PEDESTRIAN GTR TESTING OF CURRENT VEHICLES

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ABSTRACT

The Working Party on Passive Safety of the World Forum for Harmonization of Vehicle Regulations (WP.29) is developing a draft global technical regulation (GTR) for pedestrian safety. In order to evaluate the potential effects of the draft GTR on the U.S. fleet, NHTSA's Vehicle Research and Test Center (VRTC) conducted 88 pedestrian head impact tests on 11 vehicles selected to represent the U.S. fleet, with a focus on larger passenger vehicles. The goal was to generate an overall picture of current U.S. vehicle performance with respect to specific structures and test zones in order to better understand the potential challenges and benefits of meeting the regulation.

The peripheral areas of the head impact test zone defined in the draft GTR produced the most severe impacts, with the most challenging areas being in the rear of the test zone (in the area of the hinges, cowl, and wiper spindles) and the lateral edges of the test zone adjacent to the fenders. A smaller number of vehicles produced high-severity impacts at the front edge of the test zone. The challenging areas at the periphery of the test zone did not exceed the GTR requirements in every vehicle. Deformable hood hinges with adequate crushable space between the hood panel and fender, coverage of the cowl by the back edge of the hood, and flanges under the fender edge all resulted in significant HIC reductions from those areas in vehicles without these countermeasures.

The range of performance in the vehicles tested indicates that while there is room for improvement in current head impact protection in US vehicles, countermeasures exist to improve the worst areas of the test zone. The presence of pedestrian-friendly components in heavier and high-front vehicles shows that design modifications are not limited to smaller vehicles.

INTRODUCTION

Nearly 1.2 million people die annually in road crashes around the world. In a comprehensive review of epidemiological studies, the World Health Organization (WHO) estimates that between 41% and 75% of those deaths are pedestrians. Pedestrian deaths are especially prevalent in low-income and middle-income countries because of the greater variety and intensity of traffic mix and lack of separation between pedestrian and vehicle [Peden, 2004]. Although pedestrian injuries are less of an epidemic in the United States, they are still a significant problem with 4,841 pedestrians killed in 2005 alone [NHTSA, 2006]. A recent study in one U.S. urban area showed that pedestrians made up nearly half of all traffic fatalities [Nicaj, 2006]. While education, traffic design, and speed enforcement can all contribute to reducing the number of pedestrian collisions, incorporating pedestrian countermeasures into vehicle design can help to protect pedestrians from serious or fatal injuries in the event of a collision.

The Working Party on Passive Safety (GRSP) of the World Forum for Harmonization of Vehicle Regulations (WP.29) is developing a draft global technical regulation (GTR) to address pedestrian safety through vehicle design [GRSP, 2006]. This regulation includes procedures developed by the Pedestrian Safety Working Group of the International Harmonization Research Activity (IHRA) to test vehicles with child- and adult-sized headforms as well as adult-sized upper and lower legforms [Mizuno, 2005]. Because of differences in vehicle fleet composition among GRSP countries, many countries are evaluating how the GTR would affect their fleet's level of pedestrian protection.

We assume for this paper that there are four main components for evaluating the potential safety benefits of a pedestrian GTR regulation: (a) population targeted by the regulation, (b) applicable test area included in the regulation, (c) baseline performance of the vehicle fleet, and (d) injury risk reduction expected due to compliance with the regulation's performance criteria [NHTSA, 1997]. In the calculation of benefits for the pedestrian GTR, the target population is derived from accident data and vehicle statistics. The allowable test area is described in the GTR by a procedure for laying out the boundaries of the testable area. The baseline performance is evaluated in this paper by testing a representative sample of the fleet with respect to the Head Injury Criterion (HIC) limits proposed as performance criteria in the GTR.

To calculate the safety improvements afforded by the GTR, it is assumed that non-compliant HIC values from the baseline experimental data would become compliant if the vehicle were designed to meet the GTR, leading to a reduction in HIC and a corresponding reduction in injury risk. When this potential reduction is summed for all non-compliant points, a reduced overall fatality or injury risk is estimated and this reduction, along with target population and testable area, is used to determine equivalent lives saved or injuries reduced [NHTSA, 1997].

The challenges and benefits of applying the GTR requirements to high-front vehicles are of particular interest because of the prevalence of larger vehicles in the U.S. While it has been determined that improvement to smaller passenger vehicles is feasible and cost-effective [ACEA, 2005; Lawrence, 2002; NHTSA, 2005], manufacturers have argued that higher-front vehicles present different design challenges than do passenger cars [OICA, 2006b]. The GRSP has debated the applicability of the GTR to these larger vehicles [European Commission, 2006; JAMA, 2006; OICA, 2006c]. In particular, there is concern about the feasibility of improving protection in the hood leading edge area [OICA, 2006a]. To address these concerns, test data from points within this front zone are needed to evaluate the challenges of meeting the proposed GTR in this area of the vehicle.

NHTSA's Vehicle Research and Test Center (VRTC) has conducted 88 pedestrian head impact tests on 11 vehicles selected to represent the U.S. fleet with a focus on high-front vehicles. These tests include 84 baseline tests to evaluate overall current fleet performance as well as additional testing on a vehicle known to have countermeasures designed specifically for pedestrian head impact safety. The objectives of this study were to (1) determine the current baseline performance of a key subset of the U.S. vehicle fleet for the benefit assessment, (2) identify problem areas and existing countermeasures to improve them, and (3) evaluate the difficulty of meeting the GTR requirements by estimating likely relaxation zones for each vehicle. Together, these factors were used to generate an overall picture of the current level of U.S. vehicle performance, with respect to specific structures and test zones.

