PERFORMANCE OF VEHICLE BUMPER SYSTEMS WITH THE EEVC/TRL PEDESTRIAN LOWER LEGFORM

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Paper No. 09-0318

ABSTRACT

In U.S. pedestrian crashes, serious lower extremity injuries are second only to head injuries in frequency. The Global Technical Regulation (GTR) for pedestrian safety uses the EEVC/TRL pedestrian lower legform to evaluate the risk of these injuries from bumper impact. In order to evaluate the level of pedestrian lower extremity protection offered by front bumpers in the U.S. fleet, NHTSA's Vehicle Research and Test Center (VRTC) conducted 40 pedestrian lower legform impact tests on 9 vehicles. These vehicles were selected to represent the U.S. fleet, with a focus on light trucks and vans. The goal was to generate an overall picture of current U.S. vehicle performance with respect to lower extremity protection requirements in the regulation. Results showed that pedestrian lower extremity protection was poor overall, with no vehicle meeting the GTR injury limits in all locations tested. One vehicle was able to meet the requirements by a wide margin in all but one impact location. Two other vehicles each had a single passing impact location. Results are consistent with prior results from legform testing on U.S. passenger cars.

INTRODUCTION

In U.S. pedestrian crashes in the Pedestrian Crash Data Study (PCDS), injuries to the lower extremity are more frequent than injuries to any other body region (Mallory and Stammen 2006). Among serious pedestrian injuries, lower extremity injuries are second in frequency only to head injuries (Figure 1). Approximately 80% of the vehicle impact injuries to the thigh, knee, and lower leg are caused by bumper contact.

To evaluate lower extremity protection in pedestrian impacts, the Global Technical Regulation (GTR) for pedestrian safety includes front bumper testing with the EEVC/TRL lower legform or the upper legform depending on the height of the bumper. The EEVC/TRL lower legform is manufactured by TRL Limited and conforms to EEVC (European Enhanced Vehicle-safety Committee) requirements. According to the GTR, at locations where bumpers have a LBRL (Lower Bumper Reference Line) below 425 mm, the lower legform test is required. At locations where the LBRL is greater than or equal to 500 mm, the bumper is subjected to the upper legform test. At locations where the LBRL is between these two limits, the manufacturer may choose either test. As shown in Figure 2, PCDS bumper height data indicates that the majority of pedestrian-involved vehicles in the PCDS data set would be required to use the lower legform under GTR requirements (Mallory and Stammen 2006). Although the PCDS cases were collected between 1994 and 1998, they represent the most current U.S. pedestrian crash data available.

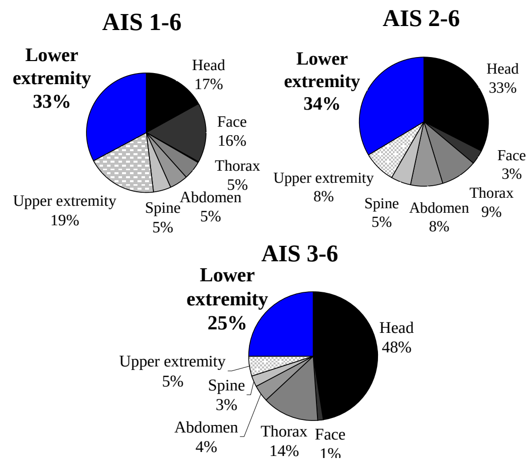

Figure 1. Distribution of injuries in the PCDS by body region (Mallory and Stammen 2006).

The performance of the U.S. fleet relative to the GTR lower legform test requirements has not previously been reported. In 2005, VRTC reported on the performance of five U.S. passenger cars in tests with the EEVC/TRL legform under EuroNCAP pedestrian test conditions (Mallory, Stammen et al. 2005). However, the EuroNCAP test conditions differ from those defined in the GTR. Furthermore, since the nature and risk of lower extremity injuries is affected by vehicle type (Ballesteros, Dischinger et al. 2004; Matsui 2005) the prior study of passenger cars may not reflect the level of pedestrian protection offered

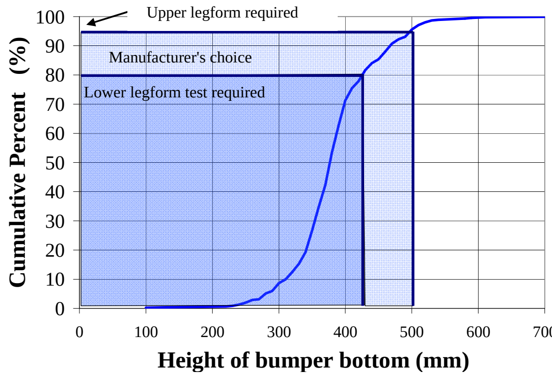

Figure 2. Lower bumper reference line height (Mallory and Stammen 2006).

by the rest of the U.S. fleet, which includes a large proportion of light trucks and vans.

In order to evaluate the performance of the current fleet relative to the GTR requirements, NHTSA's Vehicle Research and Test Center (VRTC) has conducted 40 pedestrian lower legform impact tests on 9 vehicles from the U.S. fleet with a focus on light trucks and vans. One vehicle from the previous series of testing done according to EuroNCAP test procedures was re-tested in the current series of tests according to GTR lower legform test procedures. If the results from the two sets of tests were similar enough, the prior test results with passenger cars could be combined with the current results to generate a more comprehensive picture of the current level of US vehicle performance.

METHODS

Testing was performed according to the lower legform procedures in the Proposal for a Global Technical Regulation (GTR) for the Protection of Pedestrians (GRSP 2006).

Vehicles Tested

The vehicles were selected to represent a range of vehicle types and sizes, including three sport utility vehicles (SUV), two pickups (PU) of different sizes, one minivan (MV), one full-size van (VAN), and two passenger cars (PC) as shown in Table 1**.**

Of the vehicles listed, only the Mazda Miata had been tested previously in lower extremity component tests under EuroNCAP conditions (Mallory, Stammen et al. 2005). The Passat, Wrangler, Durango, CR-V, Tacoma, and E-350 van had been previously tested in VRTC's evaluation of the U.S. fleet relative to the head test requirements in the GTR (Mallory, Stammen et al. 2007). The Silverado tested in the current series was a different vehicle than the Silverado used in the previously-reported head test series. The Sienna had not previously been used in pedestrian testing at VRTC.

Table 1.
Vehicles tested

Year	Vehicle	VIN
2002	Mazda Miata	JM1NB353320228887
2006	VW Passat	WVWGK73C56P171110
2002	Jeep Wrangler	1J4FA39S42P744167
2006	Dodge Durango	1D8HD38K66F118432
2005	Honda CR-V	JHLRD68585C000383
2006	Toyota Tacoma	5TENX22N16Z291865
2005	Chevy Silverado	1GCHC23U05F921031
2006	Toyota Sienna	5TDZA23C365448521
2003	Ford E-350 Van	1FBSS31L03HB67515

Bumper measurements made on each vehicle included the height of the Upper Bumper Reference Line and the Lower Bumper Reference Line, the width of the Bumper Test Area, and the distance from the vehicle centerline to the Corner of the Bumper. The maximum and minimum LBRL heights for each vehicle are documented in Table 2. Part of the Dodge Durango test zone is in the mandatory lower legform height range and part is in the manufacturer's option height range. The Jeep Wrangler test zone is entirely in the manufacturer's choice height range. The Silverado test zone has portions in all three ranges.

