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TECHNICAL EVALUATION OF THE FLEXIBLE PEDESTRIAN LEG IMPACTOR (FLEX-PLI)

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Abstract

The objective of this study was to evaluate the production version of the Flex-PLI (known as FlexGTR) pedestrian legform. Testing & analysis were done to examine the biofidelity, injury criteria, repeatability, reproducibility, durability, injury criteria efficacy, and sensitivity to vehicle design. Various bumper configurations from thirteen vehicles were tested with the Flex-PLI, in addition to multiple qualification tests, to evaluate these aspects of the legform. The primary findings from this evaluation were that the Flex-PLI legform is:

- **Durable**, as it didn’t sustain any significant structural damage in 30+ vehicle bumper impacts at 40 km/h. Many of these vehicles were far from complying with the proposed GTR injury limits.
- **Biofidelic**, as the legform maintained conformance with qualification corridors derived from biomechanical data
- **Repeatable**, with percent coefficients of variation (%CV) below 5% for all channels and below 2% for all injury channels (MCL and tibia 1 bending moment) in vehicle bumper tests
- **Reproducible**, with %CV 10% or below for three different legforms in vehicle bumper tests and below 4% in pendulum qualification tests without vehicle or test setup-related variance
- **Sensitive to vehicle design**, as demonstrated through testing a large range of compliant and non-compliant bumper systems. The Flex-PLI discriminated between systems containing pedestrian countermeasures, such as the lower bumper stiffener and modular energy absorber, and older model year, non-GTR compliant systems present in the U.S. fleet

In addition to these positive aspects of the Flex-PLI, testing with the legform led to a better understanding of (a) the feasibility of producing a bumper system that can comply with both GTR and bumper damageability requirements, (b) the differences expected from using the Flex-PLI instead of the EEVC leg, and (c) the current performance of the U.S. fleet with respect to the GTR. In summary, this assessment demonstrated that the Flex-PLI is an appropriate test tool for evaluating pedestrian lower extremity protection in vehicle bumper impacts.

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EXECUTIVE SUMMARY

Pedestrian knee ligament injuries and lower leg fractures are the most frequent and among the most debilitating long-term injuries in motor vehicle crashes. A global technical regulation (GTR no. 9) has been adopted by the international community (including the United States) to mitigate these pedestrian injuries through improved vehicle bumper systems. The current GTR includes the EEVC legform, which is the device that has been used for many years in the European New Car Assessment Program (EuroNCAP). While the EEVC legform has been a repeatable and durable device for evaluating vehicles, it has some notable limitations. Among them is insufficient biofidelity due to completely rigid femur and tibia elements leading to its inability to simulate the combined loading at the knee present in actual pedestrian collisions, the need to replace frangible ligaments for each test, sensitivity to temperature/humidity, and limited instrumentation for identifying pedestrian injury mechanisms. More recent vehicle designs require a more sensitive test device to drive incremental improvements for protecting pedestrians. The flexible pedestrian legform impactor (Flex-PLI) has been developed to serve as a more biofidelic test device for use in this GTR test procedure.

The objective of this study was to evaluate the production version of the Flex-PLI (known as FlexGTR). Testing & analysis were done to examine the biofidelity, repeatability, reproducibility, durability, injury criteria efficacy, and sensitivity to vehicle design. Various bumper configurations from thirteen vehicles were tested with the Flex-PLI, in addition to multiple qualification tests, to evaluate these aspects of the legform.

The primary findings from this evaluation were that the Flex-PLI legform is:

- **Durable**, as it didn’t sustain any significant structural damage in 30+ vehicle bumper impacts at 40 km/h. Many of these vehicles were far from complying with the GTR injury limits.
- **Biofidelic**, as the legform maintained conformance with qualification corridors derived from biomechanical data
- **Repeatable**, with percent coefficients of variation (%CV) below 5% for all channels and below 2% for all injury channels (MCL and tibia 1 bending moment) in vehicle bumper tests
- **Reproducible**, with %CV of 10% or below for three different legforms in vehicle bumper tests and below 4% in pendulum qualification tests without vehicle or test setup-related variance
- **Sensitive to vehicle design**, as demonstrated through testing a large range of compliant and non-compliant bumper systems. The Flex-PLI discriminated between systems containing pedestrian countermeasures, such as the lower bumper stiffener and modular energy absorber, and older model year, non-GTR compliant systems present in the U.S. fleet

In addition to these positive aspects of the Flex-PLI, testing with the legform led to a better understanding of (a) the feasibility of producing a bumper system that can comply with both GTR and bumper damageability requirements, (b) the differences expected from using the Flex-PLI instead of the EEVC leg, and (c) the current performance of the U.S. fleet with respect to the GTR.

In summary, this assessment demonstrated that the Flex-PLI is an appropriate test tool for evaluating pedestrian lower extremity protection in vehicle bumper impacts.

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1. INTRODUCTION

1.1. Background, Motivation, and Need for a Biofidelic Pedestrian Legform

There are over 4,000 pedestrian fatalities and nearly 70,000 pedestrians injured in the U.S. alone each year. Head injuries correctly receive the most attention because of their frequency and severity. The most frequently injured body region is the lower extremity. The initial contact between vehicle and pedestrian is almost always between the vehicle bumper and pedestrian lower extremity. Pedestrian knee ligament injuries and lower leg fractures are among the most debilitating long-term injuries in motor vehicle crashes (Mallory et al 2006, 2012).

It has been demonstrated through the years that these lower extremity injuries can be mitigated effectively through bumper design. Engineered structures to absorb the impact energy in an optimized manner have become commonplace in the market. The globalization of the automotive industry has led to harmonized design concepts, where individual parts within designs can be exchanged depending on the applicable region's regulatory requirements.

A global technical regulation (GTR no. 9) has been created by the international community (including the United States) to mitigate these pedestrian injuries through improved vehicle bumper systems. The current GTR includes the EEVC legform, which is the device that has been used for many years in the European New Car Assessment Program (EuroNCAP). While the EEVC legform has been a repeatable and durable device for evaluating vehicles, it has some notable limitations. Among them is insufficient biofidelity due to completely rigid femur and tibia elements leading to its inability to simulate the combined loading at the knee present in actual pedestrian collisions, the need to replace frangible ligaments for each test, sensitivity to temperature/humidity, and limited instrumentation for identifying pedestrian injury mechanisms. More recent vehicle designs require a more sensitive test device to drive incremental improvements for protecting pedestrians.

The Flexible Pedestrian Legform Impactor (Flex-PLI) has been developed to serve as a more biofidelic test device for use in this GTR test procedure. Various iterations of the Flex-PLI have been evaluated by the international community, first through the Flex Technical Evaluation Group (Flex-TEG) and then through the Phase 2 informal working group (GTR9 PS2 IWG). NHTSA has participated in these evaluations of previous Flex-PLI design iterations, in order to become familiar with the legform's capabilities and the challenges faced by industry in designing bumper systems to mitigate lower extremity injury risk (Mallory et al 2005, 2008, 2009, 2010; Suntay et al 2012). Through the collective efforts of the international working groups, the Flex-PLI design has reached a production-intent version.

1.2. Objectives

The objective of this study was to evaluate the production-intent version of the Flex-PLI (known as FlexGTR). Testing & analysis were done to examine the legform's biofidelity, injury criteria, repeatability, reproducibility, durability, injury criteria efficacy, and sensitivity to vehicle design.

2. OVERVIEW

2.1. Description of Flex-PLI Legform

The Flexible Pedestrian Legform Impactor (Flex-PLI) was introduced by the Japanese Automotive Research Institute (JARI) in the early 2000's as a suitable eventual replacement for the EEVC legform. The production-intent version of the Flex-PLI, known as FlexGTR, was used throughout the present study. This legform consists of flexible femur and tibia bone elements, each instrumented with strain gages, an articulated knee structure with four ligaments that retract/elongate, and segmented structures along its length to house the bone elements (Figure 1). The entire legform is enveloped by a series of rubber sheets to simulate the flesh characteristics of the human leg.

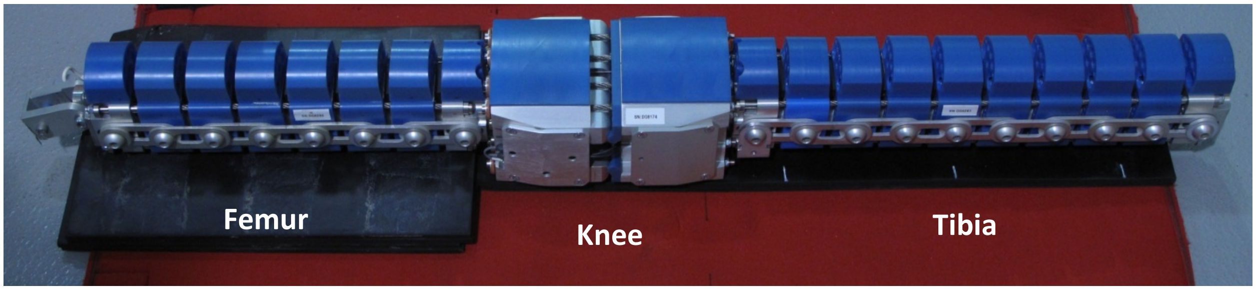


Figure 1. The Flex-PLI legform consists of flexible femur and tibia elements, an articulated knee, and a rubber flesh.