METHODS

Vehicles Tested

Head impact testing was performed on eleven vehicles chosen to cover a wide range of GVM (Gross Vehicle Mass) and BLE (Bonnet Leading Edge) heights (Table 1). GVM is a manufacturer-declared maximum mass for a fully-laden vehicle. The height of the leading edge is a wrap around distance (WAD) measured with a flexible tape in the vertical longitudinal plane of the vehicle. Variations in the geometry of the vehicle front end result in differences in the BLE WAD across the width of the vehicle front. Vehicles were selected to include multiple manufacturers, as well as vehicles known to have designed pedestrian countermeasures. Additional factors in the final selection of vehicles included availability of vehicles and the frequency of each model in the fleet. Efforts were made to avoid duplicate testing on vehicles that were undergoing simultaneous testing by manufacturers.

Table 1.
Vehicles tested in the current study sorted by Gross Vehicle Mass (GVM)

Test vehicles	GVM (kg)	Bonnet Leading Edge WAD (mm)* (Min)	Bonnet Leading Edge WAD (mm)* (Max)
2002 Jeep Wrangler	2019	916	1111
2005 Honda CR-V	2020	880	1014
2006 Volkswagen Passat	2020	840	880
2006 Toyota Tacoma	2063	992	1026
2003 Toyota 4Runner	2063	1030	1091
1999 Dodge Dakota	2200	895	995
2003 Ford Crown Victoria	2632	804	848
2006 Dodge Durango	2903	1088	1240
2003 Hummer H2	3901	1172	1196
2003 Ford E350	4127	1162	1188
2005 Chevrolet Silverado	4173	1210	1265

Impact Point Locations

The testable areas on the front structures of each vehicle were marked according to the requirements in the GTR [GRSP, 2006]. A number of GTR-defined reference lines, necessary for identification of the test zones, were drawn on each vehicle. Reference lines were drawn at wrap-around distances (WAD) of 1000 mm, 1700 mm, and 2100 mm. A bonnet leading edge (BLE) reference line was drawn across the width of the vehicle where a straight edge at 50 degrees from the vertical, parallel to the centerline of the vehicle, contacted the front structures. Side reference lines were marked along the sides of the vehicle where a straight edge at 45 degrees from the vertical, perpendicular to the vehicle centerline, contacted the front structures of the vehicle. A bonnet rear reference line was drawn, according to GTR requirements, based on the contact location on the hood and front structures by a headform-sized sphere in contact with the windshield. The child test zone was bordered at the front by the most rearward of the 1000 mm WAD line or 82.5 mm rearward of the BLE reference line; at the sides by lines 82.5 mm inboard of the side reference lines; and at the rear by the most forward of the WAD 1700 line or 82.5 mm forward of the bonnet rear reference line. The adult zone was bordered at the front by the WAD 1700 line, at the sides by lines 82.5 mm inboard of the side reference lines, and at the rear by the most forward of the WAD 2100 line or 82.5 mm forward of the bonnet rear reference line.

For each vehicle, up to 8 baseline impact points were chosen, with up to 4 in the child zone and 4 in the adult zone (Figure 1). The Passat had a very small adult test zone and was therefore subjected to only one test in the adult zone, along with four tests in the child impact zone. A data failure in a child-zone impact in CR-V testing resulted in a total of 7 of the 8 baseline impact tests, along with four additional tests run for design comparison only. The remaining nine vehicles underwent eight tests each.

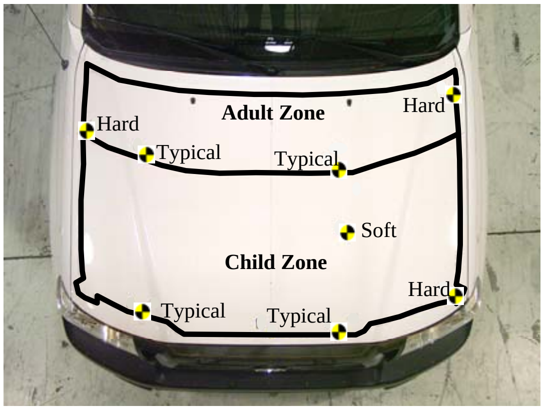


Figure 1. Test zones and eight impact points shown for the 2006 Toyota Tacoma.

In each zone, two points were chosen to correspond to a "typical" impact location. The WAD of these points was based on data from the Pedestrian Crash Data Study (PCDS), NHTSA's database of pedestrian injury cases collected between 1994 and 1998. The ratio of initial head impact WAD to pedestrian standing height was calculated for all PCDS cases where both measurements were known and impact speed was 40 km/h or less, which accounts for more than 75% of the pedestrian injured accidents according to the preamble of the draft GTR. The median WAD/standing height ratio was then calculated for each vehicle type, and multiplied by the median standing heights for a 20 year-old and a six-year old to determine the "typical" WAD for an adult head impact and a child head impact for each vehicle type (Table 2). The standing heights were 1700 mm for the adult and 1150 mm for the child, based on averaged male and female data in Centers for Disease Control growth charts [NCHS, 2000]. In each zone, one of the "typical" impacts was performed on each side of the vehicle. The lateral locations of these tests were at 1/6 and 4/6 across the total width of the testable area at that location. In this way, two unbiased points were selected across the width of the vehicle in each zone. They were located in objectively-measured locations and not selected based on the vehicle's design. They were biased toward the passenger-side of the vehicle because of the higher frequency of pedestrian head contacts on the passenger side in PCDS data. In cases where the nominal impact location for the "typical" adult and child zones were not within the boundaries of the test zone, the point in the test zone closest to the target impact location was selected as the impact point.

Table 2.
Target WAD for "typical" head impacts (median adult and child WAD based on PCDS data and 50th percentile height of adult and six year-old)

	Median WAD/ Height Ratio	Estimated Median WAD multiplied by height of adult and child	
Minivan	1.04	1768 mm	1196 mm
Pass Car	1.17	1989 mm	1346 mm
Pickup	0.96	1632 mm	1104 mm
SUV	0.94	1598 mm	1081 mm
Van	0.86	1462 mm	989 mm

The additional four tests per vehicle were targeted at locations that were the hardest and softest portions of the test zone. These tests were specific to each individual vehicle and were intended to provide points in both the best- and worst-case scenarios. The manufacturer of each vehicle was invited to contribute input on the worst-case and best-case points based on their test experience and knowledge of the design.