Table 2.
Range of LBRL height across width of test zone, color-coded by required test procedure

		LBRL Minimum (mm)	LBRL Max. (mm)
SUV	Dodge Durango	405	452
	Jeep Wrangler	451	481
	Honda CR-V	410	415
PU	Chevy Silverado	420	505
	Toyota Tacoma	378	378
MV	Toyota Sienna	260	264
VAN	Ford E350 Van	348	408
PC	VW Passat	219	230
	Mazda Miata	200	218
Color Legend: Test procedure required in GTR based on LBRL Height		Upper Leg > 500 mm	
		Manufacturer Choice	
		Lower Leg < 425 mm	

Impact Point Locations

Five impacts were planned for each vehicle. All impacts were within the test zone defined in the GTR. Assuming symmetry, these tests are equivalent to a center impact, an outboard impact, and three impacts between. In order to maximize the number of tests per bumper, the impacts were performed on both sides of the test zone as shown in Figure 3. The impacts are spaced at intervals proportional to 1/8 of the width of the bumper test zone, with the exception of the far outboard impact which was moved inboard from the edge of the test zone by 5 mm to ensure it was within the test zone. The intention of the test location selection was to represent the range of typical bumper performance. A maximum of three impacts were planned per bumper, before replacement of all bumper system parts. Damage was inspected following each impact. If post-test damage was identified that could have an effect on subsequent tests, the damaged parts were replaced prior to additional testing, or subsequent tests were cancelled. Subsequent tests were also cancelled if a vehicle produced damage to the legform in multiple tests. As a result, two vehicles underwent only four tests, and one vehicle was tested only twice. The test locations for each vehicle are listed in Table 3.

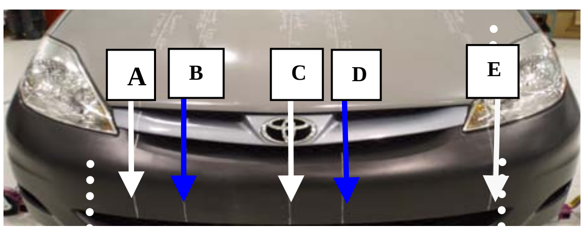

Figure 3. Example of five test locations on Toyota Sienna. Dashed boundaries show limits of test area and solid lines are impact locations. White and blue arrows indicate impacts performed on different bumper systems.

Table 3.
Location of each impact in mm from centerline of vehicle, positive toward driver's side

	A	B	C	D	E
Durango	-540	-360	0	--	715
Wrangler	-545	-364	0	182	722
CR-V	-347	-232	0	116	458
Silverado	-590	-394	0	197	782
Tacoma	--	--	0	--	503
Sienna	-404	-269	0	135	533
E350 Van	-596	-398	0	--	790
Passat	-361	-241	0	120	476
Miata	-368	-245	0	123	485

Test Procedure

Temperature and humidity were maintained within GTR-defined corridors for testing and during pre-test soaking. Impact speed in the GTR is required to be 11.1 m/s (+/- 0.2 m/s). Test speed was measured by an Aries laser speed meter (Model SM-2BL/F). During initial testing the speed meter was positioned at the approximate height of the CG of the legform. After testing demonstrated negligible pitch rotation in the legform during flight, the speed meter was moved down to allow a better lateral view of the legform-to-bumper impact. Integration of the upper tibia accelerometer was also performed to track velocity in case the speed meter failed to measure the speed. Deviations from the required speed range are documented.

The bottom of each vehicle tire was positioned 25 mm below the level of the bottom of the legform at impact.

Between tests, the ligaments and foam flesh on the EEVC/TRL legform were replaced. Legform inspection was performed and any necessary repairs were made, including replacement of the neoprene skin if needed.

The GTR specifies that the axis of the legform shall be perpendicular to the horizontal with a tolerance of +/- two degrees in the lateral and longitudinal plane, and the rotation about the vertical axis will have a tolerance of +/- five degrees. Initial video analysis of legform flight without a vehicle in place showed that legform alignment in the lateral and longitudinal planes were consistently within tolerance, but that orientation about the vertical axis showed variation. Therefore, overhead video was recorded during all vehicle testing and reviewed following each test. Any test that appeared to approach the five degree limit on rotation underwent video analysis using TEMA motion analysis software (Version 2.6, Image Systems AB).

The EEVC/TRL lower legform was instrumented as specified in the GTR. A uniaxial accelerometer (7264-2000) was mounted on the non-impact side of the upper tibia. The legform was equipped with rotary potentiometers located in the upper tibia and lower femur (Contelec, Type GL 60) to measure knee bending angle and knee shearing displacement. The knee bending angle and shear displacement are calculated based on the potentiometer angles as specified in the TRL Legform User's Manual (TRL, 2007).

Static and dynamic certification of the legform was performed after not more than 20 vehicle impacts, following GTR defined procedures.

RESULTS

Results are presented separately for each vehicle, followed by a comparison of peak measures across all vehicles. Peak injury measurements are compared to GTR requirements which limit peak knee bending angle to 19 degrees and shear displacement to 6 mm. Over most of the test area upper tibia acceleration is limited to 170 g, but the limit is relaxed to 250 g over areas totaling up to 264 mm of the width of the bumper. The location of the relaxed bumper area is designated by the vehicle manufacturer.

<u>Mazda Miata</u> - Time histories for injury measures on all tests are shown in Figure 4 and peak values are tabulated in Table 4. The Mazda Miata was below GTR limits for the impact to the center bumper (Impact C) only. In impact C, peak bending angle was within 0.3 degrees of the GTR limit of 19 degrees. In all other impacts, the bending angle limit was exceeded. Impact A, which was close to the bumper support location, resulted in the highest shear displacement, bending angle, and tibia acceleration of any of the Miata test locations.

As indicated in Table 4, impact B was slower than the required impact speed range of 10.9 -11.3 m/s and impact D was faster than the required speed.

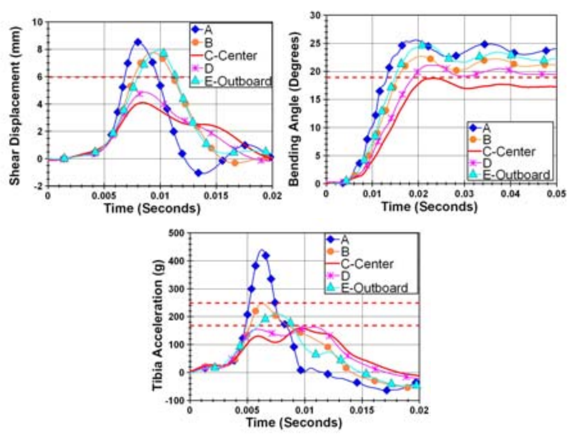

Figure 4. Time histories for shear displacement, knee bending angle, and tibia acceleration for Mazda Miata, with GTR limits shown in red.

