited to AIS 2+ tibia fractures, femur fractures, and knee ligament injuries to adults (Matsui 2005). That study showed that mean impact velocity was higher for femur fractures ($p=0.06$) and for tibia fractures ($p=0.02$) than for knee ligament injury. They proposed that while a higher impact velocity would produce fracture, lower impact energy, insufficient to fracture bone, would result in tensile stress to ligaments.

It is useful to consider the impact speed at which different vehicle structures produce injury. Since injuries produced at very high impact speeds may be considered intractable, it may not be effective to regulate pedestrian safety by testing structures that tend to produce injury only at high speeds. The variation in mean impact speed was compared for different injury sources (Figure 6.3 and Figure 6.4). The mean impact speed in moderate bumper-related injuries (39.3 km/h) was lower than for grille (57.4 km/h) or hood surface (85.3 km/h) injuries, but comparable to the mean impact speed for hood edge injuries (39.3 km/h). However, the significant overlap in impact speeds for varied injury sources and the small number of non-bumper injury sources make it difficult to identify any definite trends.

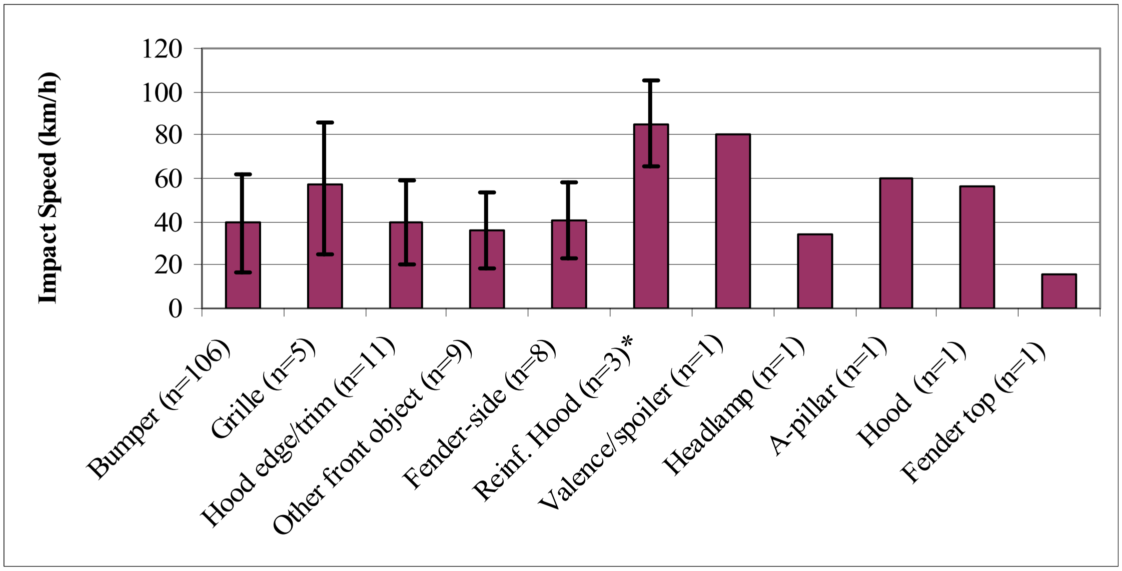


Figure 6.3. Mean impact speed (+/- 1 std dev.) for "relevant" AIS 2-6 injuries from different injury sources for all cases with known speed. (*Reinf. Hood is hood surface reinforced by under hood components.)

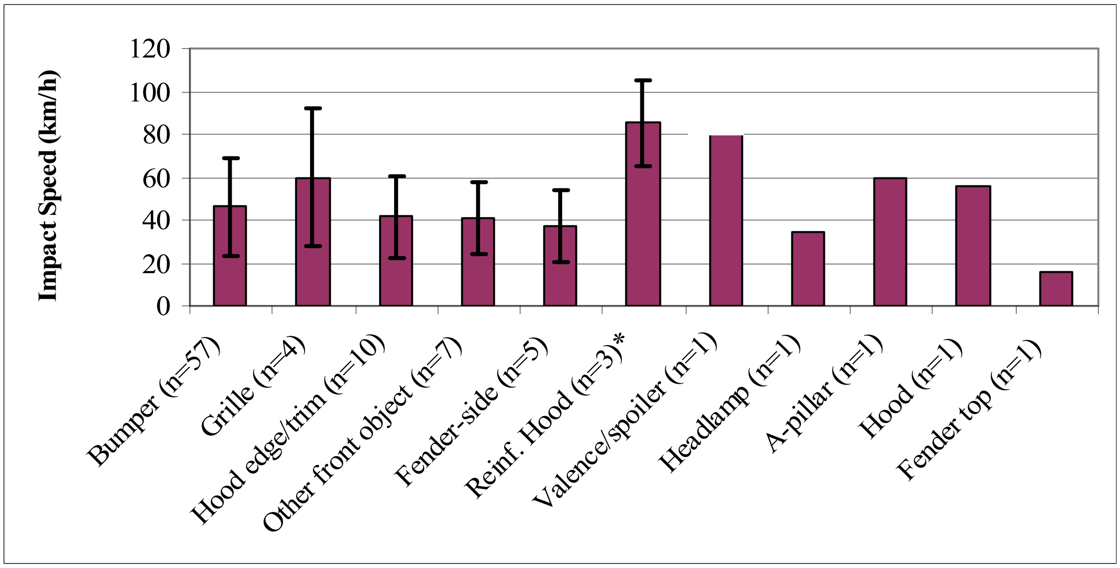
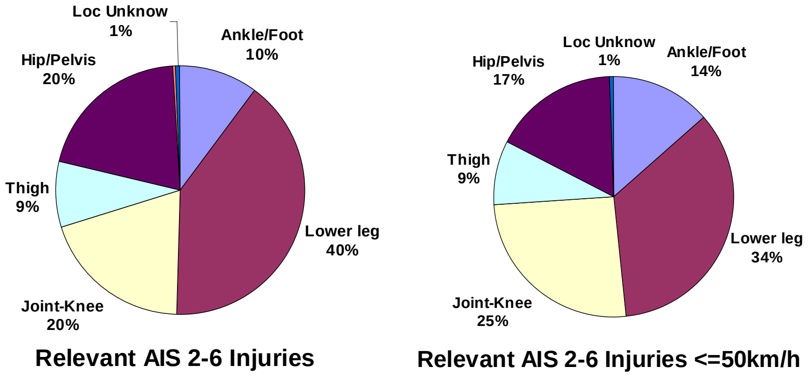


Figure 6.4. Mean impact speed (+/- 1 std dev.) for "relevant" AIS 3-6 injuries from different injury sources for all cases with known speed. (*Reinf. Hood is hood surface reinforced by under hood components.)