In addition to the baseline testing performed on all vehicles in this study, four additional tests were performed on the CR-V. The CR-V front end had features that appeared to specifically address pedestrian head safety. The four comparison-only impacts were performed as an evaluation of structures that had produced particularly severe head impacts in other vehicles. These extra tests of the CR-V pedestrian countermeasures were not included in the summary data for the 84 baseline tests because they did not follow the same guidelines as test locations for the other vehicles, but are included in this paper to better understand the potential effects of pedestrian-specific design.

Test Procedure

Free-flight impacts were performed according to the procedure in the GTR (Figure 2). Impacts in the child zone were performed with the 3.5 kg, 165 mm diameter headform defined in section 6.3.2.1 and impacts in the adult zone were performed with the 4.5 kg, 165 mm diameter headform defined in section 6.3.2.2 [GRSP, 2006]. The impact angle was 50 degrees to the horizontal for the child headform and 65 degrees to the horizontal for the adult headform. Impact speed was 9.7 ± 0.2 m/s [35 ± 0.72 km/h], for all tests except a comparison-only test (point CM-H) run on the CR-V at a speed of 9.92 m/s. The locations of first head contact for all baseline evaluation impact points were within the defined test zones. Of the four comparison-only tests performed on the CR-V, two were outside the test zone.

Figure 2. Test setup for adult headform impact on Toyota 4Runner.

Table 3 describes all the points selected for testing, including the coordinates by WAD and by lateral distance from the vehicle centerline, where positive (+) numbers are toward the driver's side of the vehicle.

The tests on each vehicle were performed on two hoods unless a significant amount of deformation was present. In cases where there was potential for damage overlap between adjacent points, the hood was replaced and the order of remaining impacts on that vehicle was adjusted if necessary.

The headforms were instrumented with 3 uniaxial accelerometers (Endevco 7264) mounted at locations within GTR guidelines for proximity to the center of mass of the headform. Acceleration data was sampled at 20 kHz, pre-filtered at 3 kHz, then zeroed and filtered using Channel Filter Class 1000 (1650 Hz) before being used to calculate peak resultant acceleration and 15 millisecond Head Injury Criterion (HIC).

Relaxation Zone Identification

According to the proposed GTR, manufacturers may designate up to one third of the test zone, including up to half of the child zone, as a relaxation zone. In this relaxation zone, head impacts must produce HIC measurements of less than 1700, where the remainder of test zone is limited to HIC of less than 1000.

After completion of testing, relaxation zones were proposed for each of the 11 test vehicles, by estimating the areas likely to be in the stiffest third of the test zone. These zones were selected based on proximity to supporting structures, under-hood clearance, and performance of different structures in testing. Overhead photographs of the vehicle with the hood open and closed were overlaid to help identify stiff under-hood structures within the test area (Figure 3). Zone definition involved identifying the most challenging portions of the test zone and measuring the remaining area relative to the whole test zone in overhead photographs. This process was repeated iteratively, adjusting the boundaries of the relaxation zone until it represented one third of the total test area +/- approximately 0.01 m^2.

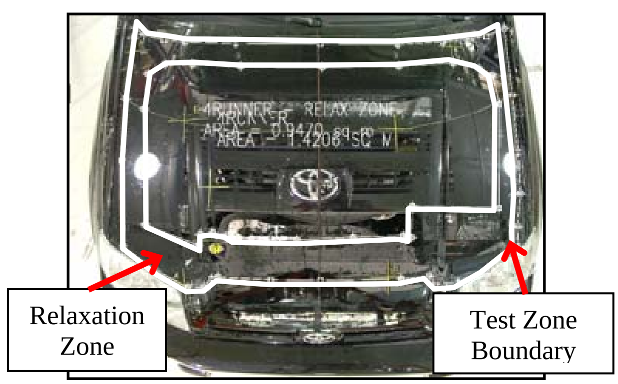


Figure 3. Example of test zone and relaxation zone boundaries in Toyota 4Runner.