The standard legform has femur, knee joint, and tibia lengths of 339 ± 2 mm, 185 ± 1 mm, and 404 ± 2 mm, respectively with an overall length of 928 ± 3 mm. The femur, knee joint, and tibia have masses of 2.46 ± 0.12 kg, 4.28 ± 0.21 kg, and 2.64 ± 0.13 kg. The rubber flesh system and neoprene skin (including tape and Velcro straps) add a mass of 3.82 kg ± 0.21 kg giving the legform a total mass of 13.2 ± 0.7 kg. The standard instrumentation consists of 12 channels that include: 3 full bridge strain gages in the femur and 4 full bridge strain gages in the tibia to measure leg bending moments; 4 string potentiometers in the knee to measure anterior cruciate (ACL), posterior cruciate (PCL), medial collateral (MCL), and lateral collateral (LCL) ligament elongations; and an accelerometer in the knee (Figures 2-5).

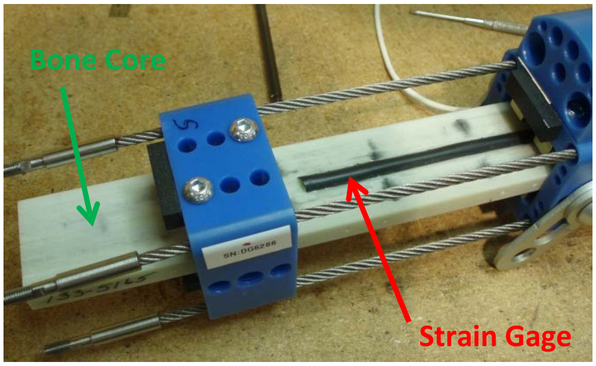


Figure 2. The disassembled femur segment with the bone core (green arrow) and strain gage (red arrow) in view.

Figure 3. The disassembled knee joint with the MCL/LCL (red) and ACL/PCL (white) string pots shown. The green arrows point to the knee tension cables.

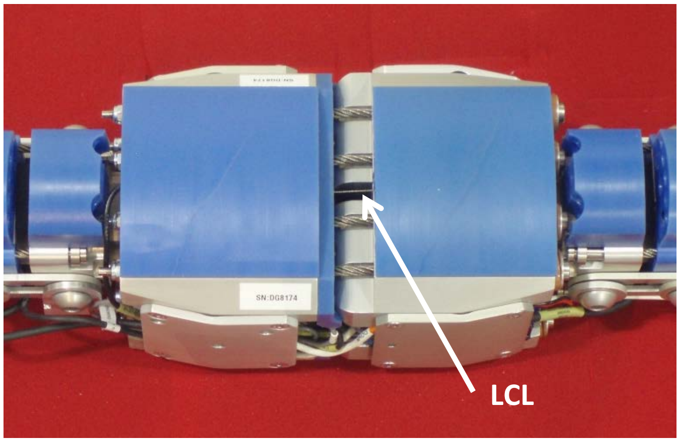


Figure 4. Assembled knee joint with the LCL potentiometer in view (white arrow).

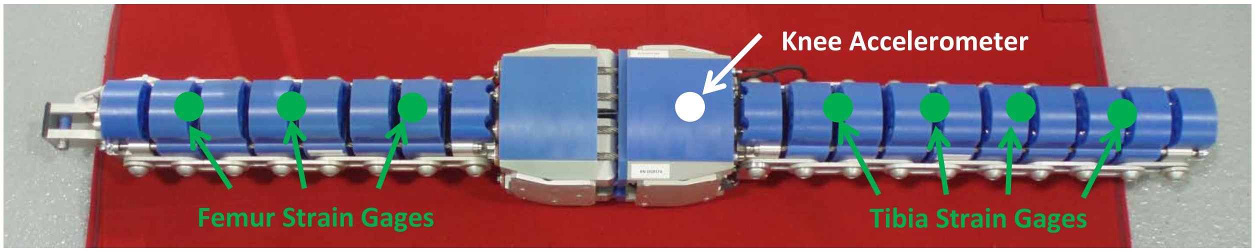


Figure 5. The legform is instrumented with three femur and four tibia strain gages (green) to measure bending moment. The legform is also instrumented with a single accelerometer at the knee (white).

2.2. GTR9 Test Procedure

Following the basic procedures as outlined in Amendment 1 of the Proposal for a Global Technical Regulation (GTR) for the Protection of Pedestrians [GRSP, 2010], the bumper test area, defined as “the frontal surface of the bumper limited by two longitudinal vertical planes intersecting the corners of the bumper and moved 66 mm parallel and inboard of the corners of the bumper”, was marked for each vehicle. The corner of the bumper is defined as “the vehicle’s point of contact with a vertical plane which makes an angle of 60° with the vertical longitudinal plane of the car and is tangential to the outer surface of the bumper” and is shown in Figure 6. Within the test area, car manufacturers may also nominate bumper test widths up to a maximum of 264 mm in total where the acceleration measured by the tibia shall not exceed a relaxed injury limit.

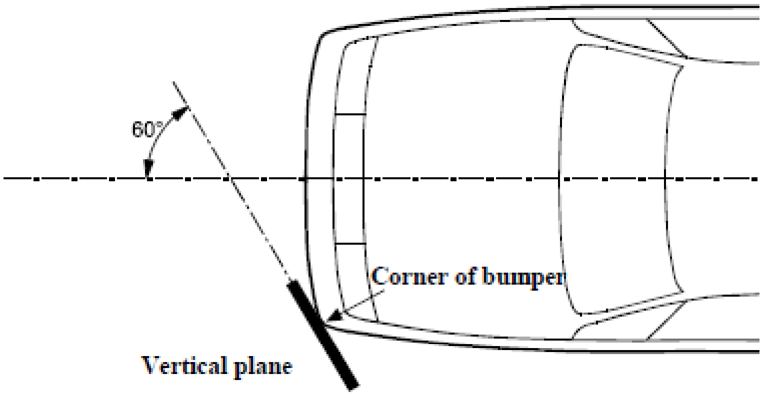


Figure 6. Corner of bumper

The Flex-PLI legforms were equipped with a DTS onboard SLICE Nano data acquisition system (Figure 7). An onboard data acquisition system was utilized in order to eliminate any effects that external cables and wiring may have on the legform during free flight. The system was connected to the data acquisition system computer via a cable that disconnected at the beginning of the launch motion (Figure 8). The cable was anchored to the stationary hydraulic impactor so that disconnect occurred immediately after the launch plate moved forward (Figure 9). After disconnect and throughout the flight of the legform, the onboard SLICE system was powered by a super capacitor. After reconnecting the legform to the data acquisition computer, test data was downloaded and the super capacitor recharged.

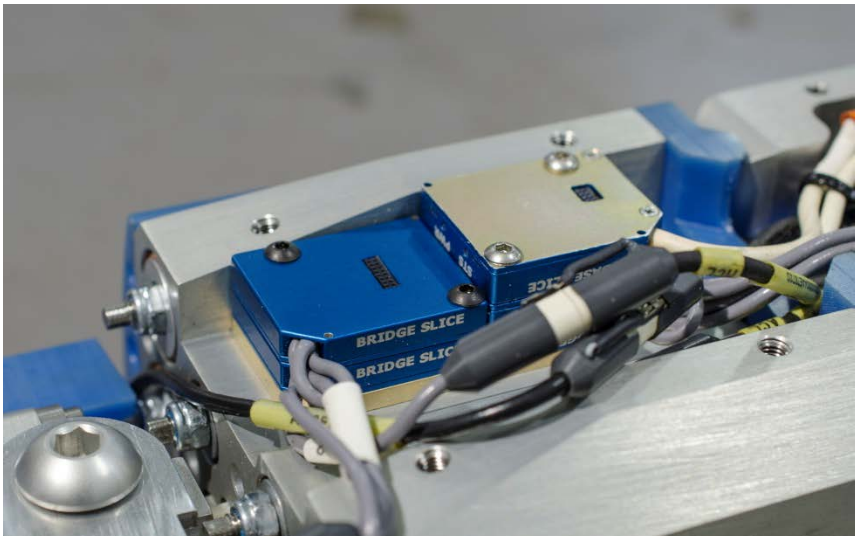


Figure 7. SLICE onboard data acquisition modules.