Table 4.
Peak results for each Mazda Miata impact, with passing impact (C) shaded green

	GTR Limit	Impact Location				
		A	B*	C	D**	E
Bending angle (degrees)	19	25.7	22.9	18.7	20.9	24.9
Shear displacement (mm)	6	8.6	7.8	4.2	4.9	7.9
Tibia acceleration (g)	170 (250)	440	247	159	163	210

* Location B impact speed was 10.87 m/s
** Location D impact speed was 11.39 m/s

A video frame showing the legform in the center impact (C) at the moment of peak bending angle is shown in Figure 5. In all impacts, the tibia segment of the legform was supported by the lower bumper structures on the Miata while the femur segment wrapped forward toward the hood.

Figure 5. Legform at time of maximum bending angle in Mazda Miata center impact (C).

<u>Volkswagen Passat</u> - None of the impacts to the Volkswagen Passat met the GTR requirements, as shown by the time histories in Figure 6 and the peak values in Table 5. Peak bending angle exceeded the 19 degree limit in every test. Shear displacement exceeded the GTR limit only in impact A. Tibia acceleration was over 170 g centrally, and exceeded 250 g in the more outboard test locations.

Figure 7 shows the legform at the moment of peak bending deformation in the center impact. At all impact locations, the legform conformed with the vehicle front by the time of maximum bending with the tibia segment essentially vertical against the bumper structures and the femur segment wrapped around the grille structures.

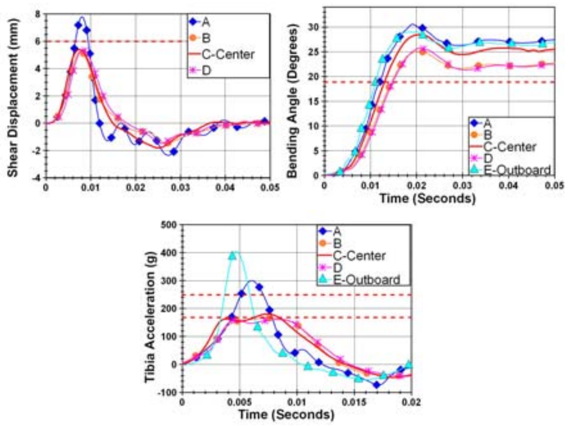

Figure 6. Time histories for shear displacement, knee bending angle, and tibia acceleration for Volkswagen Passat, with GTR limits shown in red.

Table 5.
Peak results for each Volkswagen Passat impact

	GTR Limit	Impact Location				
		A	B	C	D	E
Bending angle (degrees)	19	30.5	25.1	28.5	25.8	29.0
Shear displacement (mm)	6	7.8	5.2	5.4	5.4	--*
Tibia acceleration (g)	170 (250)	300	166	181	161	405

* Shear pot wire broken – data invalid.

Figure 7. Legform at time of maximum bending angle in Volkswagen Passat center impact (C).

Jeep Wrangler - In four of the five Jeep Wrangler impacts, all three injury measures were above the GTR limit (Figure 8, Table 6). In the fifth impact, the outboard-most point tested, the injury measures were well below the GTR limits. The negative shear displacement documented in the Wrangler tests indicates that, relative to the femur, the tibia segment moved toward the vehicle. Figure 9 shows a video frame from the moment of maximum bending angle in impact C.

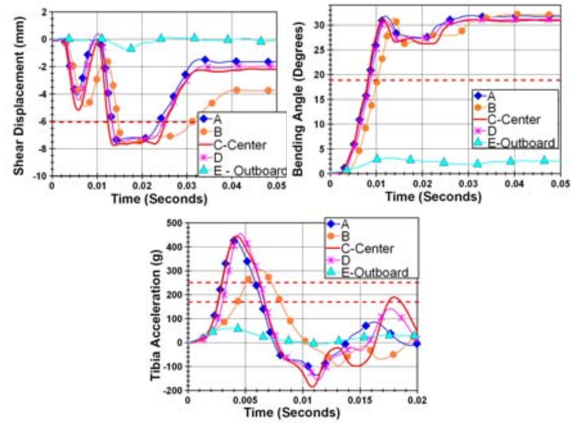

Figure 8. Time histories for shear displacement, knee bending angle, and tibia acceleration for Jeep Wrangler, with GTR limits shown in red.

Table 6.
Peak results for Jeep Wrangler each impact, with passing impact (E) shaded green

	GTR Limit	Impact Location				
		A	B	C	D	E
Bending angle (degrees)	19	31.9	32.2	31.3	31.2	3.2
Shear displacement (mm)	6	-7.5	-7.6	-7.8	-7.5	-0.75
Tibia acceleration (g)	170 (250)	427	305	445	455	60

Figure 9. Legform at time of maximum bending angle in Jeep Wrangler center impact (C).

Video showed that there was little to no bumper deformation in the four failed impacts, but there was significant deformation of the bumper end in the passing outboard impact. The end cap of the bumper bent rearward, allowing the legform to move into the front surface of the tire and fender, supporting the legform along its full length to limit bending and shear.

Dodge Durango - The Dodge Durango was tested in only four locations because legform damage was sustained in three of the first four impacts. The Durango exceeded the bending angle limit by a wide margin in three impacts, and by a narrow margin in the outboard-most impact (Figure 10 and Table 7). Tibia acceleration limits were exceeded by all but the outboard-most impact. Shear limits were exceeded at points B and C. The negative shear values indicate that, relative to the femur, the tibia moved toward the car in all impacts.

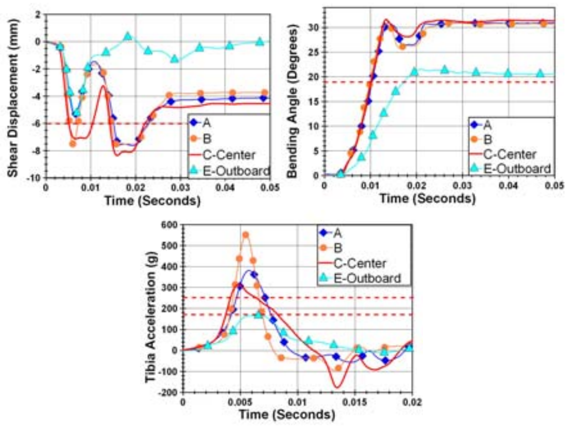

Figure 10. Time histories for shear displacement, knee bending angle, and tibia acceleration for Dodge Durango, with GTR limits shown in red.