Table 3.
Test point coordinates and descriptions

Vehicle	Point	Description	Point Type	WAD (mm)	Lateral from CL (mm)	Zone Area
4Runner	A	Hood Leading Edge	T	1114	-471	Front Child
4Runner	B	Hood Leading Edge	T	1171	236	Front Child
4Runner	C	Open Area	S	1472	-385	Middle Child
4Runner	D	Radiator Cap	H	1280	-377	Middle Child
4Runner	E	Open Area	T	1710	-497	Front Adult
4Runner	F	Open Area	T	1706	280	Front Adult
4Runner	G	Fender Area	H	1705	739	Rear Adult
4Runner	H	Hinge	H	1908	-729	Rear Adult
CrownVic	A	Hood Ridge	T	1335	-515	Middle Child
CrownVic	B	Open Area	T	1336	257	Middle Child
CrownVic	C	Battery	H	1136	-650	Middle Child
CrownVic	D	Open Area	S	1653	439	Rear Child
CrownVic	E	Open Area	T	1975	-531	Middle Adult
CrownVic	F	Insulator Bkt	T	1976	266	Middle Adult
CrownVic	G	Hinge	H	1972	-775	Rear Adult
CrownVic	H	Engine Cover	H	1874	24	Middle Adult
CR-V	A	Hood Leading Edge	T	1081	-456	Front Child
CR-V	B	Hood Leading Edge	T	1087	228	Front Child
CR-V	C	Cowl Area	T	1705	-470	Rear Adult
CR-V	D	Cowl Area	T	1705	237	Rear Adult
CR-V	E	Fender Area	H	1399	692	Middle Child
CR-V	G	Hinge	H	1704	-701	Rear Adult
CR-V	H	Hinge	H	1706	652	Rear Adult
Dakota	A	Hood Leading Edge	T	1104	-519	Middle Child
Dakota	B	Radiator Cap	T	1104	260	Front Child
Dakota	C	Air Intake Box Area	T	1705	-514	Front Adult
Dakota	D	Throttle Box	T	1706	257	Front Adult
Dakota	E	Open Area	S	1308	-284	Middle Child
Dakota	F	Latch	H	1056	0	Front Child
Dakota	G	Hinge	H	1960	-707	Rear Adult
Dakota	H	Hinge	H	1986	622	Rear Adult
Durango	A	Hood Leading Edge	T	1194	-372	Front Child
Durango	B	Hood Leading Edge	T	1197	186	Front Child
Durango	C	Battery	T	1704	-481	Front Adult
Durango	D	Open Area	T	1707	230	Front Adult
Durango	E	Battery	H	1493	-590	Middle Child
Durango	F	Open Area	S	1508	233	Middle Child
Durango	G	Cowl Area	H	1900	-120	Rear Adult
Durango	H	Cowl Area	H	1858	699	Rear Adult
E350	A	Hood Leading Edge	T	1264	-547	Front Child
E350	B	Hood Leading Edge	T	1274	276	Front Child
E350	C	Latch	H	1278	0	Front Child
E350	D	Open Area	S	1480	561	Middle Child
E350	E	Cowl Area	T	1704	-568	Rear Adult
E350	F	Cowl Area	T	1706	282	Rear Adult
E350	G	Cowl Area	H	1808	609	Rear Adult
E350	H	Hinge	H	1792	856	Rear Adult

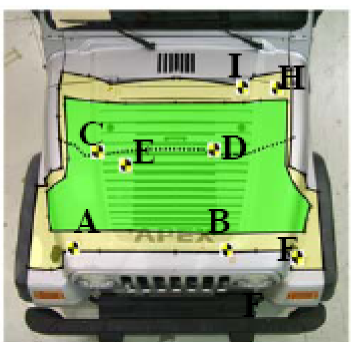
Vehicle	Point	Description	Point Type	WAD (mm)	Lateral from CL (mm)	Zone Area
H2	A	Hood Leading Edge	T	1270	-578	Front Child
H2	B	Hood Leading Edge	T	1275	289	Front Child
H2	C	Open Area	T	1705	-534	Front Adult
H2	D	Handle	T	1727	267	Front Adult
H2	E	Hood Leading Edge	H	1328	382	Front Child
H2	F	Hood Ridge	H	1445	765	Middle Child
H2	G	Open Area	S	1856	487	Middle Adult
H2	H	Latch	H	2053	126	Rear Adult
Passat	A	Open Area	T	1346	-480	Middle Child
Passat	B	Open Area	T	1346	240	Middle Child
Passat	F	Open Area	S	1174	435	Middle Child
Passat	G	Hinge	H	1501	-683	Rear Child
Passat	H	Cowl Area	T	1698	0	Middle Adult
Silverado	1	Open Area	T	1705	320	Front Adult
Silverado	2	Open Area	S	2030	-310	Rear Adult
Silverado	3	Hood Leading Edge	T	1335	-580	Front Child
Silverado	4	Fender Area	H	1337	750	Front Child
Silverado	5	Fluid Cap	T	1705	-632	Front Adult
Silverado	6	Hinge	H	2095	779	Rear Adult
Silverado	7	Latch	H	1340	0	Front Child
Silverado	8	Hood Leading Edge	T	1342	291	Front Child
Tacoma	A	Hood Leading Edge	T	1110	-487	Front Child
Tacoma	B	Hood Leading Edge	T	1100	243	Front Child
Tacoma	C	Open Area	T	1710	-487	Front Adult
Tacoma	D	Open Area	T	1710	243	Front Adult
Tacoma	E	Hood Leading Edge	H	1103	693	Front Child
Tacoma	F	Open Area	S	1462	275	Middle Child
Tacoma	G	Fender Area	H	1706	-726	Middle Adult
Tacoma	H	Hinge	H	1942	716	Rear Adult
Wrangler	A	Hood Leading Edge	T	1153	-501	Front Child
Wrangler	B	Hood Leading Edge	T	1168	250	Front Child
Wrangler	C	Hood Ridge	T	1705	-389	Front Adult
Wrangler	D	Open Area	T	1705	195	Front Adult
Wrangler	E	Open Area	S	1599	-246	Rear Child
Wrangler	F	Latch	H	1072	603	Front Child
Wrangler	H	Cowl Area	H	2014	534	Rear Adult
Wrangler	I	Hinge	H	2071	350	Rear Adult
CRV	CM-L	Latch Area	CM	1072	3	Front Child
CR-V	CM-W	Wiper Base	CM	1822	76	Outside Zone
CR-V	CM-H	Headlight Area	CM	1050	-634	Front Child
CR-V	CM-C	Cowl Area	CM	1810	-292	Outside Zone

T Typical
S Soft
H Hard
CM Countermeasure comparison test

RESULTS

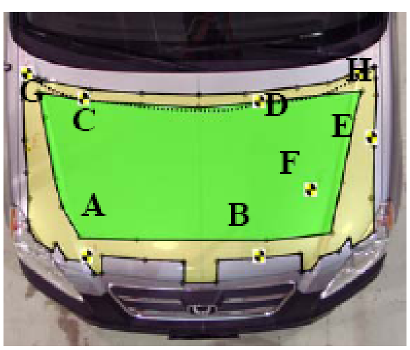
For the baseline 84 tests, Figures 4 through 14 show the location of impact points relative to the estimated relaxation zones that were identified after testing was complete, along with the 15-millisecond HIC result from each test. The test zones are outlined in black, with the outer, lighter (yellow) zone representing the relaxation zone and the inner, darker (green) zone representing the remaining two thirds of the test zone. The child and adult zone boundary is a dashed line. The relaxation zones represent approximately one third of the total allowable test area. The relaxation zones on each vehicle met the GTR requirement that the relaxation zone not exceed one half of the child zone. Removing that requirement, however, would not have had any effect on the relaxation zones estimated for this set of vehicles.