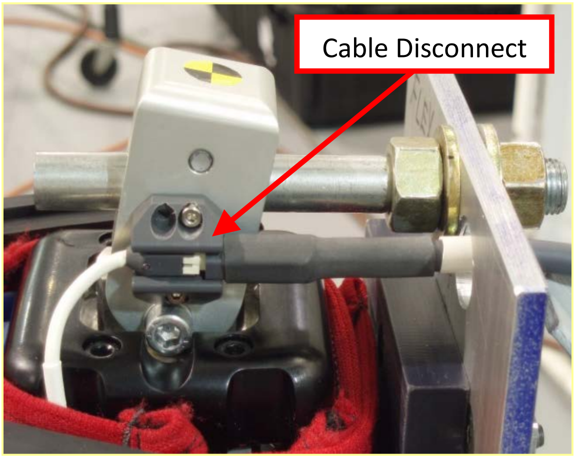


Figure 8. Cable disconnect for the SLICE onboard data acquisition system.

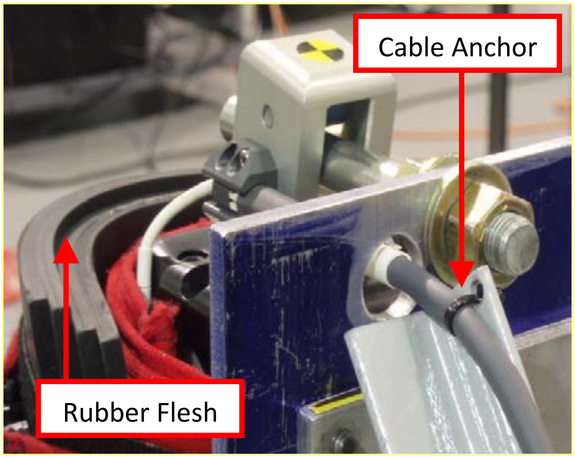


Figure 9. Data acquisition cable anchored to fixed structure. Rubber flesh shown on the legform's impact side.

The Flex-PLI was launched into free-flight using a hydraulic cylinder. A launch plate with a horizontal top-mounted pin cradled the suspended legform on the front of the actuator. The launch plate was mounted so that the actuator was aligned with the approximate height of the legform's center of gravity. The legform was suspended by a launch guide that was rested on the plate's horizontal pin (Figure 10).

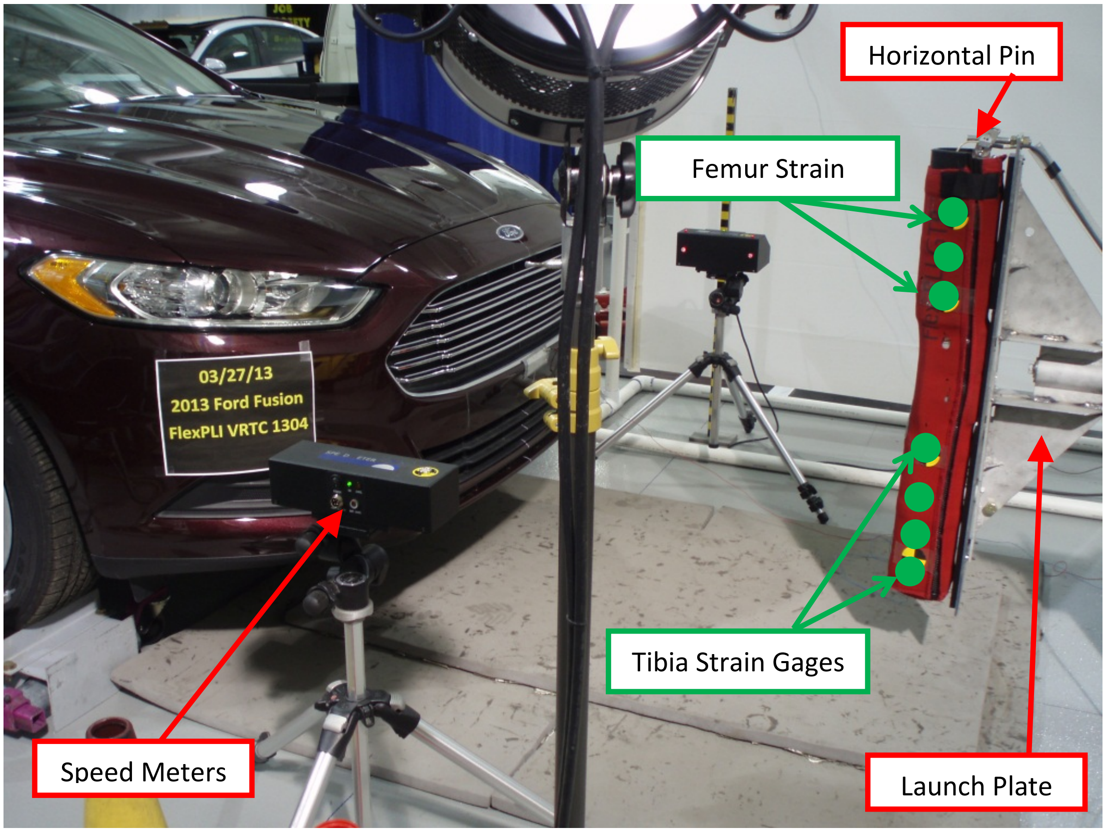


Figure 10. Flex-PLI test setup.

Testing was performed according to the basic procedures (as described in the previous section) and outlined in Amendment 1 of the Proposal for a Global Technical Regulation (GTR) for the Protection of Pedestrians [GRSP, 2010] at NHTSA's Vehicle Research and Test Center (VRTC) using three certified Flex-PLI legforms: the VRTC legform, the Master SN01 legform, and the Master E-Leg legform.

The masses of each legform were measured prior to testing and were found to be different but within the tolerance for legform mass (VRTC: 13.096 kg; SN01: 13.260 kg; E-Leg: 13.13 kg). Due to the differences in mass the actuator was fired at different input pressures in order to meet the speed requirement: 9010 to 9030 psi (VRTC), 9050 psi (SN01), and 9030 psi (E-Leg). After approximately 400 mm of travel, the actuator's motion was braked, allowing for the legform to move forward in free-flight toward the vehicle. According to GTR specifications, impact speed was 11.1 m/s (± 0.2 m/s). Impact speed was measured using high speed video analysis using TEMA v.3.5. When available, speeds were confirmed with an Aries laser speed meter (Model SM-2BL/F) with emitter and receiver modules positioned perpendicular to the flight of the legform, immediately before the bumper impact point.

During flight, the GTR specifies that the long axis of the legforms should be perpendicular to horizontal with a tolerance of +/- two degrees in both the lateral (roll) and longitudinal (pitch) planes. Along the vertical axis (twist or yaw), the legform has a tolerance of +/- five degrees. Initial video analysis of the legform flight during speed shots, without a vehicle in place, showed that legform alignment in the lateral plane (roll) was consistently within tolerance. However, orientation about the longitudinal plane and vertical axis showed some variation. Therefore, overhead and lateral cameras were utilized to review the amount of pitch and twist during the legform's flight in each test and verify that they remained within tolerance.

2.3. Vehicles & Bumper Configurations

Table 1 presents the vehicles identified as candidates for testing.

Table 1. List and descriptions of tested vehicles.

Vehicle				**Gross Vehicle Weight (lbs)**	**Energy Absorber Type**	**Lower Bumper Stiffener**	**Bumper Beam Height (mm)**
Model Year (MY)	**Make**	**Model**	**Description**				
2011	Chevrolet	Cruze	Sedan	4072	Foam	No	432
2009	Chevrolet	Equinox	SUV	5070	None	No	483
2007	Chevrolet	Silverado	Pickup	6800	None	No	597
2012	Ford	Focus	Sedan	3990	Plastic	No	N/A
2013	Ford	Fusion	Sedan	4460	Plastic	Yes	430
2002	Honda	Civic	Sedan	3485	Foam	No	445
2011	Honda	Odyssey	Minivan	6019	None	No	470
2003	Honda	Pilot	SUV	5952	Foam	No	515
2011	Hyundai	Tucson	SUV	4365	Foam	No	480
2011	Jeep	Grand Cherokee	SUV	6500	Foam	No	600
2002	Mazda	Miata	Coupe	2943	Plastic	No	430
2010	Toyota	Yaris	Sedan	3230	None	No	465
2006	Volkswagen	Passat	Sedan	4445	Foam	No	460

Figures 11 through 33 show the under-fascia components for each of the vehicles.