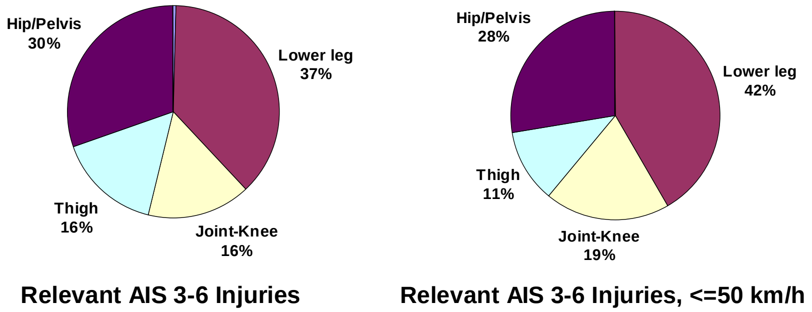
Considering that there is some variation in surfaces impacted at different speeds, PCDS was analyzed to determine if different body parts were injured at different speeds. Assuming that injuries occurring at impact speeds greater than 50 km/h are high-energy impacts that would be difficult to prevent, the distribution of structures injured in crashes at speeds lower than 50 km/h were separated. The resulting distribution of injuries including and excluding the high speed cases are shown in Figure 6.5 for AIS 2-6 injuries and in Figure 6.6 for AIS 3-6 injuries.



Relevant AIS 2-6 Injuries

Relevant AIS 2-6 Injuries <=50km/h

Figure 6.5. Distribution of relevant AIS 2-6 injuries for all PCDS LE injuries and with high-speed cases excluded



Relevant AIS 3-6 Injuries

Relevant AIS 3-6 Injuries, <=50 km/h

Figure 6.6. Distribution of relevant AIS 3-6 injuries for all PCDS LE injuries and with high-speed cases excluded.

As shown in these figures, the proportions of lower leg to upper leg injuries change if high-speed, potentially intractable, cases are removed. At AIS 2-6, the proportion of hip/pelvis/thigh injuries changes from 29% for all cases to 26% of the cases under 50 km/h. At AIS 3-6, the proportion of hip/pelvis/thigh injuries changes from 45% for all cases to 39% of the cases under 50 km/h.

The combined effects of considering only cases under 50 km/h and projecting into the future on the percentage of injuries that involve the hip/pelvis/thigh were considered (Figure 6.7 and Figure 6.8). Section 5 showed that an overall increase in the percentage of above-the-knee injuries was expected in the future. Meanwhile, exclusion of cases over 50 km/h resulted in an overall decrease in the percentage of above knee injuries. Combining these opposing effects to project the total percentage of future relevant injuries sustained at speeds < 50 km/h shows that above-the-knee injuries would be expected to continue to comprise approximately 30% of AIS 2-6 injuries and close to 50% of AIS 3-6 lower extremity injuries.

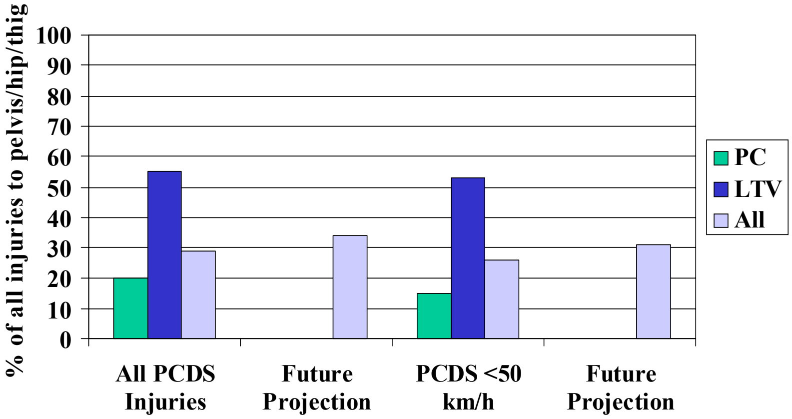


Figure 6.7. Percentage of all AIS 2-6 relevant lower extremity injuries that are above-the-knee injuries: future projection of cases at less than 50 km/h.

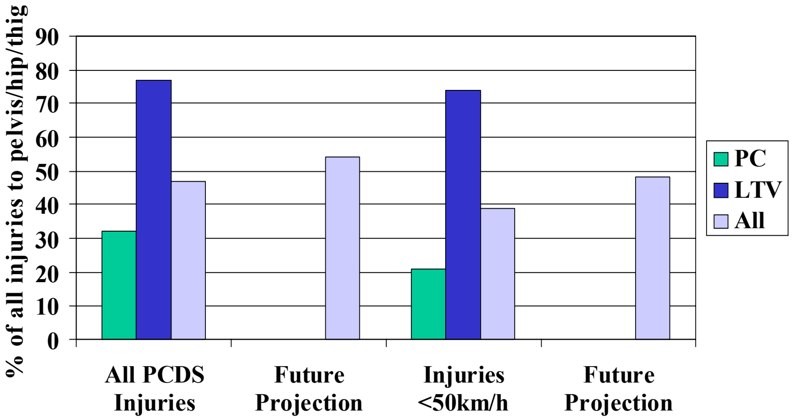


Figure 6.8. Percentage of all AIS 3-6 relevant lower extremity injuries that are above-the-knee injuries: future projection of cases at less than 50 km/h.

In summary, exclusion of higher-speed impacts changes the proportions of injuries sustained to different parts of the lower extremity. Eliminating potentially intractable high-speed cases results in lower incidence of above-the-knee injury in the target population for a regulation; however, this result is offset by the increasing number above-the knee injuries expected with increasing presence of LTV in the fleet.

7 Front Bumper Dimensions

Bumper dimensions of American vehicles are of interest for evaluating the applicability of international test procedures in the US. In particular, data on US bumper dimensions is useful for estimating the effect of a "high-bumper" limit on a lower extremity test procedure. A search of vehicles involved in pedestrian impacts in the PCDS case set was performed to determine the percentage and types of US vehicles that would be required or allowed to use a guided upper legform procedure instead of the projectile lower legform test procedure.

The tendency toward larger vehicles in the US fleet, along with the large number of light trucks and vans, result in a very different range of bumper heights and dimensions than in Japan or Europe. Although a more accurate estimate of fleet geometry could be made with measurements from current vehicles and registration data, the measurements readily available from PCDS cases provide an initial estimate. Informal data presented to NHTSA by the Alliance for Automobile Manufacturers in 2004 showed that vehicle front-end dimensions for current models were not outside of the range of dimensions for vehicles included in the PCDS database.

It has been proposed that using a legform for evaluating lower extremity injury may not be valid for "high-bumper" vehicles [IHRA PSWG, 2005] and that a free-flight legform test should only apply to vehicles with a bumper under a certain height. A Proposed Draft Global Technical Regulation (GTR) on Pedestrian Regulation listed a proposed bumper height limit of 50.0 cm; vehicles with higher bumpers would be required to pass a guided upper legform test instead of the projectile legform test. Vehicles with a lower bumper height between 45 and 50 cm would be given an option between the projectile legform test and the guided upper legform test. In order to ultimately evaluate the target population for each procedure, PCDS data can be used to get a rough estimate of the bumper geometry in vehicles involved in pedestrian impacts in the US. Cumulative frequency of bumper dimensions was calculated from the cases in the PCDS database (Figure 7.1). If a proposed projectile standard was limited to vehicles with bumpers that were less than 45 cm at the bottom edge, for example, 84.1% of the US fleet included in the PCDS data would be covered by the procedure. If vehicles with bumpers between 45 and 50 cm could be tested with a projectile lower legform or a guided upper legform at the option of the manufacturer, 11.5% of vehicles would be given this option. The remaining 4.4% of vehicles would be required to pass the guided upper legform test.