The results of an additional four tests performed on the CR-V for comparison purposes only are shown in Figure 15.



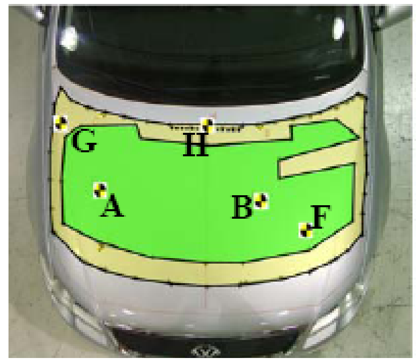
	HIC
A	1699
B	1697
C	553
D	456
E	379
F	3574
H	2902
I	4302

Figure 4. 2002 Jeep Wrangler results.



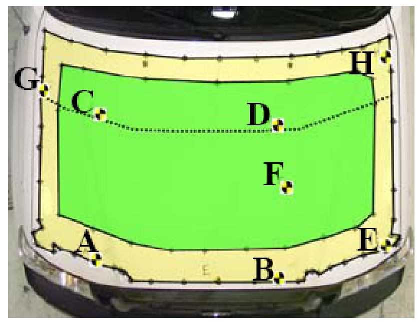
	HIC
A	749
B	671
C	938
D	1013
E	1054
F	No Data
G	1660
H	1224

Figure 5. 2005 Honda CR-V results (baseline).



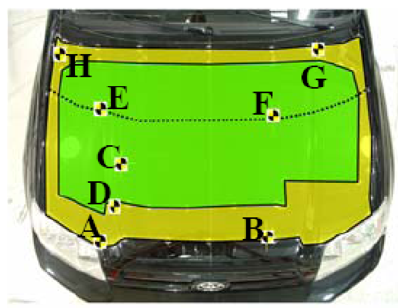
	HIC
A	734
B	378
F	565
G	1302
H	836

Figure 6. 2006 Volkswagen Passat results.



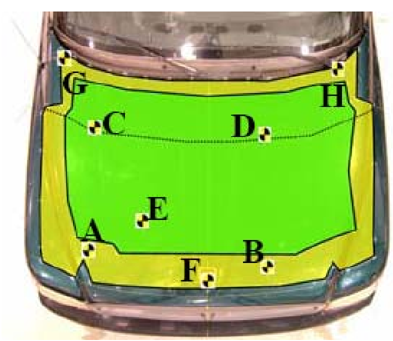
	HIC
A	889
B	947
C	513
D	415
E	1385
F	309
G	1443
H	1814

Figure 7. 2006 Toyota Tacoma results.



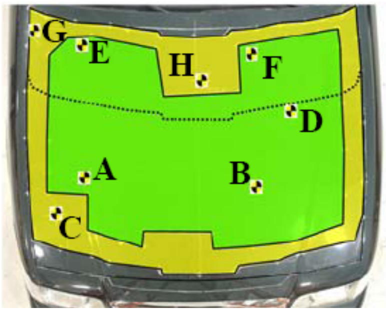
	HIC
A	1756
B	1344
C	356
D	838
E	580
F	732
G	1774
H	2288

Figure 8. 2003 Toyota 4Runner results.



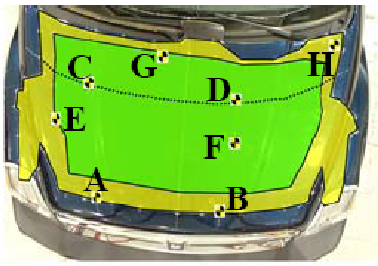
	HIC
A	1483
B	1203
C	859
D	763
E	448
F	1658
G	2276
H	1737

Figure 9. 1999 Dodge Dakota results.



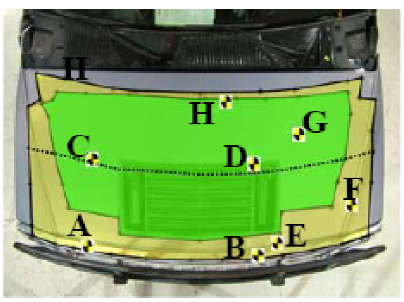
	HIC
A	514
B	480
C	1012
D	481
E	711
F	536
G	3583
H	1186

Figure 10. 2003 Ford Crown Victoria results.



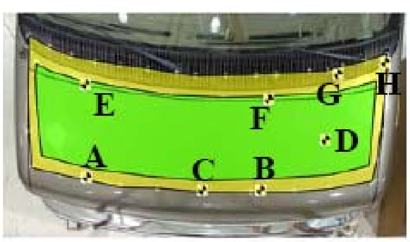
	HIC
A	1032
B	1685
C	729
D	476
E	769
F	343
G	981
H	1766

Figure 11. 2006 Dodge Durango results.



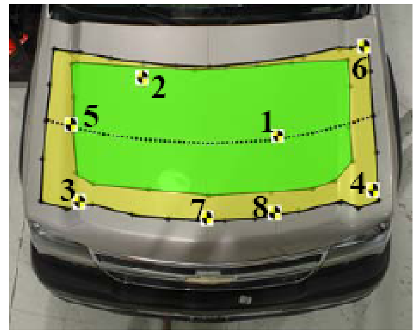
	HIC
A	4252
B	4594
C	1220
D	909
E	6773
F	2307
G	1220
H	1493

Figure 12. 2003 Hummer H2 results.