Table 7.
Peak results for each Dodge Durango impact

	GTR Limit	Impact Location			
		A	B	C	E
Bending angle (degrees)	19	31.0	30.9	31.6	21.5
Shear displacement (mm)	6	-8.4	-7.6	-8.4	-5.3
Tibia acceleration (g)	170 (250)	314	552	314	167

A video frame from the moment of maximum displacement (Figure 11) shows that the upper leg and lower leg both rotate toward the car around the bumper. In the outboard-most impact at location E, the legform has started to rotate outboard by the time of maximum bending.

Figure 11. Legform at time of maximum bending angle in Dodge Durango center impact (C).

Honda CR-V - In four of the five impacts, the Honda CR-V was well below GTR limits in all measures. The exception was the outboard-most impact, where the tibia acceleration exceeded even the relaxed limit of 250 g, and the bending angle exceeded the 19 degree limit (Figure 12, Table 8). Shear displacement in the outboard impact E was negative, indicating that the tibia displacement was toward the vehicle relative to the femur, rather than away from the vehicle relative to the femur as was seen in the other four tests.

As indicated in Table 8, the rotation about the Z axis exceeded the GTR limit of 5 degrees in the impacts at locations D and E. Table 8 also shows the higher peak bending angle in outboard impact E, compared to the much lower peak bending angles in the remaining tests. The outboard impact E also shows dramatically less bumper and vehicle-front deformation than the inboard, passing impacts.

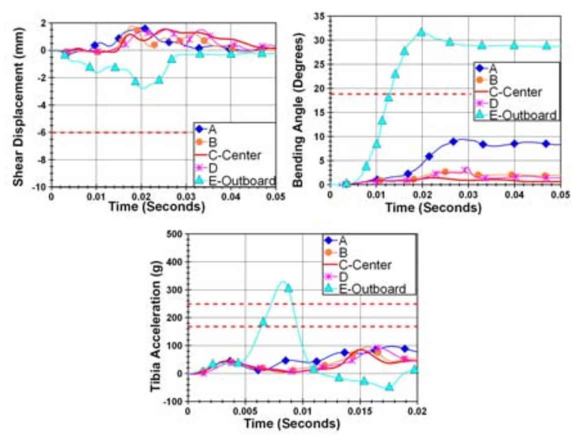

Figure 12. Time histories for shear displacement, knee bending angle, and tibia acceleration for Honda CR-V, with GTR limits shown in red.

Table 8.
Peak results for each Honda VR-V impact, with passing impacts shaded green

	GTR Limit	Impact Location				
		A	B	C	D*	E**
Bending angle (degrees)	19	9.5	2.8	1.5	3.6	31.5
Shear displacement (mm)	6	1.6	1.8	1.8	1.5	-2.8
Tibia acceleration (g)	170/250	97	96	85	91	329

* Location D rotation about Z axis exceeded 5 degrees.
** Location E rotation about Z axis exceeded 5 degrees.

Figure 13. Legform at time of maximum bending angle in Honda CR-V impact (C).

<u>Toyota Tacoma</u> - Only two tests were performed on the Toyota Tacoma due to vehicle damage. After two tests there was extensive unforeseen damage to the grille, the grille surround and to the headlamp mounts. With no replacement parts available, subsequent testing was suspended because these structures could potentially have been limiting the peak bending angle and shear displacement of the legform. Therefore, testing with damaged structures may not have been valid. Figure 14 and Table 9 show that all injury limits were exceeded in both tests. Figure 15 shows that the upper leg tended to rotate into the grille structures while the tibia segment of the legform rotated much less.

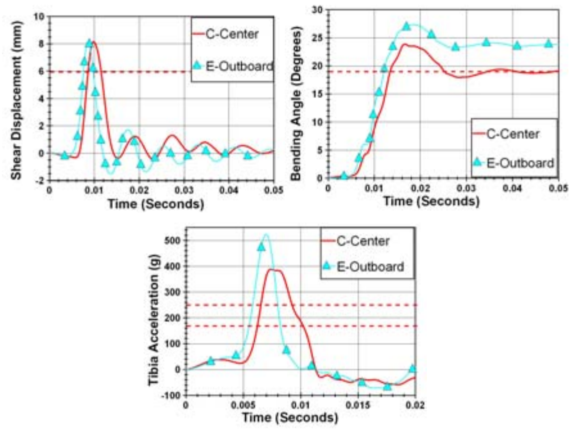

Figure 14. Time histories for shear displacement, knee bending angle, and tibia acceleration for Toyota Tacoma, with GTR limits shown in red.

Table 9.
Peak results for each Toyota Tacoma impact

	GTR Limit	Impact Location	
		C	E
Bending angle (degrees)	19	23.9	27.4
Shear displacement (mm)	6	8.2	8.1
Tibia acceleration (g)	170 (250)	388	523

Figure 15. Legform at time of maximum bending angle in Toyota Tacoma center impact (C).

<u>Chevrolet Silverado</u> - None of the Chevrolet Silverado impacts met the GTR requirements. In contrast to other vehicles, two of the failing impacts did meet bending angle requirements (Figure 16 and Table 10). Shear displacement limits were exceeded in every test. Tibia acceleration was over 170 g in all tests, but below the relaxed limit of 250 g in one test.

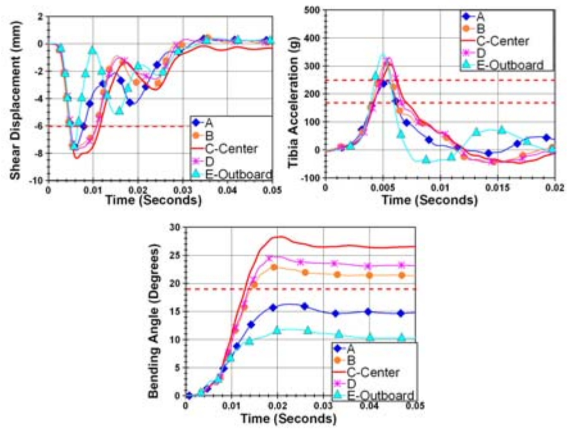

Figure 16. Time histories for shear displacement, knee bending angle, and tibia acceleration for Chevrolet Silverado, with GTR limits shown in red.

Table 10.
Peak results for each Chevrolet Silverado impact

	GTR Limit	Impact Location				
		A	B*	C	D	E
Bending angle (degrees)	19	16.3	22.9	28.3	24.8	11.8
Shear displacement (mm)	6	7.6	7.8	8.4	7.8	7.5
Tibia acceleration (g)	170 (250)	245	311	306	330	342

* LBRL higher than 500 mm at location B.

As indicated in Table 10, impact location B was tested with the lower legform in spite of the fact that the Lower Bumper Reference Line at this test location put it in a zone where upper legform testing would have been required per the GTR requirements.

Figure 17 illustrates the interaction of the legform with the bumper at peak bending angle, with the lower leg bending under the bumper and the upper leg supported almost vertically by the bumper structures.