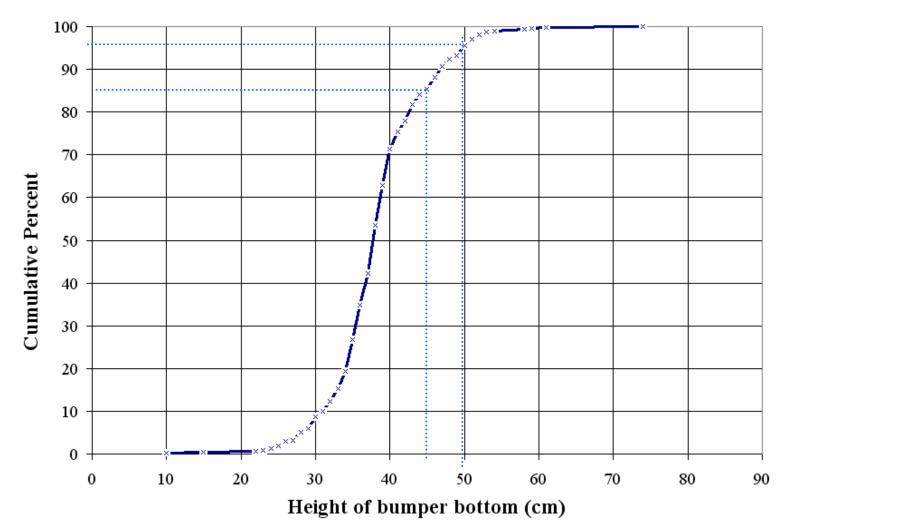


Figure 7.1. Cumulative frequency of bumper bottom edge for all PCDS cases, n=550

The PCDS data is also useful for comparing the differences in bumper geometry between different types of vehicles. Figure 7.2 to Figure 7.4 show the mean bumper dimensions for PCDS case vehicles. The mean bumper top is 9.8 cm higher for LTV than for passenger cars, while mean bottom height is 6.4 cm higher. The total height from top to bottom of the bumper is 3.4 cm greater for LTV than for passenger cars. These height differences between LTV and passenger cars are all statistically significant (alpha<0.01) Among types of LTV, minivans have the lowest bumpers on average (mean top height 56.5 cm) while SUV's have the highest bumpers (mean top height 66.0 cm). The variation in mean bumper height for different classes of vehicle underscore why the US fleet, which has a growing proportion of LTV as discussed in Section 5, may have more "high-bumper" vehicles than other countries.

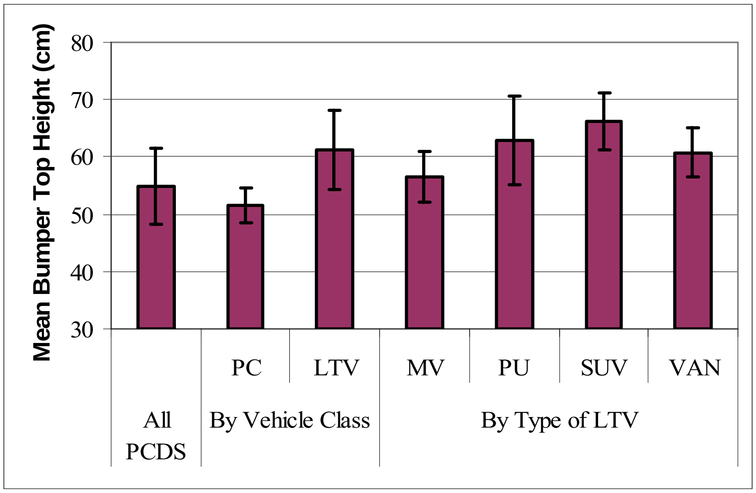


Figure 7.2. Mean height of the top of the bumper in all vehicles in the PCDS database.

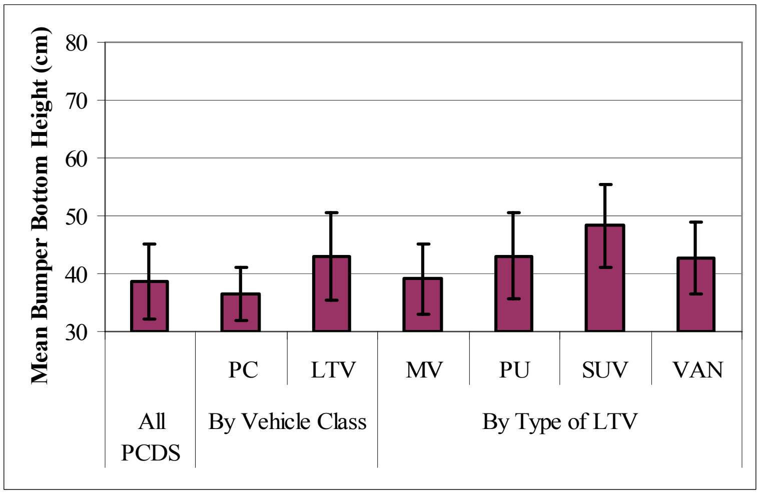


Figure 7.3. Mean height of the bottom of the bumper in all vehicles in the PCDS database.

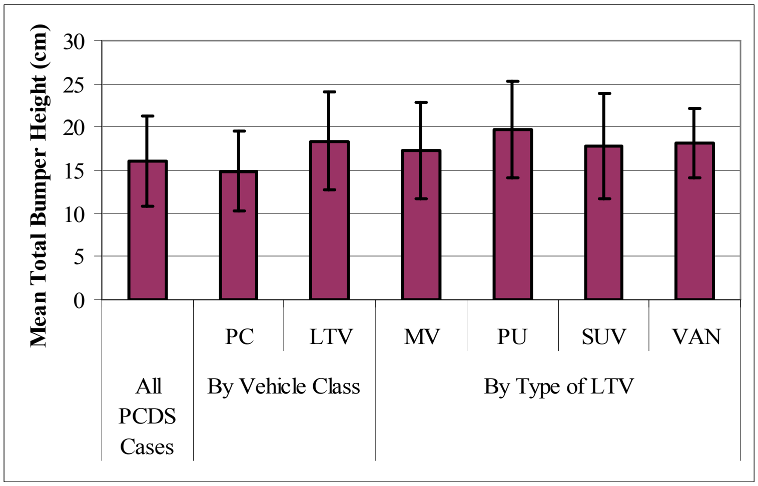


Figure 7.4. Mean distance from the top of the bumper to the bottom of the bumper in all vehicles in the PCDS database.