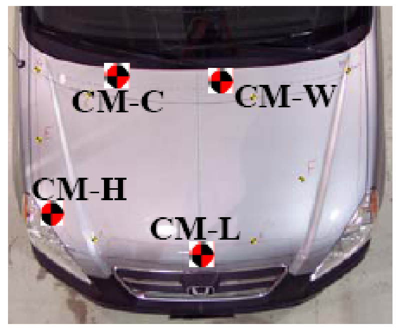
	HIC
A	1394
B	1433
C	1422
D	868
E	1297
F	1321
G	2448
H	3993

Figure 13. 2003 Ford E350 results.



	HIC
1	740
2	864
3	889
4	1048
5	833
6	1133
7	929
8	1274

Figure 14. 2005 Chevrolet Silverado results.



	HIC
CM-L	626
CM-W	926
CM-H	1197
CM-C	508

Figure 15. 2005 Honda CR-V counter-measure impacts for comparison only.

Table 4 summarizes statistics from the 84 baseline test results grouped by location within each test zone. The child and adult zones were each divided into a front, middle, and rear region, where the front and rear regions were within approximately one head radius (82.5 mm) from the front and rear boundaries of the test zone respectively. The pass/fail status is indicated by the number of impacts with HIC below 1000, which would pass at any location in the test zone and the number of impacts with HIC above 1700, which would fail at any location in the test zone. Also listed is the number of impacts between HIC 1000 and HIC 1700, which would pass only if located within a manufacturer-defined relaxation zone.

Table 5 summarizes the baseline test data by vehicle. The Silverado, Passat, and CR-V had no "failing" impacts. Although all three vehicles had impacts with HIC between 1000 and 1700, these points were all within the estimated relaxation zones for these vehicles. The H2 and the E350 had failing impacts over 1700, as well as points between 1000 and 1700 that were *not* in the estimated relaxation zone. The remaining six vehicles had failing points over 1700, but all tested points between 1000 and 1700 fell in the estimated relaxation zone.

Sixteen of the 17 points with HIC above 1700 were in the peripheral areas of the test zone. Table 6 shows the relative severity of impacts near various structures in the test zone. The five highest average HIC values by impacted structure were obtained for components along the front, rear, and side of the hood. The only central structure having a HIC above 1700 was the hood ridge of the H2.

Table 4.
Summary of HIC results by location within test zone

Zone	Avg HIC	Std Dev	Min	Max	N	Pass (<1000)	Pass only if in relaxation zone (1000-1700)	Fail (>1700)
Rear Adult	1943	1005	864	4302	21	3	7	11
Middle Adult	989	348	536	1443	6	3	3	0
Front Adult	698	220	415	1220	14	13	1	0
Rear Child	721	506	379	1302	3	2	1	0
Middle Child	779	519	309	2307	16	12	3	1
Front Child	1846	1472	671	6773	24	6	13	5
Adult	1378	942	415	4302	41	19	11	11
Child	1205	1134	309	6773	43	20	17	6
Total	1374	1110	309	6773	84	39	28	17

Table 5.
Summary of results by vehicle, in descending order by average HIC

Vehicle	Avg HIC	Std Dev	Min	Max	N	Pass (<1000)	Pass only if in relaxation zone (1000-1700)	Fail (>1700)
Hummer H2	2846	2125	909	6773	8	1	3 (none in estimated relax zone)	4
Jeep Wrangler	1945	1505	379	4302	8	3	2	3
Ford E350	1772	1001	868	3993	8	1	5 (3 in estimated relax zone)	2
Dodge Dakota	1303	600	448	2276	8	3	3	2
Toyota 4Runner	1208	685	356	2288	8	4	1	3
Ford Crown Victoria	1063	1052	481	3583	8	5	2	1
Honda CR-V	1044	329	671	1660	7	3	4	0
Dodge Durango	973	519	343	1766	8	5	2	1
Chevrolet Silverado	964	176	740	1274	8	5	3	0
Toyota Tacoma	964	544	309	1814	8	5	2	1
Volkswagen Passat	763	348	378	1302	5	4	1	0

Table 6.
Summary of results by impacted structure, in descending order by average HIC

	Impacted Structure	Avg HIC	Std Dev	Min	Max	N	Pass (<1000)	Pass only if in relaxation zone (1000-1700)	Fail (>1700)
Peripheral	Hinge	2301	1140	1133	4302	11	0	4	7
	Hood Leading Edge	1892	1578	671	6773	19	5	10	4
	Latch	1815	1020	929	3574	5	1	3	1
	Cowl Area	1500	731	836	2902	9	3	3	3
	Fender Area	1330	349	1048	1774	4	0	3	1
Central	Engine Cover	1186	NA	1186	1186	1	0	1	0
	Hood Ridge	1125	1024	514	2307	3	2	0	1
	Radiator Cap	1020	258	838	1203	2	1	1	0
	Handle	909	NA	909	909	1	1	0	0
	Air Intake Box Area	859	NA	859	859	1	1	0	0
	Battery	837	153	729	859	3	2	1	0
	Fluid Cap	833	NA	833	833	1	1	0	0
	Throttle Box	763	NA	763	763	1	1	0	0
	Open Area	603	260	309	1220	22	20	2	0
	Insulator Bracket	536	NA	536	536	1	1	0	0

DISCUSSION

The results of the GTR head testing on eleven US vehicles did not show a clear connection between vehicle size and performance in head testing. Although two of the three vehicles with the highest average HIC were among the heaviest and highest-front vehicles (the H2 and the E350), the Jeep Wrangler also showed high average HIC, in spite of being one of the lighter vehicles with moderate front-end height. Conversely, the Silverado was the heaviest, highest-front vehicle in the test series, but had an average HIC below 1000 and had no failing impacts. Location within the test zone and hood material selection appeared to have more effect on impact severity than did vehicle size. Figure 16 shows that HIC values measured centrally on the hood tended to be lower than those measured peripherally at the rear, sides, and front of the test area.