Figure 17. Legform at time of maximum bending angle in Chevrolet Silverado center impact (C).

Toyota Sienna - All impacts to the Toyota Sienna failed to meet GTR requirements. Although the center impact (C) was below the shear displacement limit and impact D was below the 170 g limit on tibia acceleration, bending angle was well over the 19 degree limit in all tests (Figure 18 and Table 11). The video frame at the moment of maximum bending angle show that the top of the bumper contacts the legform near the knee and the upper portion of the legform wrapped down to the hood of the Sienna in all impacts (Figure 19).

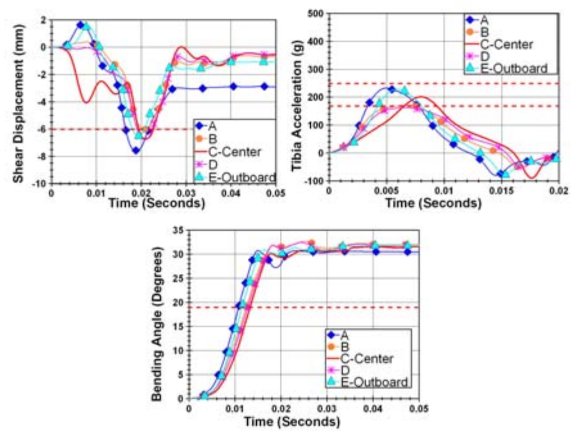

Figure 18. Time histories for shear displacement, knee bending angle, and tibia acceleration for Toyota Sienna, with GTR limits shown in red.

As indicated in Table 11., the rotation about the vertical axis exceeded the GTR limit of 5 degrees in the impact at location B.

Table 11.
Peak results for each Toyota Sienna impact

	GTR Limit	Impact Location				
		A	B*	C	D	E
Bending angle (degrees)	19	30.8	32.7	31.0	32.5	31.4
Shear displacement (mm)	6	-7.6	-6.0	-6.7	-6.8	-6.5
Tibia acceleration (g)	170 (250)	233	172	202	162	228

* Location B rotation about vertical axis exceeded 5 degrees.

Figure 19. Legform at time of maximum bending angle in Toyota Sienna center impact (C).

Ford E-350 Van - The first four impacts to the Ford E-350 bumper exceeded injury limits by a wide margin with bending angle over 31 degrees in all tests and tibia acceleration exceeding 350 g's in three tests (Figure 20 and Table 12). In the center impact (C), acceleration data was not collected due to wire damage. In the fourth impact (B) the pot arm of the potentiometer sustained damage. Due to a limited number of replacement pot arms, and the assumption that point D results would be similar to points B and C, testing was suspended prior to testing point D. Figure 21 shows that the femur segment tended to rotate into the grille while the tibia segment rotated under the bumper in all impacts. The knee was approximately centered over the height of the bumper.

As indicated in Table 12, the rotation about the vertical axis exceeded the GTR limit of 5 degrees in the impact at location C.

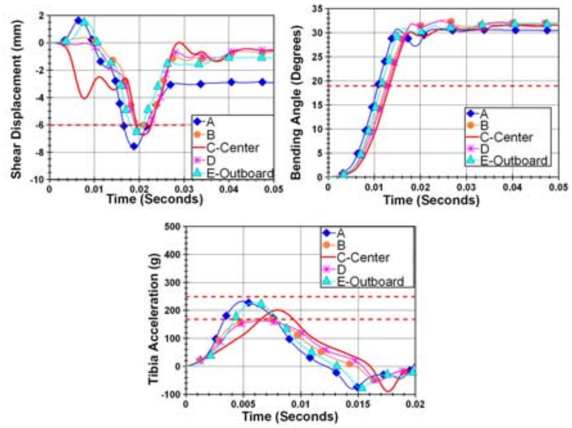

Figure 20. Time histories for shear displacement, knee bending angle, and tibia acceleration for Toyota Sienna, with GTR limits shown in red.

Table 12.
Peak results for each Ford E-350 impact

	GTR Limit	Impact Location			
		A	B	C*	E
Bending angle (degrees)	19	31.8	31.7	32.0	32.7
Shear displacement (mm)	6	-7.5	-7.5	-7.6	-7.5
Tibia acceleration (g)	170/250	516	592	--*	379

* Location C rotation about vertical axis exceeded 5 degrees.

Figure 21. Legform at time of maximum bending angle in Ford E-350 center impact (C).

Comparison of results among vehicles

Peak results for tibia acceleration are shown for all vehicles in Figure 22. The acceleration limit of 170 g and the relaxation limit of 250 g are indicated in red.

Only five of 39 (13%) test locations met the 170 g limit with a wide margin: the four passing CR-V impacts and the outboard Wrangler impact. The remaining impacts were all either very close to, or in excess of, 170 g. Some tests exceeded the acceleration limits dramatically and six vehicles exceeded 400 g in at least one test location.

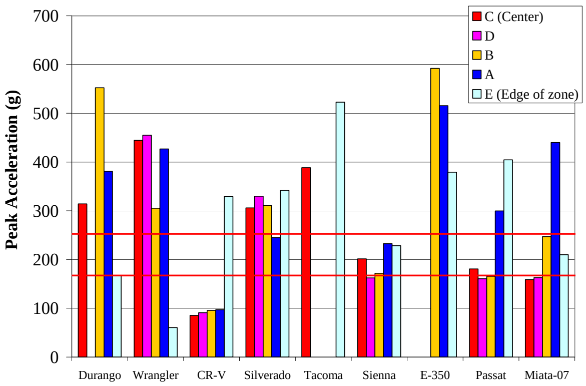

Figure 22. Peak acceleration for all impacts by vehicle and impact location.

Peak magnitude of shear displacement is shown in Figure 23. This peak is an absolute value, representing the peak magnitude. The GTR shear displacement limit of 6 mm is indicated in red. Only the CR-V passed shear limits in all tests, but six of the nine vehicles were able to pass the shear requirement in at least one test location.

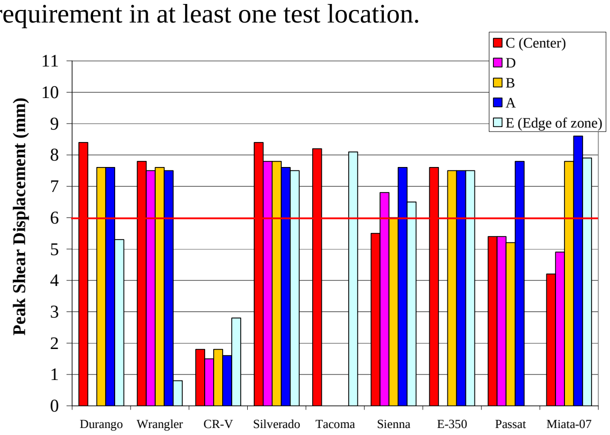

Figure 23. Peak shear displacement for all impacts, by vehicle and impact location.