8 Relative Height of Knee and Bumper

Searches of the PCDS database to determine the height of the bumper relative to the pedestrian's leg in pedestrian crashes were initially performed to determine appropriate impact heights for VRTC testing of a stationary legform with a linear impactor. These results may also be useful for understanding the relevance of test tools and procedures that are focused on lower leg impact for US pedestrian injuries.

Given that injuries above the knee are common, the PCDS data was used to determine if *impacts* above the knee are also common. Consideration of the relative knee-to-bumper height may also be useful for determining if launching a legform at the height a mid-size male would impact is representative of real-world pedestrian impacts. Passenger cars (PC) and light trucks and vans (LTV) were considered separately because of the geometry differences between the two vehicle types.

Relative height of the knee and bumper was estimated from all PCDS cases. Bumper height was established from measurements of the upper and lower edges of the bumper on the crash vehicle. Knee height, defined as the distance between the ground and the center of the kneecap, was taken from case data if available. Since the kneecap is positioned anterior to the distal femur when the leg is extended, knee height measurements made to the center of the patella are actually slightly higher than the contacting surfaces of the femur and tibia. When knee height was not documented but stature was recorded, knee height was estimated as 28.8% of standing height, based on the mean ratio between standing height and knee height in all cases where both measurements were available. This ratio is consistent with previously reported anthropometry data collected in 1975, which showed knee height as 28.5% of standing height [Chaffin, 1991]. The frequency of bumper impacts estimated above, below, or at knee-level without accounting for braking is listed in Table 8.1 for all PCDS cases with known bumper height and pedestrian knee height or standing height. Bumper impacts "at" knee-level are considered those where the PCDS knee height was above the height of the bottom of the bumper and below the height of the top of the bumper, while bumper impacts above and below knee-level are those where the knee height is lower than the bottom of the bumper and higher than the top of the bumper respectively. The analysis was repeated, accounting for the change in bumper height that results from pre-impact braking by estimating an average 6 cm drop in bumper height in cases where pre-impact braking was documented in case records (Table 8.2). This drop in bumper height represents a typical average and does not account for differences in braking-level or vehicle type.

Table 8.1. Frequency of Estimated Bumper Impact Location (for all PCDS cases with known bumper height and pedestrian knee height or standing height) (% listed is the percent of known bumper-knee height for each vehicle type)

Bumper Impact Height	Passenger Cars (n=260)	Light Trucks & Vans (LTV) (n=133)	Total (n=393)
Above knee-level	26 (10%)	45 (34%)	71 (18%)
At knee-level	175 (67%)	84 (63%)	259 (66%)
Below knee-level	59 (23%)	4 (3%)	63 (16%)

Table 8.2. Frequency of Estimated Bumper Impact Location (for all PCDS cases with known bumper height and pedestrian knee height or standing height) accounting for estimated drop in bumper height in cases with pre-impact braking

Bumper Impact Height	Passenger Cars (n=260)	Light Trucks & Vans (LTV) (n=133)	Total (n=393)
Above knee-level	15 (6%)	29 (22%)	44 (11%)
At knee-level	136 (52%)	91 (68%)	227 (58%)
Below knee-level	109 (42%)	13 (10%)	122 (31%)

While stationary bumper heights would show that approximately 18% of cases with known bumper height and stature result in bumper impacts above the knee, accounting for pre-impact braking suggests that only 11% of these cases would result in an above-the-knee impact. In the majority of PCDS cases the bumper would be expected to contact the lower extremity at knee height, i.e. with the knee height above the bottom of the bumper and below the top of the bumper.: 66% of cases if braking is neglected and 58% of cases if braking is considered. This estimate is necessarily approximate, since case-by-case conditions such as pedestrian position or variation in braking severity would alter the actual knee to bumper height. Extrapolating these values to the current or future US fleets show that the majority of bumper impacts are still expected to be *at* knee height.

The relationship between the impact height of the bumper relative to the knee and the part of the lower extremity that is injured is shown in Figure 8.1 with no adjustment for braking, and in Figure 8.2 with adjustment for braking. Matsui recently reported a study based on a subset of PCDS data that showed that vehicle bumper heights causing femur fracture tended to be higher than those causing knee ligament injury (Matsui 2005). Mean bumper height in knee ligament injuries was higher than for tibia fracture, although this difference was reported as not statistically significant at the alpha=0.05 level. These results were based on a subset of PCDS cases that excluded pedestrians younger than 16 years old and included only AIS 2+ femur fractures, tibia fractures, or knee ligament injuries caused by bumper impact. Matsui's findings echo those in the current study, supporting the link between bumper height and the lower extremity region that is injured.

Relative height in Figure 8.1 and Figure 8.2 was measured from the top of the bumper to the reported center of the knee. Heights of the "top" and "bottom" refer to undamaged or "pre-crash" heights. The mean relative knee height for "relevant" lower leg and knee injuries was between 0 and 5 cm *below* the top of the bumper, depending on whether braking was considered and what injury severity was included. The mean relative knee height for pedestrians with hip, pelvis and thigh injuries was approximately 8 to 15 cm below the top of the bumper. Given that the mean bumper height in the PCDS database is 16.1 cm, based on reported bumper top and bumper bottom heights, this comparison shows that knee and lower leg injuries tend to occur, on average, when the knee is impacted when aligned with approximately the top third of the bumper, while hip, pelvis, and thigh injuries are most common when the knee height aligns with the bottom half of the bumper.

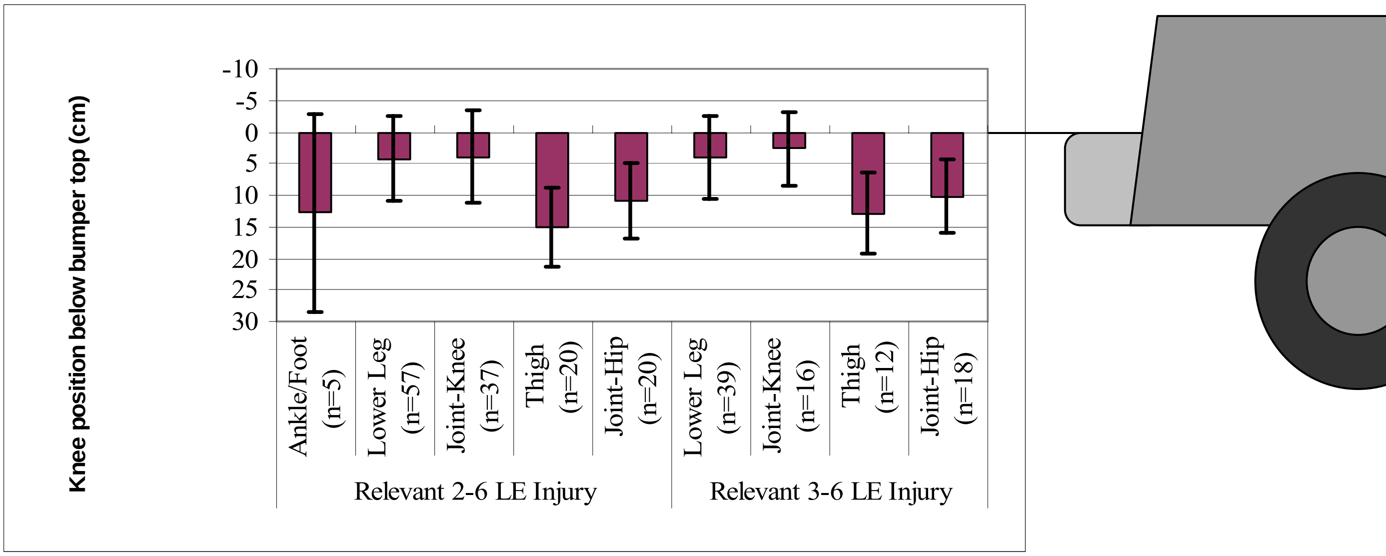


Figure 8.1. Mean estimated knee position below top of bumper (+/- 1 std dev) for injuries to each region (without adjustment for braking)