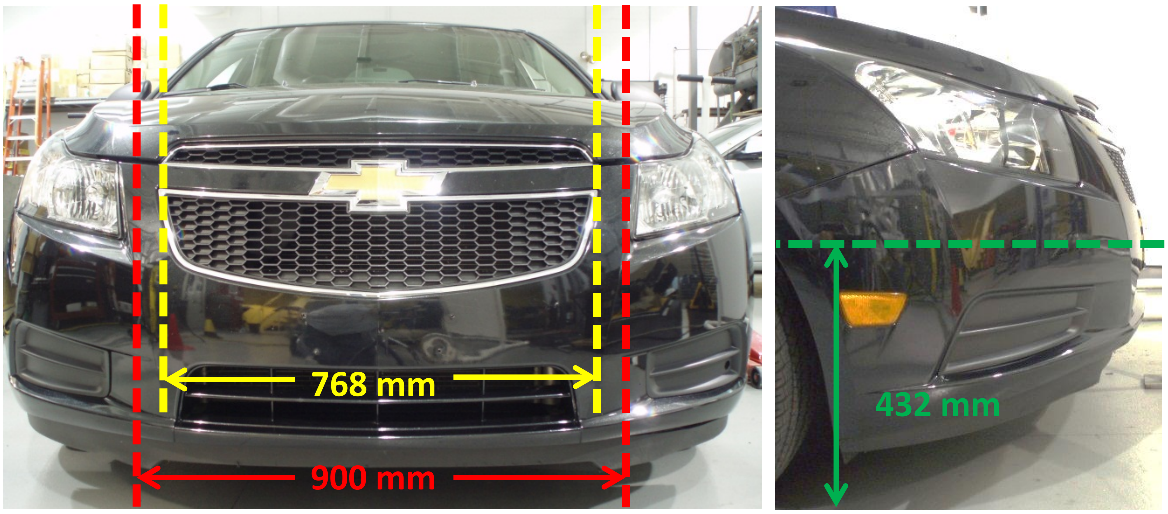


Figure 11. 2011 Chevrolet Cruze front and profile views.

Figure 12. 2011 Chevrolet Cruze front and profile views without the fascia.

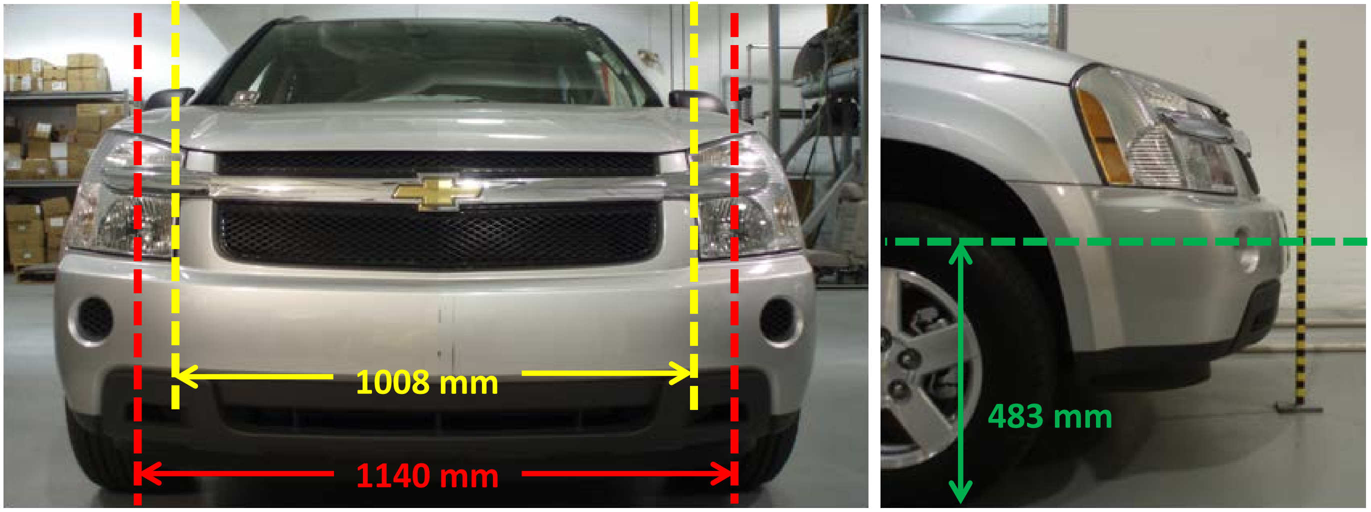


Figure 13. 2009 Chevrolet Equinox front and profile views.

Figure 14. 2009 Chevrolet Equinox front view without the fascia.

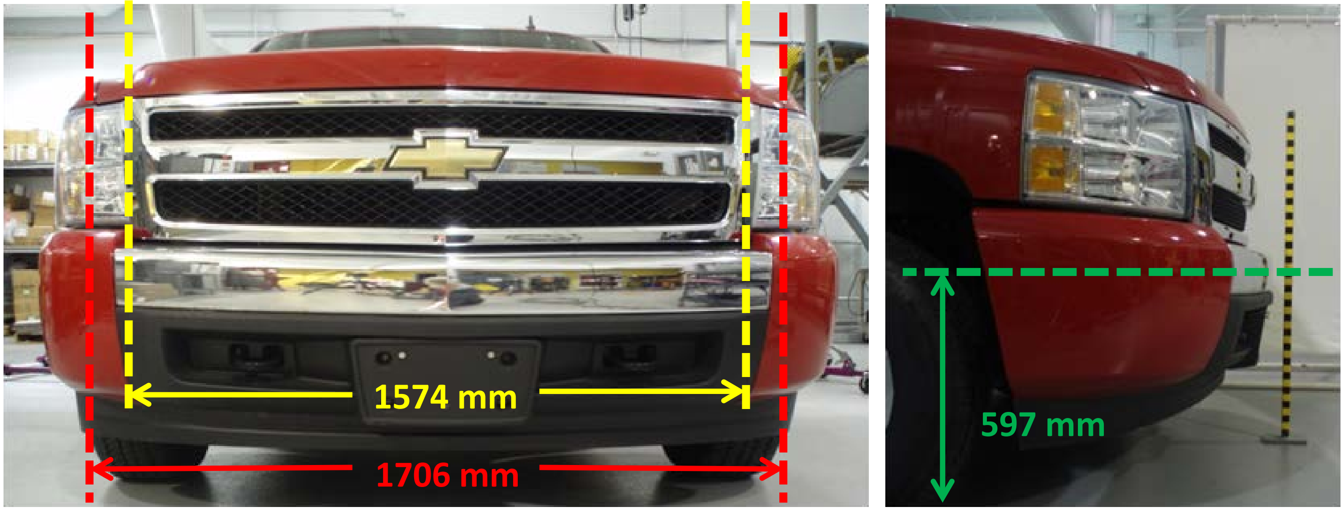


Figure 15. 2007 Chevrolet Silverado front and profile views. The chrome bumper is equivalent to the bumper beam for the Chevrolet Silverado.

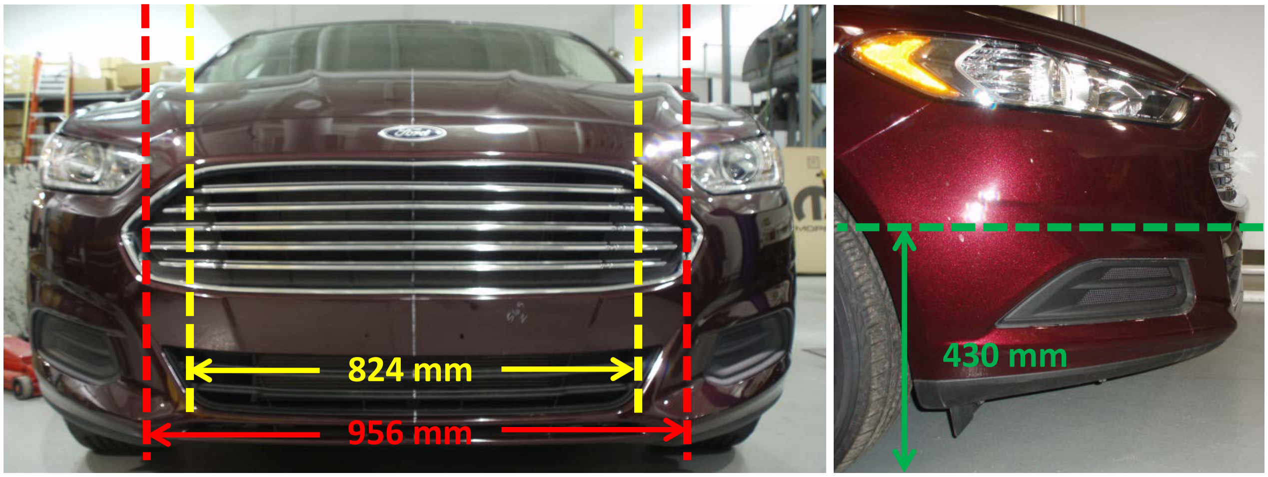


Figure 16. 2013 Ford Fusion front and profile views.