Peak knee bending angle is shown in Figure 24. Only 8 of 40 (20%) impacts resulted in bending angle peaks below the injury limit of 19 degrees, which is shown in red. The majority of the failing impacts showed bending angles in excess of 30 degrees.

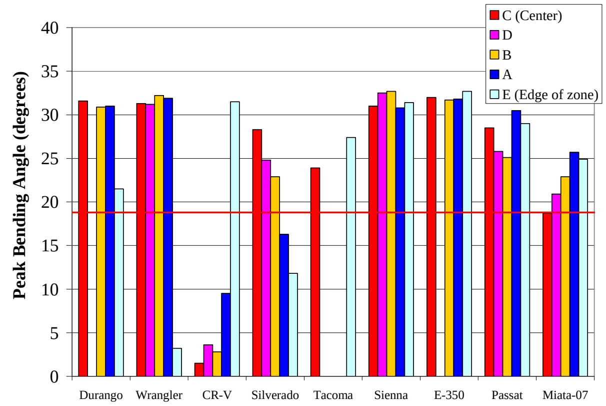

Figure 24. Peak bending angle for all impacts, by vehicle and impact location.

DISCUSSION

Adherence to GTR Testing Requirements

Several tests in the results section are reported as not meeting the test *conditions* required by the GTR. The test parameters that were “failed” in those tests will be discussed in this section, along with implications for interpreting the results of those tests.

In four tests, axial rotation about the vertical axis exceeded the 5 degree limit listed in the GTR: locations D and E on the Honda CR-V, location B on the Toyota Sienna, and location C on the E-350. In all of these tests axial rotation was 7 degrees or less. It is likely that the injury measures were the same or lower than they would have been had the axial rotation been less than 5 degrees. Since acceleration is a single-axis measurement in the direction of impact, pre-impact rotation would reduce the acceleration measured. Based on trigonometry, a rotation of up to 7 degrees would be expected to lead to a drop in measured acceleration of less than 1% compared to a perfectly aligned impact. Similarly, the EEVC/TRL legform is designed to measure shear and bending angle in only one direction. If the measured shear displacement and knee bending angle are affected by rotation of the legform off its normal design direction, the rotation would be expected to lead to lower measured shear displacement and knee bending angle.

Two tests on the Mazda Miata were not within the impact speed requirements of the GTR, which are 11.1 m/s +/- 0.2 m/s. The test at impact location B was slow at 10.87 m/s and the test at location D was fast at 11.39 m/s. It is assumed that impact D produced higher injury measures than those expected had the test been within the speed range, and the impact B produced lower injury measures than those expected had the test been within the speed range. In the case of the impact at location D, the higher-than-allowed impact speed may have been responsible for the failing bending measurement, which was only 1.9 degrees beyond the injury limit. Had the impact been in the correct speed range, impact D may have met GTR requirements. In the case of impact location B, the lower-than-allowed impact speed did not have an effect on its failure to meet GTR requirements.

Impact B on the Silverado (Figure 25) deviated from the requirements of the GTR in that it was performed at a location where the Lower Bumper Reference Line exceeded 500 mm and therefore was not subject to lower legform testing. Shear and bending measurements may have been affected by LBRL height, as these measures were lower for impacts C and D in the lower central portion of the bumper. However, all tests on the Silverado failed the GTR limits by a wide margin. The height of the LBRL at location B was not believed to have been the cause of the failure at this test location.

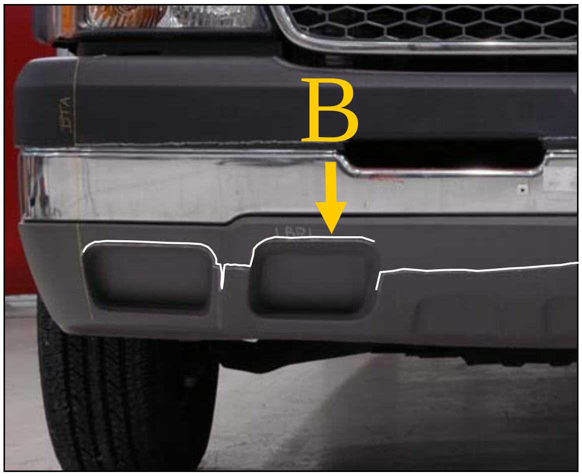

Figure 25. Chevy Silverado bumper showing Lower Bumper Reference Line (LBRL) in white and impact location B in yellow, where LBRL is greater than 500 mm.

The tests listed above were not tested in strict accordance with the GTR procedures. These should not therefore be used directly to evaluate compliance with the GTR. The results are reported here because they are not expected to be significantly different from the expected result had the GTR test procedure requirements been met. With the exception of location D on the Miata, all of the impacts that failed would still have been expected to fail had the GTR test requirements been met. Location D on the Miata, which was impacted too fast and exceeded injury measures by a narrow margin, may have passed had it been tested within the GTR test procedure limits.

Relative Difficulty of Injury Measures

Six of the nine vehicles tested met the 170 g limit on *upper tibia acceleration* in at least one test location. Of the 39 impacts where acceleration was measured, 20 indicated upper tibia acceleration over 250 g, and 8 were above 170 g but below the relaxed limit of 250 g (Figure 22). Of the 11 impacts that were below 170 g, only 5 impacts met the requirement with a margin wider than 10 g. The relaxed GTR acceleration limit of 250 g applies only to a width of bumper equal to approximately 2 widths of the legform, which is equivalent to one test location on each side of the car. In the current series, it is assumed that a vehicle could potentially pass the requirements if it has only one test over 170 g (but under the relaxed limit of 250 g) with the remainder of the tests under 170 g. The CR-V came closest to achieving those requirements with four of five tests under 170 g, but exceeded the limits with a fifth test over the relaxed limit of 250 g. The Sienna was able to remain under 250 g for all tests, but exceeded the 170 g limit in four out of five tests; given that there is not enough relaxation zone to cover all four of those impact locations, this vehicle would not meet the GTR acceleration requirement.

As shown in Figure 22, whether acceleration was higher in inboard locations or outboard locations was design-specific. The highest measures of acceleration were often measured near the bumper support, suggesting that tibia acceleration is more sensitive to stiffness of structures under the bumper than to the gradual changes in profile shape that occur across the front of the vehicle. Among vehicle types, the pickup trucks and the full-size van showed consistently high levels of acceleration, with all impacts close to or in excess of the 250 g limit.

Six of nine vehicles tested passed the *knee shear displacement* limit in at least one location, and one vehicle (CR-V) passed the shear requirement in all locations tested (Figure 23). Fourteen impact locations were at or below the shear limit of 6 mm, and 25 impact locations exceeded the knee shear limit of 6 mm. Many of the tests that exceeded 6 mm indicated shear displacements in the range of 7.5 mm to 8.5 mm suggesting a possible physical limit on the magnitude of shear displacement allowed by the EEVC/TRL legform. If this injury measure is bottoming-out, estimates of injury risk based on this level of shear may be underestimated.