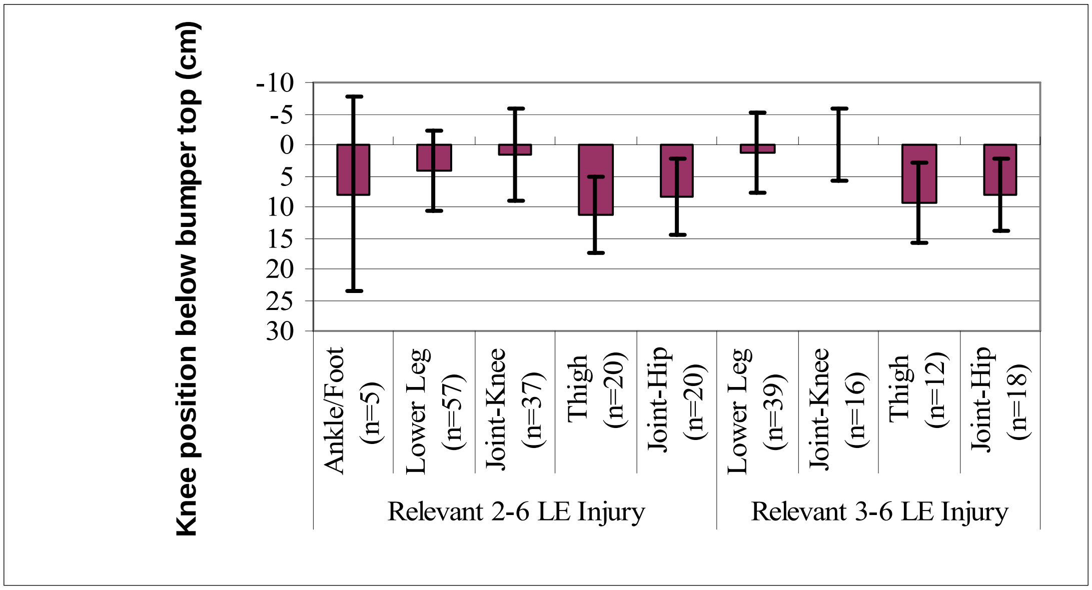


Figure 8.2. Mean estimated knee position below top of bumper (+/- 1 std dev) for injuries to each region (with adjustment for braking)

Based on the fact that a majority of pedestrian impacts occur with the knee height at the level of the bumper (that is, impacts where the knee is above the bottom of the bumper and below the top of the bumper), this is the height range in which testing would ideally be focused. In order to evaluate the risk of knee and lower leg injury, a legform test would be most effective if the legform knee impacted at the level of the top third of the bumper. In order to evaluate the risk of thigh, hip, and pelvis injuries, an effective test tool would impact the vehicle with the knee height aligned with the bottom half of the bumper. Smaller percentages of impacts occur below the knee~~,~~ and above the knee.

The data in this chapter can be used to evaluate the need for a high-bumper limit for application of a projectile legform lower extremity test on US vehicles. The IHRA PSWG proposal for projectile lower extremity testing (IHRA PSWG, 2005) proposes using a mid-size male legform with a knee height of 49.3 cm, positioned 2.5 cm above ground reference level. This procedure would result in a knee impact at 51.8 cm. Research by members of the IHRA PSWG is currently ongoing to understand the relative bumper-knee height at which a projectile leg test is valid. Based on the PCDS data on cumulative bumper height data from section 7, a test impact at 51.8 cm would result in the knee being above the top of the bumper for 37% of those vehicles, below the bottom of the bumper for 2 % of those vehicles, and within the face of the bumper for the remaining 61% of vehicles.

In summary, case data on relative knee-bumper height in pedestrian injury cases shows that the knee is most often at the height of the bumper in a lower-extremity injury, and the current projectile legform test procedure would be expected to result in a legform-to-bumper impact with the knee height aligned with the face of the bumper 61% of the time.

9 Summary of Findings

- **Pedestrian injuries and deaths are frequent in the US.** During the five-year period of the PCDS data collection, there were approximately 78,000 pedestrians injured and 5,395 pedestrians killed annually in the US. Although that rate has continued to decrease, in 2004 4,641 pedestrians were reported killed and 68,000 were reported injured.

- **Lower extremity injuries account for a large proportion of US pedestrian injuries.** Lower extremity injuries made up approximately one third of all AIS 2-6 pedestrian injuries and one quarter of AIS 3-6 injuries. The high incidence of AIS 2-6 and AIS 3-6 lower extremity injuries among pedestrians in US accident data supports efforts to improve pedestrian safety performance of US vehicles.

- **Many pedestrian lower extremity injuries are above the knee.** Although IHRA PSWG and GTR planning has focused on evaluation of lower leg injuries, analysis of US pedestrian injury data shows that above-the-knee injuries account for 29% of AIS 2-6 lower extremity injuries and almost half of AIS 3-6 lower extremity injuries. Ignoring potentially intractable impact surfaces, above-the-knee injuries make up 46% of AIS 3-6 lower extremity injuries. Upper leg injuries are even more frequent among children with approximately two-thirds of the serious lower extremity injuries sustained by children occurring above the knee.

- **For all injury types at thigh level and below, the front bumper was the most common injury source.** At hip and pelvis level, however, injuries were caused most often by impacts with the hood edge/trim, hood surface, and grille. A pelvis test to the hood edge area may be required if hip/pelvis injury risk is to be evaluated as part of a pedestrian regulation.

- **Light trucks and vans produce a disproportionately large number of upper leg injuries for the number of cases in PCDS.** Projecting to current or future fleets to account for growing numbers of LTVs on the road, upper leg injuries are expected to make up an increasing percentage of lower extremity injuries. The frequency of upper leg injuries in the PCDS database supports consideration of upper leg injury evaluation in test procedures for the US fleet.