Figure 17. 2013 Ford Fusion front and profile views without the fascia.

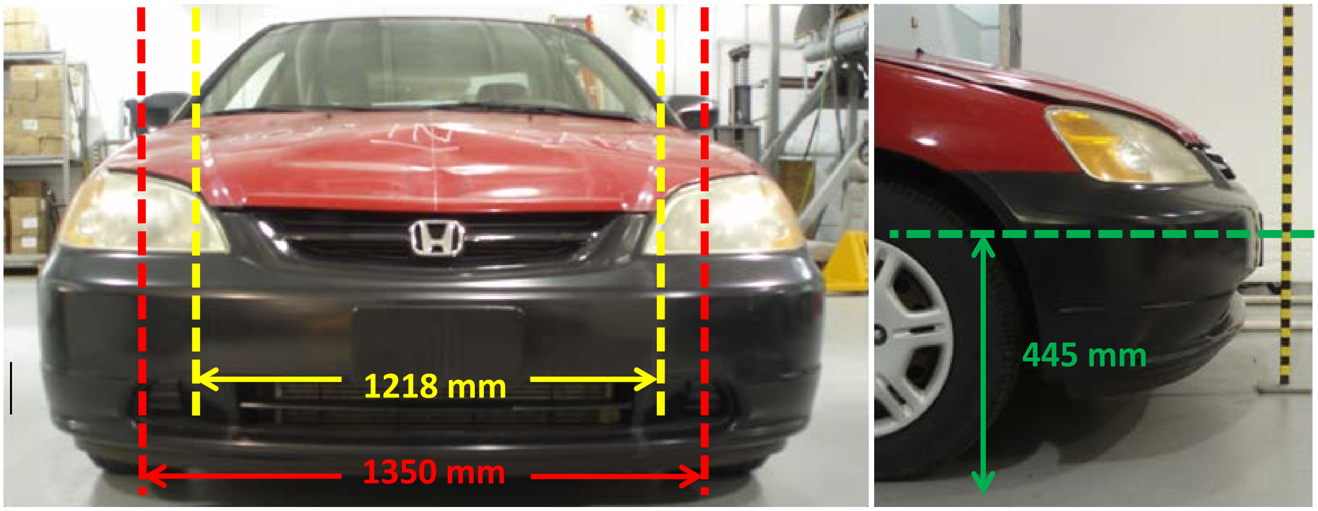


Figure 18. 2002 Honda Civic front and profile views.

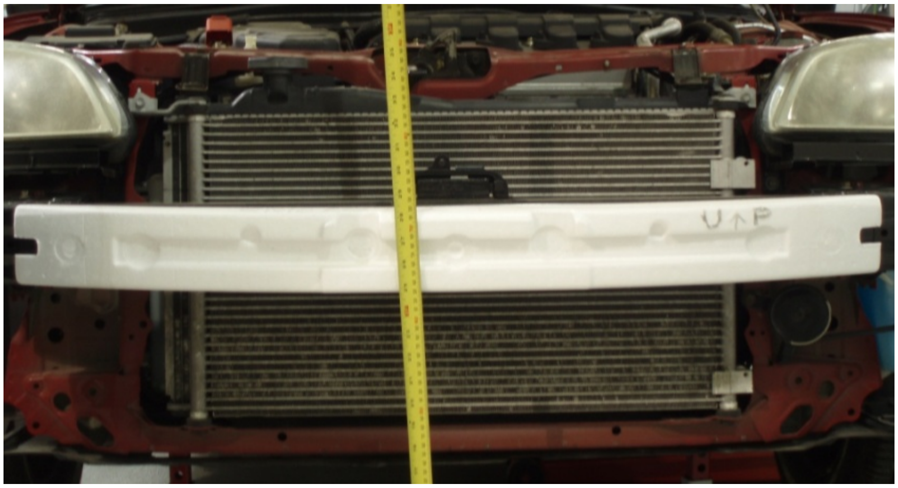


Figure 19. 2002 Honda Civic front view without the fascia.

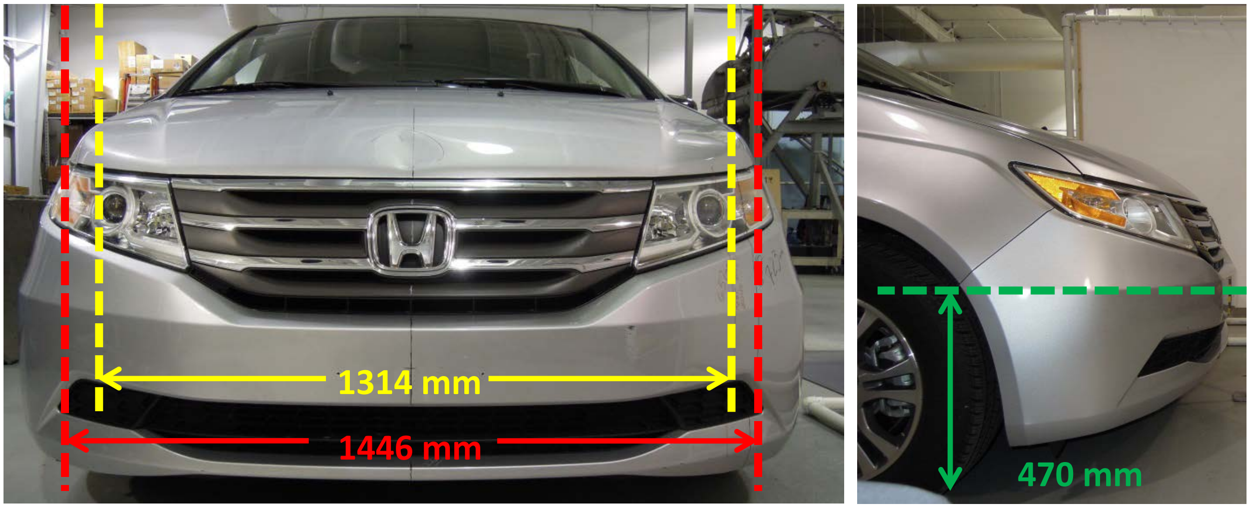


Figure 20. 2011 Honda Odyssey front and profile views.

Figure 21. 2011 Honda Odyssey front and profile views without the fascia.

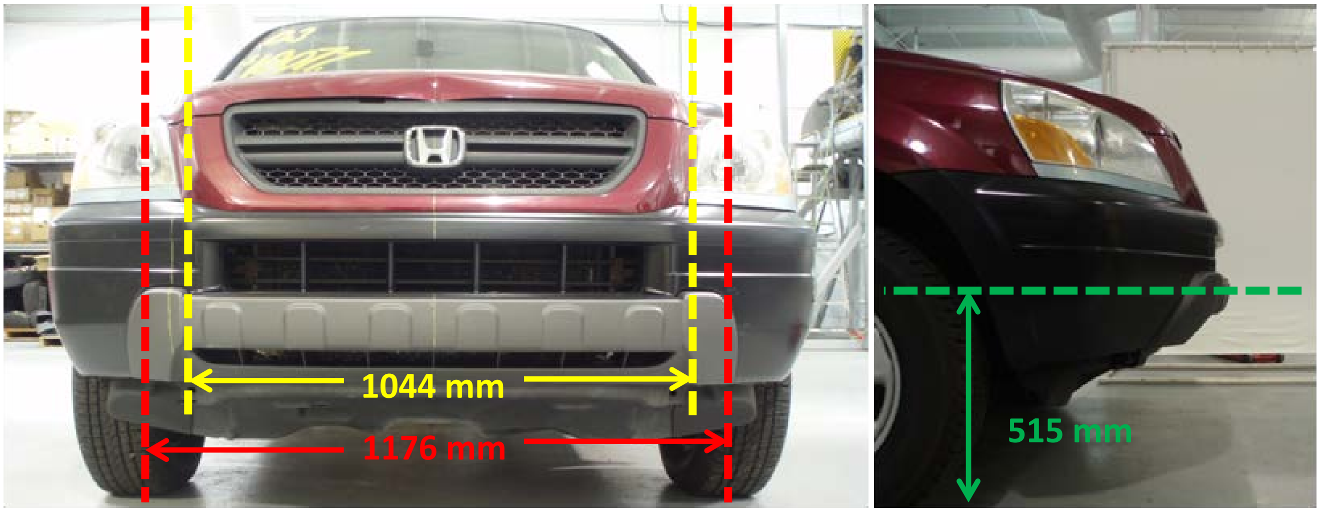


Figure 22. 2003 Honda Pilot front and profile views.