Knee shear measures appeared to be related to inboard/outboard position on the vehicle. Most vehicles either showed a trend toward increased or decreased shear displacement as the impacts moved outboard, suggesting that shape change across the front of the vehicle may have more effect on shear displacement than the stiffness of under-bumper structures.

The *knee bending angle* limit appeared to be the most challenging to meet for the vehicles tested. Only four of the nine vehicles tested met the 19 degree bending angle limit in at least one location, and only 8 impacts in the series passed this limit. Many of the failing impacts showed peak bending angle clustered between 30 and 32 degrees, suggesting a physical limit on knee bend in this range. It is likely that the legform is physically bottoming out so estimates of injury risk based on this level of bending may be underestimated.

Peak bending angle tended to either increase or decrease as the impacts moved outboard, suggesting that, as with knee shear, the shape change across the front of the vehicle had more effect on bending angle than did stiffness of under-bumper structures.

To summarize the relative difficulty of the injury measures, bending angle was the most frequently failed injury criterion. Shear and bending angle appeared related to the change of shape across the front of the vehicle while acceleration seemed more linked to stiffness of the underlying structures. Measurements of knee shear and bending angle may be bottoming out, leading to potential underestimation of injury risk.

Results by Vehicle Type

Based on the vehicles tested in this series, the passenger vehicles (Miata and Passat) and minivan (Sienna) showed relatively better results in acceleration and peak shear displacement compared to the full-size van (E-350) and pickup trucks (Silverado and Tacoma). Results for the SUVs were mixed, with the CR-V performing better than other vehicles in all three injury measures, and the Wrangler and Durango performing relatively poorly.

Characteristics of Passing Impacts

There were a total of six passing impacts in the current series, four for the CR-V, one for the Wrangler, and one for the Miata.

In the passing impacts, video showed visibly more bumper deformation than there was in impacts that exceeded acceleration limits. Passing and failing CR-V impacts (Figure 26), Miata impacts (Figure 27), and Wrangler impacts (Figure 28) are compared below to illustrate that deformation appears to be associated with better performance relative to upper tibia acceleration. In all three passing impacts illustrated below, there was visible deformation of the bumper, resulting in varying degrees of damage. In the CR-V center impact (C), the CR-V sustained permanent deformation to the bumper cover, the underlying bumper support, and adjacent grille and air conditioning structures. The Miata center impact impact (C) resulted in damage to the ribbed energy absorber immediately adjacent to the impact point but showed no external evidence of damage. On the Wrangler, the end-cap on the bumper snapped off at impact allowing the legform to move into the front face of the fender and the tire tread. The fender, which is parallel to the bumper in its undeformed state, then deformed to absorb additional energy from the impact. In the passing impacts, the bumper and underlying structures absorbed energy and reduced the levels of deceleration in the legform by deforming during impact.

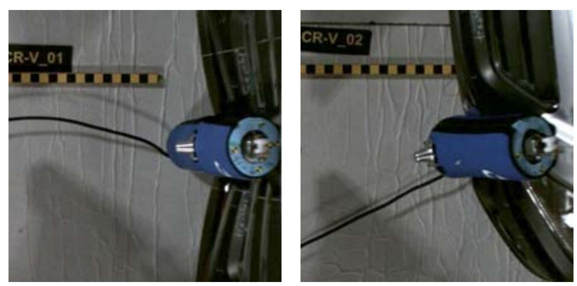

Figure 26. Passing CR-V center impact C on left (acceleration 85.3 g) and failing CR-V outboard impact E on right (acceleration 329 g).

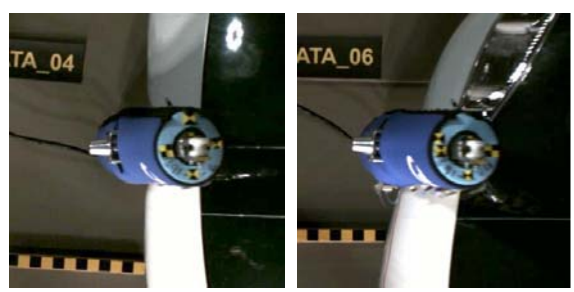

Figure 27. Passing Miata center impact C on left (acceleration 159 g) and failing Miata impact A on right (acceleration 40 g).

Figure 28. Passing outboard Wrangler impact E on left (acceleration 60 g) and failing Wrangler impact center impact C on right (acceleration 445 g).

Another characteristic of passing impacts appears to be the distribution of impact forces over a large area on the legform above *and* below the knee. In passing CR-V tests, the load is applied over a relatively tall bumper that makes contact above and below the knee of the legform (Figure 29). In the Miata passing impact C, the top of the bumper is adjacent to the lower femur, and tibia loads are shared by a lower spoiler. On the passing Wrangler test, the failure of the bumper end-cap allowed the femur to move into the vertical fender and the tibia to move into the tire tread, sharing the loads over a large portion of the legform.

Figure 29. Bumper contact area in passing impacts CR-V (C), Miata(C), and Wrangler(E).

It should be noted that the low injury measures indicated in passing Wrangler impact E do not account for the potential injury risk posed by striking the tread of a tire on a moving vehicle.

Comparison to Prior Testing of U.S. Vehicles using EuroNCAP Test Procedures

Testing was performed previously with the EEVC/TRL legform in a collaborative study with Transport Canada (Mallory, Stammen et al. 2005). That initial series of testing was done using EuroNCAP procedures. Those EuroNCAP procedures were similar to, but not the same as, GTR lower legform test procedures. Each vehicle underwent impacts to the center of the bumper and over the bumper support. The following North American vehicles were tested:

- 1999 Ford Focus,
- 2001 Honda Civic,
- 2002 Mazda Miata MX5,
- 1999 VW Beetle, and
- 1997 Volvo S40.

The 2005 series of tests performed according to EuroNCAP procedures and the current series of GTR tests both used the EEVC/TRL legform at an impact speed of 40 km/h. The primary difference between the tests defined in the EuroNCAP procedure and the GTR procedure, and between the two series of tests run at VRTC, is the height of the bottom of the legform, which is at ground reference level in the EuroNCAP procedure/VRTC's 2005 series and 2.5 cm above ground reference level in the GTR test series being reported in this paper.

Test data from the Mazda Miata was compared for the two series in order to evaluate whether the passenger car results from the first series of EuroNCAP testing at VRTC could be combined with the results from the currently reported GTR testing. Figure 30 shows the location of comparable impacts in the two series. Each series had at least one test at the center of the bumper that can be compared directly. The 2005 EuroNCAP tests included an impact directly over the bumper support that can be compared to tests adjacent to the bumper support in 2007 GTR testing. Figure 31 compares the test results for impacts in the center of the bumper for both series, and Figure 32 compares the results for impacts near the bumper support.