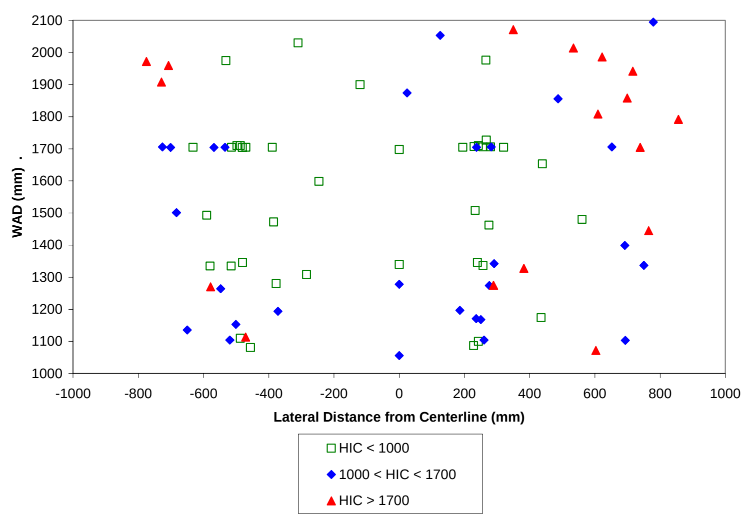


Figure 16. Two-Dimensional Locations of Impacts.

The hood hinge location had the highest average HIC value of all impacted areas with a HIC value over 1000 in every case. The hood hinge was selected as a potential hard point on nine of the eleven test vehicles. On two of those vehicles, two locations on the hinge were tested for a total of eleven hinge impacts. Hinge impacts that were particularly severe (over HIC 1700) tended to produce less damage and be shorter duration impacts while those that were under 1700 tended to produce more deformation and be longer in duration (Figure 17).

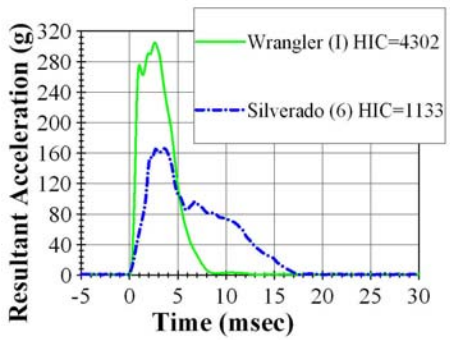


Figure 17. Resultant acceleration of most severe hinge impact (Wrangler, green solid) and least severe hinge impact (Silverado, blue dashed), showing difference in impact duration.

The hinge is a difficult area to design for pedestrians because of the strength required to support the hood and the necessary lack of clearance due to its location. The two vehicles that did worst were the two with an exposed hinge with no hood covering (E350 and Wrangler) to dissipate energy before direct contact (Figure 18).

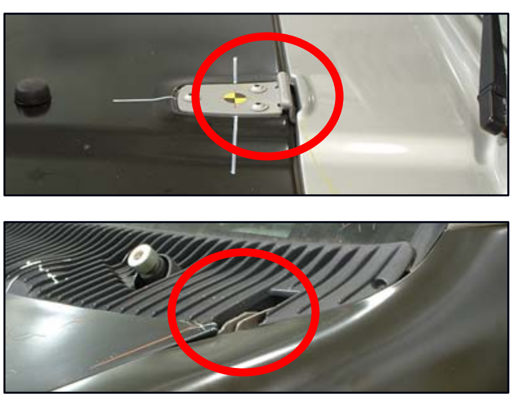


Figure 18. Wrangler (Top) & E350 Hinges.

The more compliant hinge designs on the Passat, Silverado, and CR-V appeared to be a deformable hinge, combined with an overlaid layer of crushable hood space (Figure 19).

Figure 19. Passat hinge with low-profile deformable hinge and crush space over hinge.

Even apart from the hinges, the entire area on or adjacent to the cowl, including over the wiper spindles, appeared to be challenging for pedestrian design. The worst performers in the cowl area did not have hood overhang over the cowl, and in fact the E350 had an exposed cowl that allowed direct contact by the headform (Figure 20). Vehicles that did best in the cowl area were those whose rear hood edge extended over the cowl, leaving a crush space between the hood and the structures below and preventing direct exposure of the head to the cowl (Figure 21).

Figure 20. Exposed Cowl on E350.

Figure 21. Hood Coverage of the Cowl (Durango).

The test zone markup procedure at the rear hood appeared to be effective at keeping likely impact areas in the zone and unlikely impact areas out of the zone. The test zone boundary at the rear of the hood was the most forward of the WAD 2100 line or 82.5 mm forward of the bonnet rear reference line. The bonnet rear reference line was located at the point of contact between a headform-sized sphere and the hood, cowl or other front structure when the sphere is traversed across the vehicle while maintaining contact with the vehicle. Therefore, if the geometry of the windshield and rear edge of the hood prevented the headform from contacting the cowl, the cowl was not included in the test zone. Since the headform represents the size of a typical adult head, a cowl that was not in the test zone seemed unlikely to be contacted by a human pedestrian while a cowl that was in the test zone appeared that it could be contacted by a pedestrian head.

The area of the test zone adjacent to the fender appears to be another difficult area for many vehicles. Although there was only one failure (HIC 1774 on 4Runner), none of the four fender area impacts in the series had HIC under 1000. The solutions that work at the rear (such as overhanging hood to allow crush space at the edge) simply would not work with a standard side hood edge, supported laterally by the fender. The best performer in a fender-adjacent impact was the CR-V, which has deformable flanges under the fender-hood junction as well built-in crush space in adjacent areas of the hood reinforcement (Figure 22).