Figure 23. 2003 Honda Pilot front view without the fascia.

Figure 24. 2011 Hyundai Tucson front and profile views.

Figure 25. 2011 Hyundai Tucson front and profile views without the fascia.

Figure 26. 2011 Jeep Grand Cherokee front and profile views.

Figure 27. 2011 Jeep Grand Cherokee front and profile views without the fascia.

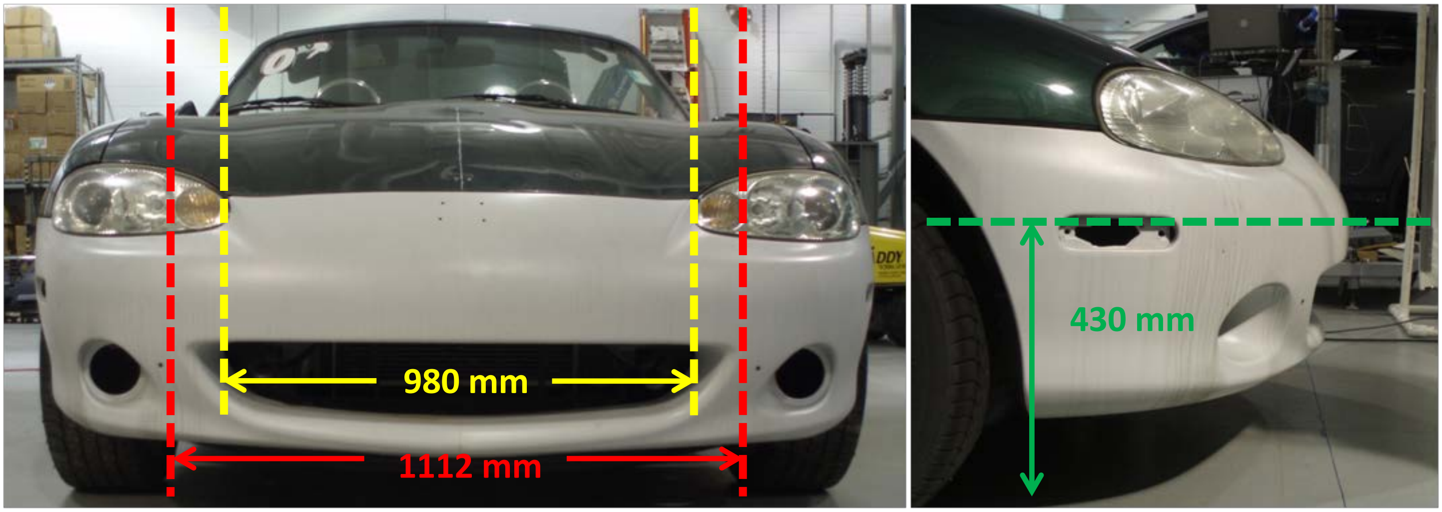


Figure 28. 2002 Mazda Miata front and profile views.

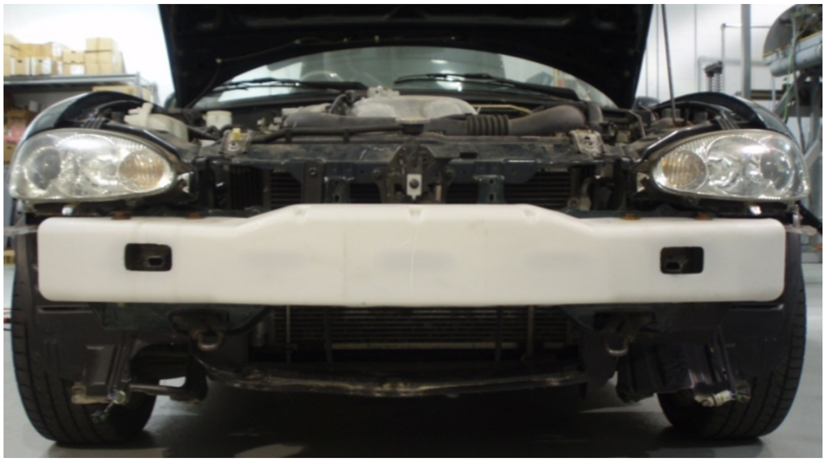


Figure 29. 2002 Mazda Miata front and profile views without the fascia.

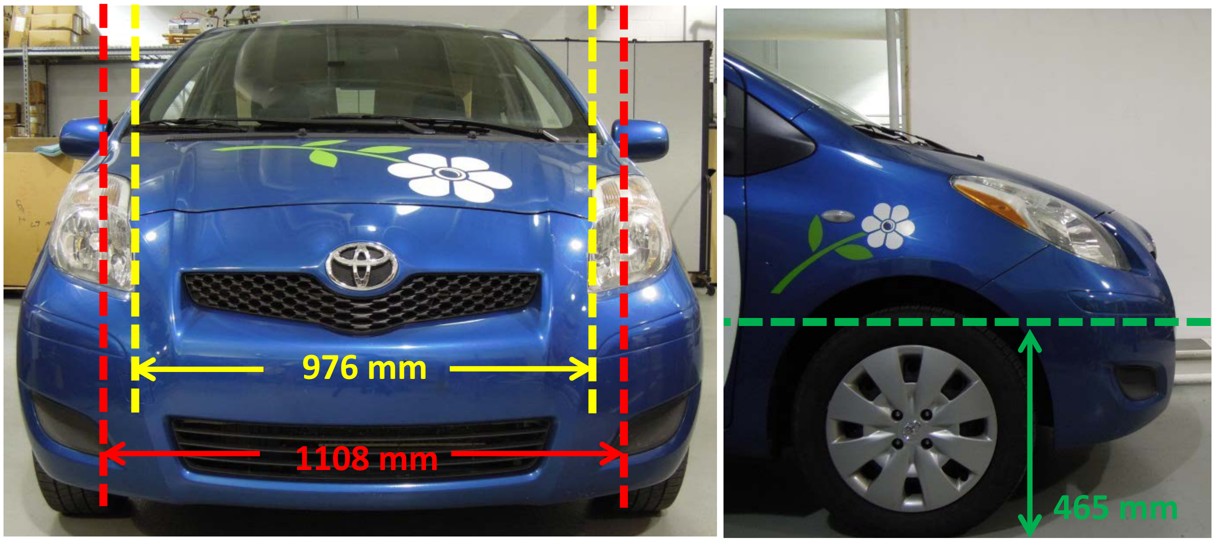


Figure 30. 2010 Toyota Yaris front and profile views.

Figure 31. 2010 Toyota Yaris front and profile views without the fascia.

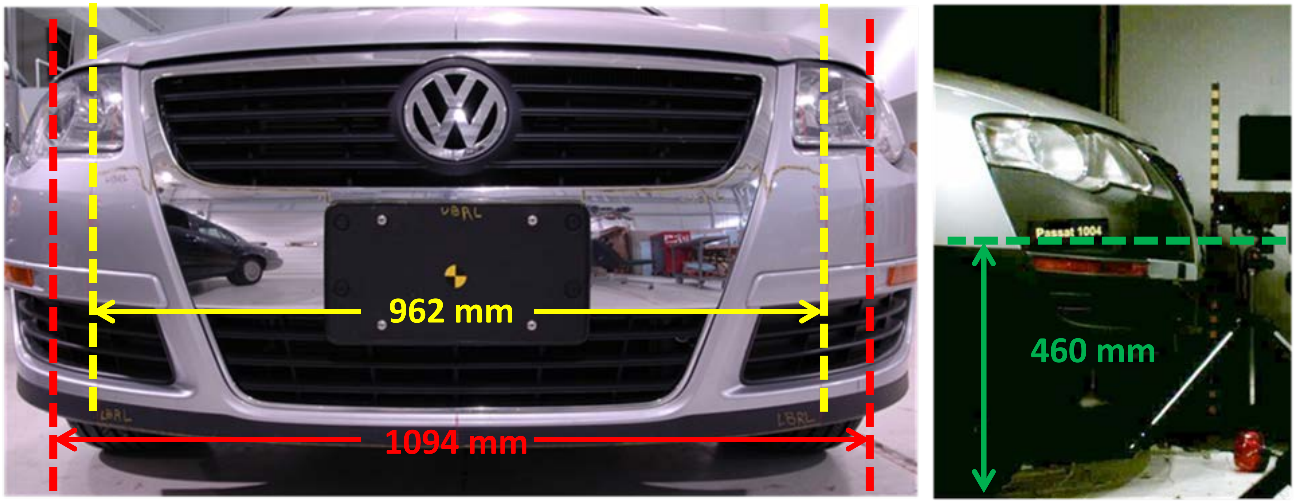


Figure 32. 2006 Volkswagen Passat front and profile views.