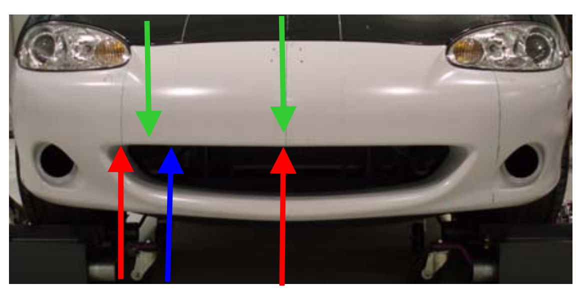

Figure 30: Photograph of Mazda Miata showing comparable impact locations in 2005 EuroNCAP testing (green, upper arrows) and in 2007 GTR testing (red and blue, lower arrows).

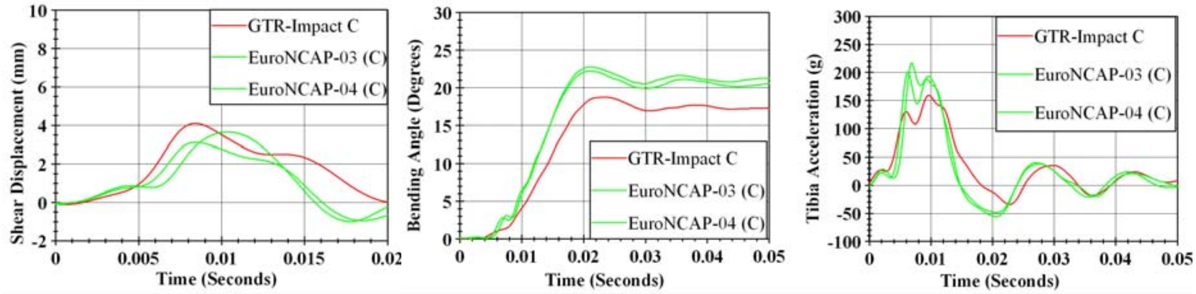

Figure 31: Shear displacement, bending angle and tibia acceleration for center impact using GTR procedure in 2007 VRTC testing (red) compared to prior testing at the center bumper according to 2005 EuroNCAP testing (green).

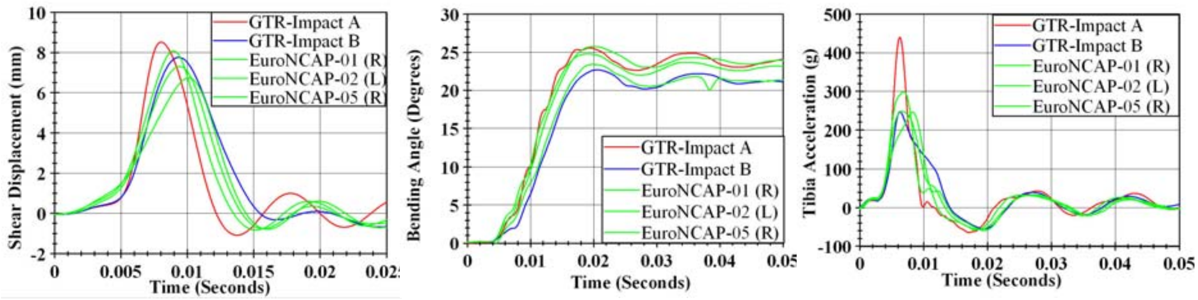

Figure 32: Shear displacement, bending angle and tibia acceleration for impacts adjacent to bumper support 2007 GTR testing (red, blue) compared to prior testing over left and right bumper support according to 2005 EuroNCAP testing (green).

Figure 31 and Figure 32 show that the differences between the peak values from 2005 EuroNCAP testing and 2007 GTR testing do not appear significantly greater than the differences in peak results among repeats of individual 2005 EuroNCAP tests over the lateral bumper in spite of difference in leg-to-ground-reference height. However, it should be noted that the difference in test results at the center bumper location in Figure 32 are important, in that the 2005 tests failed the acceleration and bending angle requirements in the current GTR (175 g and 19 degrees, respectively), while the 2007 tests passed.

In spite of the differences in results between the 2005 series of tests and the 2007 series, data from the 2005 offer pedestrian performance information on four U.S. passenger cars, in addition to the two tested in the 2007 series, even if results must be considered approximate relative to the requirements in the GTR (Table 13).

Table 13.
Peak measures in 2005 test series (Mallory, Stammen et al. 2005), average values for tests at center bumper and over bumper support

		Tibia Acceleration (g)	Bending Angle (degrees)	Shear Displ. (mm)
Ford Focus	Center	195	33.4	-4.9
	Support	209	32.3	-3.8
Honda Civic	Center	221	31.0	4.7
	Support	369	30.7	7.7
Mazda Miata	Center	209	24.7	3.4
	Support	264	25.1	7.4
VW Beetle	Center	462	34.7	8.3
	Support	264	29.1	8.2
Volvo S40	Center	263	31.1	8.2
	Support	246	30.2	6.2

As with the larger vehicles that were the focus of the current study, all of the U.S. passenger cars tested exceeded the GTR limits. The best performing vehicle in the 2005 EuroNCAP series, the Mazda Miata, was only able to pass GTR requirements in one test location when retested to GTR conditions. Given the wide margin by which most of the passenger car test locations exceeded the injury limits, it is assumed that these vehicles would not have met the requirements even had they been run under GTR conditions. Average values for all impact locations exceeded the 19 degree bending limit and the 170 g upper tibia acceleration limit. Four of five vehicles showed higher acceleration in impacts over the support, while four of five vehicles showed higher bending values in the central bumper area. These passenger car results are consistent with the performance of the vehicles in the currently reported series of tests.

CONCLUSIONS

The results from the current series of tests, along with tests previously reported, can be used to provide a snapshot of the level of pedestrian lower extremity protection provided by the current U.S. fleet.

Relative to GTR requirements, pedestrian lower extremity protection was poor overall in the U.S. vehicles tested. No vehicle was able to meet GTR injury limits in all locations tested, although the CR-V came closest by meeting the requirements by a wide margin in all but one of the impact locations tested. Two other vehicles each had a single passing impact location.

Knee bending angle limits were the most difficult requirement for the tested U.S. vehicles to meet. Only 8 impacts in the current series were below the 19 degree limit, and only 4 vehicles met that requirement in any location. Bending angle appeared to be most associated with the shape of the front of the vehicle. Upper tibia acceleration limits were also challenging for the vehicles tested, with only 11 impacts meeting the 170 g limit and 8 more over 170 g but below the relaxed limit of 250 g. Acceleration appeared to be associated with the stiffness and deformation of structures under the bumper, and tended to be highest in the area of the bumper support.

Impacts that passed all injury measures tended to be associated with deformation of bumper structures at the impact point and distribution of loads over a large area on the legform, both above and below the knee.

ACKNOWLEDGEMENTS

The authors acknowledge Transportation Research Center Inc.'s David Hyder and Patrick Biondillo who performed the testing reported in this paper.

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