- **Above-the-knee injuries are frequent, even after intractable cases are culled.** Knee injuries tend to occur at lower speeds than other lower extremity injuries. If injuries sustained at greater than 50 km/h are assumed intractable and deleted from this analysis, the proportion of upper leg injuries drops relative to lower leg injuries. However, when projecting into the future to account for a growing LTV presence on US roads, above-the-knee injuries are still expected to account for nearly 50% of AIS 3-6 injuries.

- **Based on “high-bumper” limits in the current draft of the GTR, different leg test procedures would apply to different vehicles in the US fleet.** Cumulative frequency plots in Section 7 can be used to determine the portion of the US fleet covered by each test procedure.

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Appendix A: Categorization of Injuries

Injury Description	Injury Category
Hip joint injury (various)	Hip/Pelvis
Femur fracture: head, intertrochanteric, neck	Hip/Pelvis
Pelvis fracture, sacroilium fracture	Hip/Pelvis
Symphysis pubis separation	Hip/Pelvis
Amputation above knee	Thigh
Femoral vessel injury (various)	Thigh
Femur fracture: site NFS	Thigh
Femur fracture: shaft, supratrochanteric, or subtrochanteric	Thigh
Femur fracture: codes not listed in AIS-90, update 98 manual	Thigh
Popliteal vessel injury (various)	Knee
Collateral or cruciate lig. laceration - knee	Knee
Collateral or cruciate lig. laceration - PCL	Knee
Knee joint injury (various)	Knee
Femur fracture: condylar	Knee
Patella fracture	Knee
Tibial condyles/plateau/intercondyloid spine fracture	Knee
Amputation below knee, entire foot, calcaneus	Lower leg
Fibula fracture: Site NFS	Lower leg
Fibula fracture: Head, neck, shaft	Lower leg
Tibia fracture NFS	Lower leg
Tibial shaft fracture	Lower leg
Tibia injury, NFS	Lower leg
Ankle joint injury (various)	Ankle/Foot
Foot joint injury (various)	Ankle/Foot
Metatarsal, phalangeal, or IP joint (NFS)	Ankle/Foot
Subtalar, transtarsal, transmetatarsal joint	Ankle/Foot
Calcaneous fracture	Ankle/Foot
Fibula fracture: Lat malleolus, bimalleolar, or trimalleolar	Ankle/Foot
Foot fracture or leg fracture NFS	Ankle/Foot
Metatarsal or tarsal fracture	Ankle/Foot
Tibial fracture, medial malleolus or posterior malleolus	Ankle/foot
Toe injury	Ankle/Foot
Skin	Skin
Amputation location NFS	Unknown
Traumatic LE injury not further spec.	Unknown
Other named arteries (various)	Unknown
Muscle laceration, strain contusion	Unknown

Appendix B: Vehicle Classification

The following table includes all codes which appear at least once in the PCDS dataset.

PCDS Code	Body Type	Vehicle Type
1	Convertible	Pass Car
2	2-door sedan	Pass Car
3	3-door/2-door hatchback	Pass Car
4	4-door sedan	Pass Car
5	5-door/4-door hatchback	Pass Car
6	Station wagon (excl. van and truck based)	Pass Car
14	Compact utility (includes models of Jeep CJ, Scrambler, Golden Eagle, Renegade, Laredo, Wrangler, Cherokee, Dispatcher, Raider, Bronco II, Bronco, Explorer, S-10 Blazer, Geo Tracker, Bravada, S-15 Jimmy, Thing, Pathfinder, Trooper, Trooper II, Rodeo, Amigo, Navajo, 4-Runner, Montero, Samurai, Sidekick, Rocky)	LTV – SUV
15	Large utility (includes models of Jeep Cherokee, Ramcharger, Trailduster, Bronco, Blazer, Jimmy, Landcruiser, Rover, Scout	LTV-SUV
16	Utility station wagon (Chevy Suburban, GMC Suburban, Travelall, Grand Wagoneer)	LTV-SUV
20	Minivan (includes models of Chrysler Town and Country, Caravan, Grand Caravan, Voyager, Grand Voyager, Mini-Ram, Dodge/Plymouth, Vista, Aerostar, Villager, Lumina APV, Trans Sport, Silhouette, Astro, Safari, Toyota Van, Toyota Minivan, Previa, Nissan, Minivan, Quest, Mitsubishi Minivan, Vanagon/Camper)	LTV – Minivan
21	Large van (includes models of B150-B350, Sportsman, Royal, Maxiwagon, Ram, Tradesman, Voyager, E150-E350, Econoline, Clubwagon, Chateau, G10-G30, Chevy Van, Beauville, Sport Van, G15-G35, Rally Van, Vandura)	LTV – Van
22	Step van or walk-in van (<= 4,500 kg GVWR)	LTV – Van
30	Compact pickup (includes models of D50, Colt P/U, Ram 50, Dakota, Arrow pickup, Ranger, Courier, S-10, T-10, LUV, S-15, T-15, Sonoma, Datsun/Nissan Pickup, P'up, Mazda Pickup, Toyota Pickup, Mitsubishi Pickup)	LTV – Pickup
31	Large pickup (includes models of Jeep Pickup, Comanche, Ram Pickup, D100-D350, W100-W350, F100-F350, C10-C35, K10-K35, R10-R35,V10-V35, Silverado, Sierra, R100-R500)	LTV-Pickup

Use of the TRL Legform to Assess Lower Leg Injury Risk

AB NOTE
06-02

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February 2006

BACKGROUND

Matsui et al (2001)[1] showed that the TRL legform possesses limited biofidelity by testing the legform in a controlled certification setup. This setup replicated the configuration used by Kajzer to examine human leg injury tolerance. They found that the legform was considerably stiffer than the human leg. To account for this discrepancy in the response, they proposed transfer coefficients by taking the TRL-human ratios of peak impact force and slope of the shear displacement vs. time curve to assess the probability of tibia fracture (Figure 1) and cruciate ligament injury (Figure 2) in shear given TRL legform measurements:

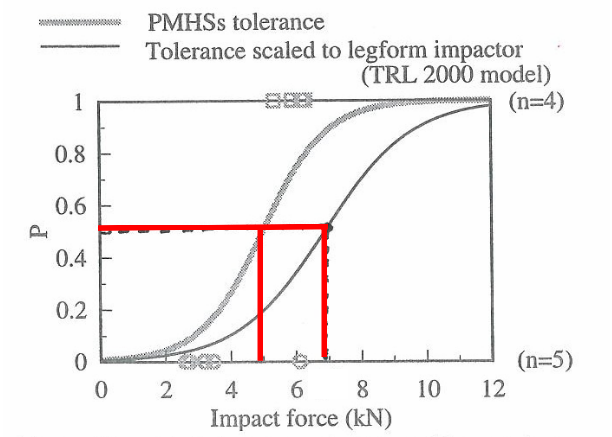

Figure 1: Tibia fracture risk curve using impact force. The ratio of TRL legform peak impact force to PMHS force in the same impact condition was 1.38. Horizontal line denotes 50% fracture risk (PMHS = 5 kN, TRL legform = 6.9 kN).