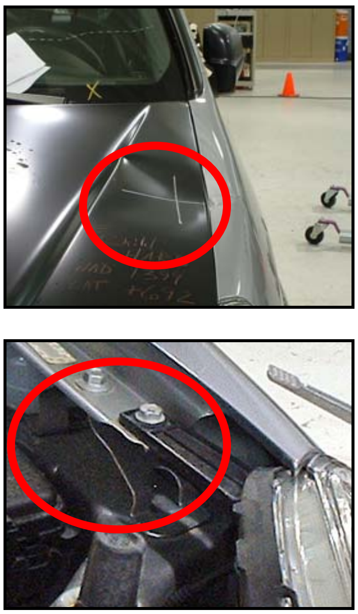


Figure 22. CR-V Countermeasures at Fender.

In the hood leading edge and latch area, eight of eleven vehicles passed the HIC requirements, based on the assumption that this area would be in the relaxation zone. Although the average HIC of the latch and hood leading edge areas were more severe than all other areas except for the hinge (Table 6), these high average values were a result of a small number of very severe impacts (HIC> 3000) on two vehicles. Nineteen of 24 impacts in this area were below the relaxation zone limit of 1700 HIC, and six were below 1000.

The vehicles that did best in hood leading edge impacts tended to have high, rounded front hood areas like those on the Silverado, Durango, and CR-V, allowing plenty of crush space to shield stiffer underlying components including the front structural support, latch components, and underhood components (Figure 23). Those that failed the HIC<1700 requirement in this area tended to have specific design features that presented unique risks for pedestrians. Three of those failures were in the H2, whose stiff composite hood was shaped into a very harsh corner at the front edge, resulting in HIC values of 4252, 4594, and 6773. A fourth failure was at the external latch on the Jeep Wrangler, which produced a HIC of 3574. These two designs are unlike any others tested; thus the countermeasures that worked well for the Silverado and Durango would not necessarily address these problems. The Wrangler's latch and the stiff front area of the H2 both represent pedestrian design challenges that may require unique solutions. A fifth failure in a 4Runner test adjacent to a headlamp may be a more typical issue for US large vehicles. An impact performed adjacent to the CR-V's headlamp for comparison, produced a HIC of 1197. The CR-V showed more deformation to hood area adjacent to the headlamp than the 4Runner did, indicating more crush space available at the edge of the CR-V hood.

Figure 23. Sloped Hood at Leading Edge (Silverado and Durango shown here).

As shown in Table 6 and Figure 16, HIC values measured in central hood impacts were low, compared to the peripheral areas of the test zones at the fender, cowl area, and hood leading edge. Of 36 central-area tests, only one test exceeded HIC 1700 and only five others were above 1000. It may be that the larger vehicles tested in this series had larger than average engine compartments, allowing sufficient clearance over stiff engine compartment components, and avoiding the engine compartment clearance issues faced by designers of small cars. As a result of this large amount of clearance, dynamic deformation was very high in most central hood cases.

The relaxation zones approximated in the current study indicate that there is enough relaxation area available such that most failing vehicles would be able to pass the GTR requirements by focusing on redesign of the specific peripheral areas that produced greater than 1700 HIC. Six of the eight vehicles with failing points had no points between 1000 and 1700 outside the estimated relaxation zone. This pass rate suggests that most vehicles will require improvement to only the very stiffest structures to meet the requirements of the proposed GTR. Only the H2 and the E350 had failing impacts (>1000 HIC) that were outside the relaxation zone. These may represent vehicles in the fleet that will require more widespread design modifications. These two vehicles were the only vehicles in the study that had hoods made of a composite material, rather than steel or aluminum. Impacts to these hoods resulted in little damage or evidence of deformation, particularly in impacts around the periphery, suggesting that hood material changes may be required for these vehicles to meet the GTR in and out of the relaxation zone.

Test results indicate that many areas around the periphery of the hood present design challenges for manufacturers. Of the three vehicles that had no "failing" impacts (Table 5), the CR-V and the Passat appeared to have pedestrian countermeasures designed specifically to address these challenges as described earlier in this discussion. In contrast, the third vehicle with no failing impacts (Silverado) did not appear to have design countermeasures such as those identified on the CR-V and the Passat, or other structures that appeared to be designed specifically for pedestrians. The performance of these three vehicles shows that design problems introduced by the proposed requirements, though challenging, can be solved.

A limitation of the current study is that a relatively small sample of vehicles and points were tested. This study's focus on larger vehicles in the US fleet also limits the conclusions that may be drawn regarding the benefit of the regulation for the entire US fleet.

CONCLUSIONS

The results of this series of head impact tests show that design improvements would be required in order for many vehicles in the US fleet to meet the proposed pedestrian GTR. These improvements would be expected, in turn, to reduce pedestrian fatalities and injuries. An estimate of the magnitude of these benefits will require additional test data and assessment.

Based on the relaxation zones estimated for each test vehicle, three of the eleven vehicles in this test series had no failing test points. Six of the eleven vehicles tested would likely require design improvements to specific structures around the periphery of the test zone to bring HIC in these areas below 1700. Two of the vehicles are expected to require more widespread design changes to reduce HIC in the relaxation zone below 1700 and to reduce HIC outside the relaxation zone to below 1000.

Head impact performance in pedestrian GTR testing does not appear to depend on vehicle size. For example, the large Silverado was one of the best performers, while the small Wrangler was among the worst performers in this series of tests.

For the vehicles tested, the hinges and impact locations adjacent to the cowl and fender appeared to be the most challenging areas of the GTR test zone. However, the ability of several vehicles to limit the impact severity in these areas to passing levels suggests that pedestrian-friendly design is possible in these areas, even for larger vehicles.

A smaller number of vehicles showed high-severity impacts toward the front of the test zone, adjacent to the hood leading edge. These results represented unique design features that were particularly aggressive toward pedestrians. The majority of the vehicles in this test series were able to limit HIC in this area to less than 1700, in some cases without any obvious pedestrian-specific design countermeasures.

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