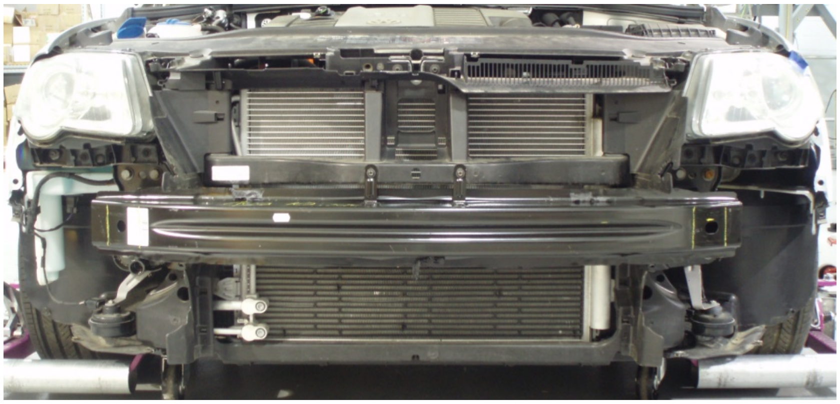


Figure 33. 2006 Volkswagen Passat front and profile views without the fascia.

2.4. Regulatory Aspects of a Test Device

Historically, NHTSA has evaluated test tools intended for regulatory evaluations of vehicle safety systems by characterizing its technical performance in the following areas:

- Biofidelity: how closely does the tool mimic human behavior?
- Sensitivity to Bumper Design: is the tool sensitive enough to discern incremental differences in vehicle system performance with respect to other vehicles, test tools, or other regulatory requirements for that part of the vehicle?
- Repeatability: if the tool is tested multiple times in the same conditions, does it exhibit a consistent response?
- Reproducibility: do multiple tools exhibit consistent response in the same condition?
- Durability: does the tool maintain its structural integrity in the most aggressive test conditions that it would experience when evaluating vehicle systems in the field?

3. BIOFIDELITY

The Flex-PLI response was derived from adult post-mortem human subject (PMHS) lower extremity testing, both in full body and bone experiments. This section reviews the biomechanical studies used to derive response criteria and corridors for certifying the Flex-PLI as a biofidelic test tool. The VRTC Flex-PLI was then evaluated against those corridors to assure humanlike response characteristics.

3.1. Component Biofidelity Response

- **Biomechanical studies to develop femur, tibia, and knee response corridors**

Response corridors for the pedestrian thigh, leg, and knee were developed by Ivarsson et al. in 2004. The corridors were developed using experimental PMHS test data from Kerrigan et al. (2003a, 2003b, 2004), and Bose et al. (2004) in which symmetric 3-point dynamic bend tests characterized the thigh and leg while 4-point dynamic bend tests characterized the knee.

In 2005, Ivarsson et al. supplemented the 2004 study by providing force-deflection and moment-deflection response corridors for the thigh and leg subjected to non-midpoint 3-point bend testing in the lateral-medial direction. The thigh was impacted at the distal third while the leg was impacted at the distal third as well as the proximal third. A loading rate of 1.5 m/s was utilized in order to achieve a longitudinal strain rate equivalent to that observed in a 40 kph pedestrian impact. Data was geometrically scaled to the 50th percentile femur and tibia lengths (448.5 mm and 378.7 mm, respectively). Dynamic response corridors were developed around the average response ± standard deviation of both dependent and independent variables using procedures outlined by Lessley et al. (2004). Average subject response curves were developed such that the shape characteristics of individual responses were maintained. Corridors developed by Ivarsson were used to assess legform biofidelity at the component level. Subsequently, these corridors were used to develop qualification corridors through the pedestrian safety informal working group (GTR9 PS IWG) to assure biofidelity and reproducibility. Figures 34, 35, and 36 display the biofidelity corridors and corresponding Flex-PLI qualification corridors.

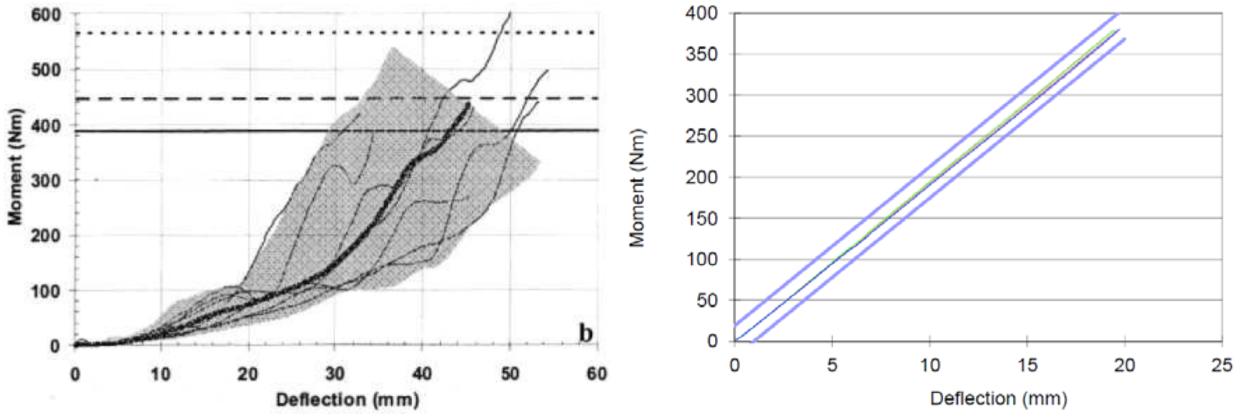


Figure 34. (Left) Human femur response corridor from Ivarsson et al (2004). The solid, dashed, and dotted horizontal lines represent 25%, 50%, and 95% risk of femur fracture, respectively. (Right) Flex-PLI femur qualification corridor with typical response.

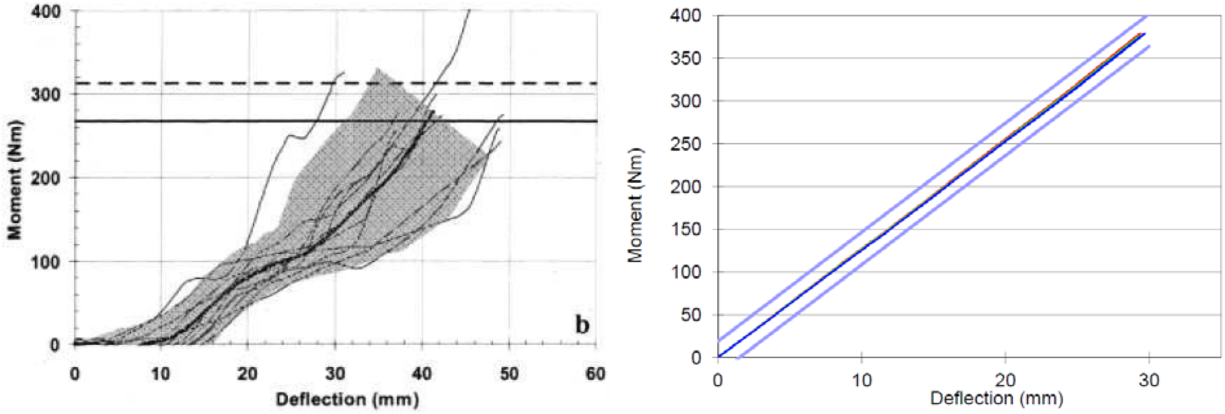


Figure 35. (Left) Human tibia response corridor from Ivarsson et al (2004). The solid and dashed horizontal lines represent 25% and 50% risk of tibia fracture, respectively. (Right) Flex-PLI tibia qualification corridor with typical response.