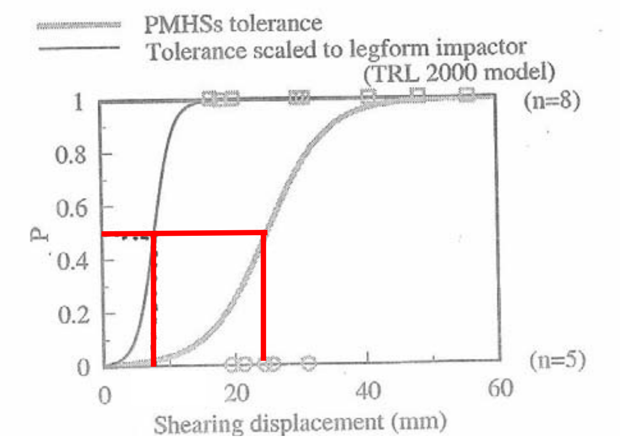

Figure 2: Ligament injury risk curve using shearing displacement. Since the slope of the human displacement versus time history was different for humans than for the TRL legform, the ratio of TRL legform slope to PMHS slope in the same impact condition was 0.314. Horizontal line denotes 50% injury risk (PMHS = 25.1 mm, TRL legform = 7.9 mm).

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[1] Matsui, Y. "Biofidelity of TRL Legform Impactor and Injury Tolerance of the Human Leg in Lateral Impact," Forty-Fifth Proceedings of the Stapp Car Crash Journal (November 2001): pp. 495-510.

In a subsequent study, Matsui (2003)[2] used accident reconstruction to relate TRL legform bending angle and tibia acceleration to collateral ligament injury and bone fracture, respectively (Figures 3 & 4):

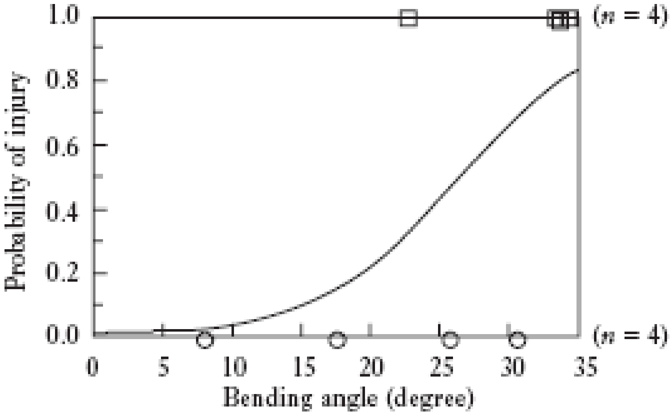

Figure 3: Collateral ligament risk curve using TRL legform bending angle.

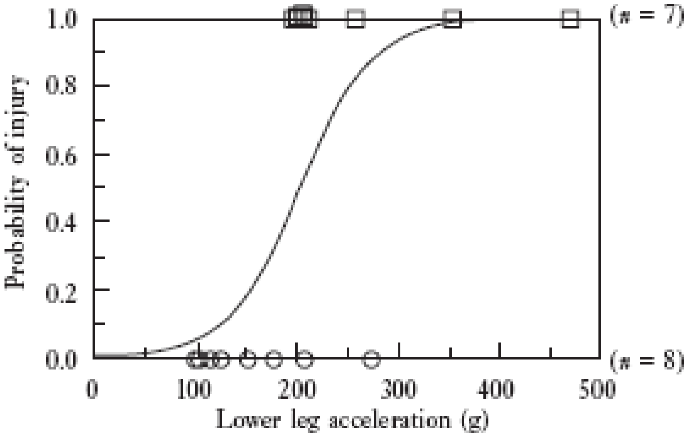

Figure 4: Tibia fracture risk curve using TRL legform upper tibia acceleration.

APPROACH

Given concerns about the biofidelity of the TRL legform, we thought it would be a useful exercise to use Matsui's approach to see if the legform could be effectively used to evaluate the relative performance of vehicle bumpers as well as injury risk.

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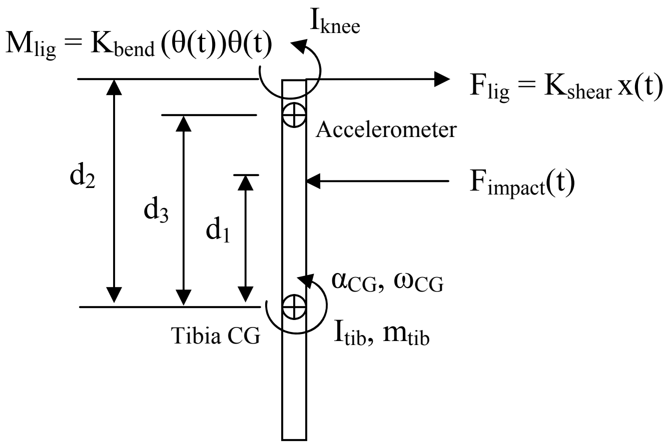
[2] Matsui Y, "New Injury Reference Values Determined for TRL Legform Impactor from Accident Reconstruction Test," *International Journal of Crashworthiness*, 8 (2); 89-98 (2003).

In our Transport Canada tests[3], we used the TRL legform to assess a sample of North American vehicle bumpers. We measured tibia acceleration, bending angle, and shear displacement in these tests. We also have data from the European versions of these vehicle models. The TRL impact force was not measured directly and it could not be calculated from measured tibia acceleration because the effective mass of the tibia is dependent upon several quantities, some of which change with time. Therefore a solution for impact force must be derived.

A free body diagram of the TRL legform tibia component can be drawn as follows:



An equation of motion can be derived by summing the forces and moments, relating angular to translational acceleration using rigid body mechanics, and relating the moment of inertia of the knee and tibia using the Parallel Axis Theorem:

(1) $\overset{+}{\leftarrow} \sum F_{CG} : F_{impact}(t) - K_{shear}x(t) = m_{tib}a_{cg}(t)$ (Sum of Forces)

(2) $\overset{+}{\circlearrowleft} \sum M_{knee} : F_{impact}(t)(d_2 - d_1) - K_{bend}(\theta(t))\theta(t) = I_{knee}\alpha_{cg}(t)$ (Sum of Moments)

(3) $a_{cg}(t) = a(t) + \alpha_{cg}(t)d_3 + \omega_{cg}{}^2 d_3$ (Rigid Body Mechanics)

(4) $I_{knee} = I_{tib} + m_{tib}d_2{}^2$ (Parallel Axis Theorem)

By substituting equation (4) into equation (2) and also substituting equation (3) into equation (1), we can solve the resulting two expressions for $\alpha_{cg}(t)$. Then, by equating

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[3] Mallory, A., Stammen, J.A., Legault, F. “Component Leg Testing of Vehicle Front Structures,” Paper No. 05-0194, Nineteenth International Technical Conference on the Enhanced Safety of Vehicles ESV Paper (June 2005).

those two expressions, we eliminate $\alpha_{cg}(t)$ and get an equation for the impact force $F_{impact}(t)$:

$$F_{impact}(t) = \frac{(K_{shear}x(t) + m_{tib}(a(t) + \omega_{cg}{}^2 d_3))(I_{tib} + m_{tib}d_2{}^2) - K_{bend}(\theta(t))m_{tib}d_3\theta(t)}{I_{tib} + m_{tib}d_2{}^2 - m_{tib}d_3(d_2 - d_1)}$$

Where

$F_{impact}(t)$ = impact force (N)
m_{tib} = mass of tibia = 4.8 kg
K_{shear} = ligament shear stiffness = 600 N/m
$K_{bend}(\theta(t))$ = ligament bending stiffness as a function of bending angle (N/rad)
$x(t)$ = measured shear displacement (m)
$a(t)$ = measured tibia acceleration (m/s^2)
$\theta(t)$ = measured bending angle (radians)
$\omega_{cg}(t)$ = measured angular velocity (rad/sec) measured from high speed film analysis
I_{tib} = tibia moment of inertia = 0.120 kg-m^2
d_1 = distance from tibia center of gravity to bottom bumper edge contact (m)
d_2 = distance from knee pivot to tibia center of gravity = 0.233 m
d_3 = distance from accelerometer to tibia center of gravity = 0.167 m

This equation assumes that the steel tibia is a rigid body. The quantities m_{tib}, I_{tib}, d_1, d_2, and d_3 are known quantities based on the TRL legform specifications. The shear displacement, bending angle, and tibia acceleration were measured in time during the test, and the contact location of the lower bumper edge could be viewed using high speed video. The ligament shear stiffness K_{shear} is linear and approximately 600 kN/m as shown by the following shear certification test corridor (Figure 5):

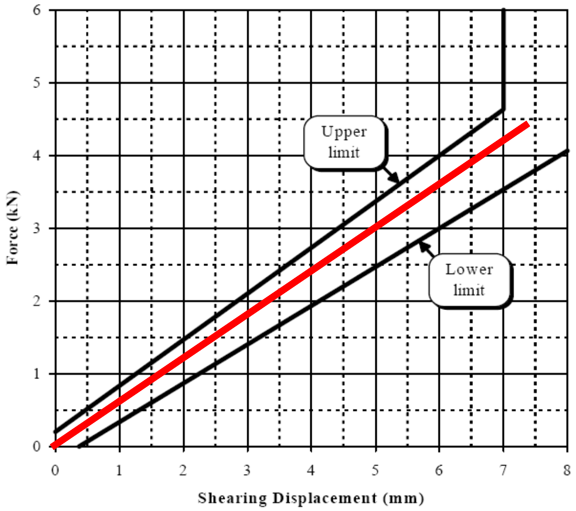

Figure 5: Ligament shear stiffness

The bending stiffness K_{bend}, on the other hand, varies with bending angle according to its certification corridor (Figure 6). For the purpose of this exercise, we'll assume two linear portions. From 0 to 3 degrees, we'll assume a bending stiffness of 60 N/deg. For 3 degrees and beyond, we'll assume a stiffness of 6 N/deg.

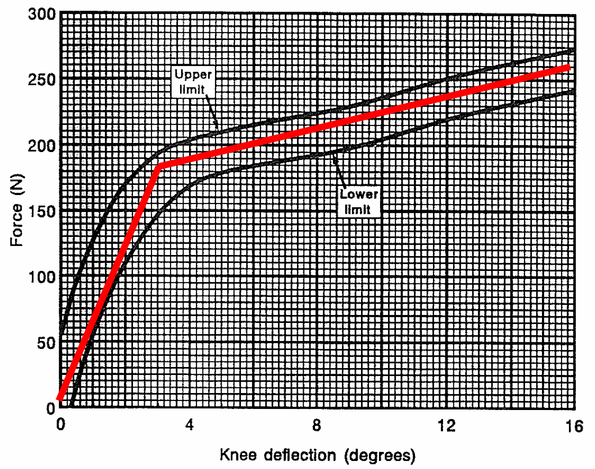

Figure 6: Ligament bending stiffness

APPLICATION TO VRTC TESTING

After calculating the peak impact force seen by the TRL legform, the probability of tibia fracture due to impact force/tibia acceleration, cruciate ligament injury due to shear displacement, and collateral ligament injury due to bending angle can all be estimated for each test. The leg data time histories of the European vehicle tests are unknown (only peak values are known) and therefore the impact force could not be calculated. The TRL-measured impact force can be converted to the equivalent human impact force by dividing by the transfer coefficient of 1.38. Then the TRL-measured shear displacement can be divided by 0.314 to get the estimated human knee shear displacement. The risk of human tibia fracture and ligament injury can then be found directly using the risk curves shown previously (Figures 1 and 2). The values in Table 1 are averages for several impacts to different locations on each vehicle bumper.

Table 1: Injury risk assessment for TRL leg testing of vehicle bumpers

Vehicle	TRL impact force (N)	Estimated human impact force (N)	Risk of tibia fracture * (%)	TRL upper tibia acceleration (g)	Risk of tibia fracture ** (%)	TRL bending angle (deg)	Collateral ligament injury risk (%)	TRL shear displacement (mm)	Estimated human shear displacement (mm)	Cruciate ligament injury risk (%)
1999 Ford Focus (NA)	10476	7591	92	204	51	32.8	77	4.3	13.7	7
1999 Ford Focus (E)				521	100	33.7	81	6.8	21.7	28
2001 Honda Civic (NA)	17485	12670	100	290	92	30.9	68	6.2	19.7	23
2001 Honda Civic (E)				135	11	11.6	6	2.1	6.7	2
2002 Mazda MX5 (NA)	16084	11655	100	242	75	24.9	44	5.8	18.5	18
2002 Mazda MX5 (E)				315	94	31.8	76	5.6	17.7	10
1999 VW Beetle (NA)	27738	20100	100	463	100	31.3	71	8.2	26.1	57
1999 VW Beetle (E)				469	100	29.6	63	7.1	22.7	39
1997 Volvo S40 (NA)	16392	11878	100	256	83	30.6	68	7.2	22.9	40
1997 Volvo S40 (E)				210	52	32.3	77	7.3	23.3	40

* Based on impact force calculated by VRTC and Matsui (2001) tibia fracture risk curve
** Based on Matsui (2003) tibia fracture risk curve

DISCUSSION

TRL pedestrian legform biofidelity has been identified as one of the major technical issues in developing the pedestrian GTR. It has been shown to possess limited biofidelity, but it has been used with success for several years in assessing vehicle structures in Europe. It requires replacement of ligament surrogates for each test and has limited measurement capabilities, but it has been shown to be a durable and repeatable test tool. The purpose of this exercise was to investigate whether concerns about the limited biofidelity and limited measurement capability could be resolved. Specifically, we need to find if the TRL measurements can adequately and accurately estimate human leg injury risk.

This analysis illustrates that while the TRL legform possesses limited biofidelity, it can still be used to estimate relative human knee injury risk for vehicles. This is possible through the use of human-to-test tool transfer functions developed by Matsui and calculation of the impact force applied to the TRL legform by the vehicle.