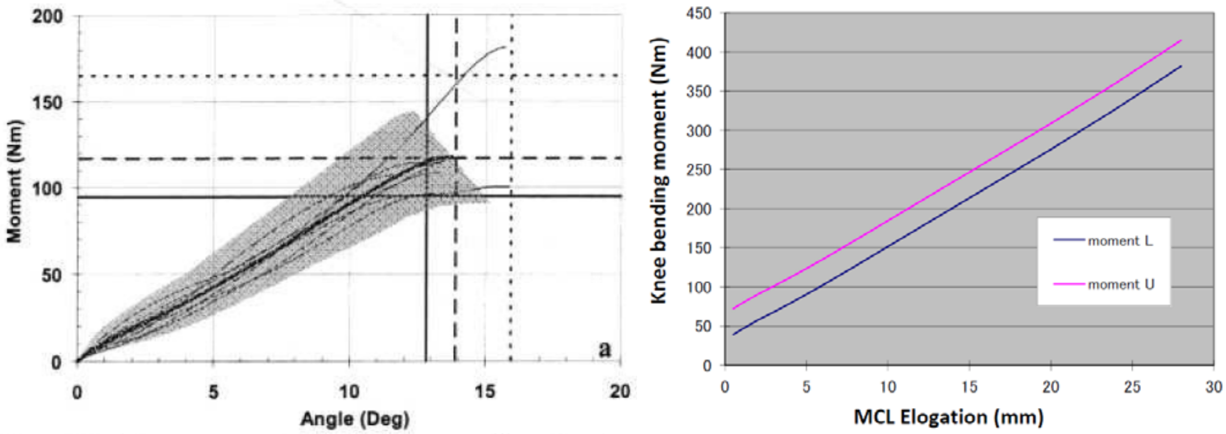


Figure 36. (Left) Human knee bending response corridor from Ivarsson et al (2004). The solid, dashed, and dotted lines represent 25%, 50%, and 95% risk of knee ligament injury, respectively. (Right) Flex-PLI knee qualification corridor. Modeling was used to relate bending angle to MCL elongation.

- **VRTC Flex-PLI data vs. tibia, knee, and femur component corridors**

To evaluate the Flex-PLI response versus the component biofidelity corridors, quasi-static tibia & femur three-point bending and knee assembly four-point bending qualification tests (Figure 37) were done by Humanetics on the VRTC Flex-PLI leg to assure that the legform displayed biofidelic response characteristics.

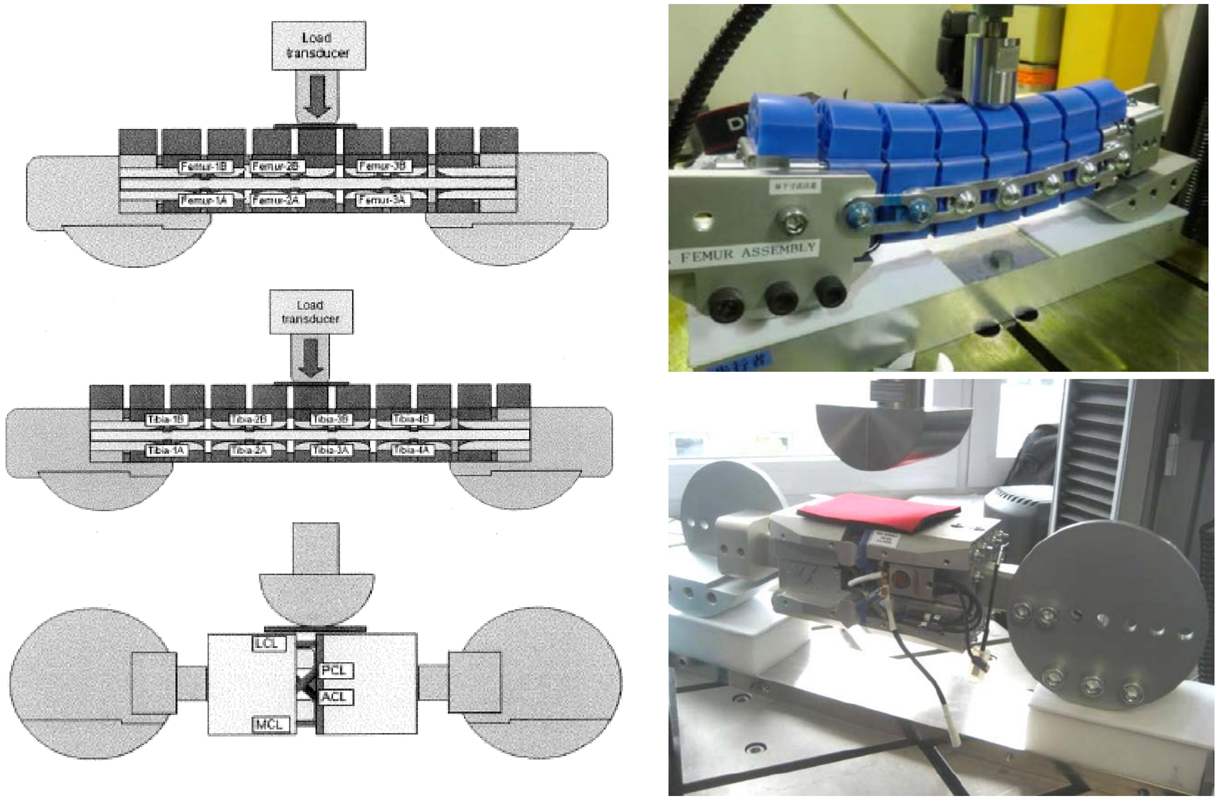


Figure 37. (Top) Femur, (center) tibia, and (bottom) knee component qualification test setups (photographs from Flex-PLI User's Manual).

3.2. Full Leg Biofidelity Response

- **Biomechanical studies to develop full assembly response corridors**

A full pedestrian finite element model was developed and validated with human biomechanical data (Takahashi et al. 2003, Kikuchi et al. 2006, 2008). To prove the full leg biofidelity, a CAE correlation study was conducted comparing responses of that human full body FE model and the Flex-PLI FE model (GTR9-1-05r1). The Flex-PLI FE model was validated with experimental Flex-PLI data.

- **VRTC Flex-PLI data vs. full assembly corridors**

A pendulum qualification test (Figure 38) was developed to reflect the biofidelity test condition used in the CAE correlation study (GTR9-4-07e). To evaluate the VRTC Flex-PLI full assembly biofidelity, pendulum qualification tests were done throughout testing to assure that the legform full assembly maintained biofidelic response characteristics throughout testing. The peak value windows are shown in Table 2.

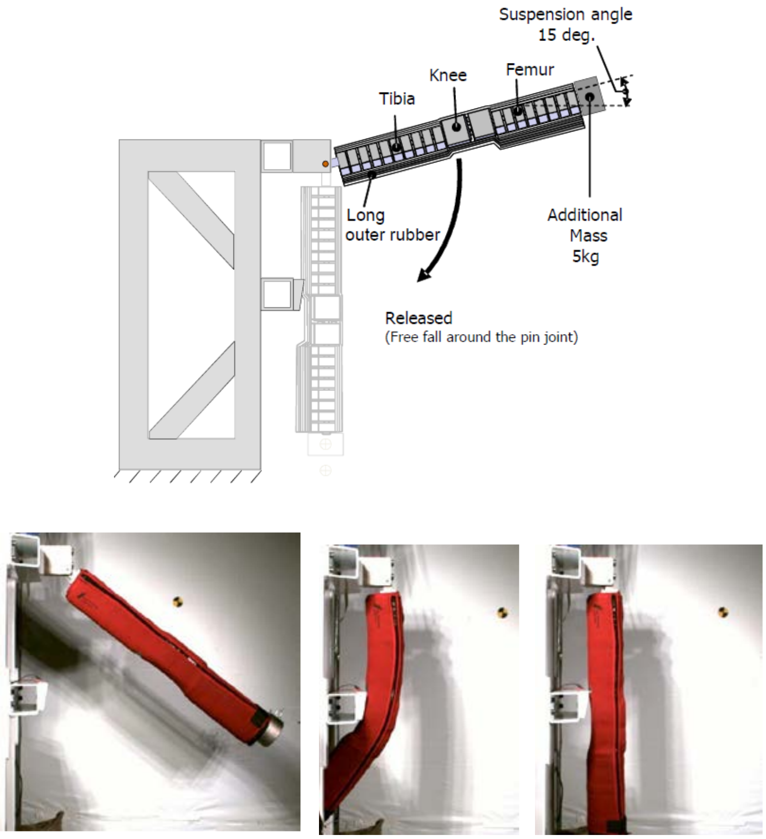


Figure 38. Pendulum qualification test (diagram from Flex User's Manual).

Table 2. Pendulum qualification requirements

Injury Measurement	**Corridor**	
	Lower Bound	**Upper Bound**
Tibia 1 (N-m)	235	272
Tibia 2 (N-m)	187	219
Tibia 3 (N-m)	139	166
Tibia 4 (N-m)	90	111
MCL Elongation (mm)	20.5	24
ACL Elongation (mm)	8	10.5
PCL Elongation (mm)	3.5	5

3.3. Results: Biofidelity

3.3.1. Tibia, Knee, & Femur Component Response

The response of a Flex-PLI finite element model validated with experimental Flex-PLI data was compared with the PMHS biofidelity corridor from Ivarsson in the same condition by the GTR9 Phase 2 Flex informal working group (GTR9-1-05r1). Figure 39 shows the biofidelity of the Flex-PLI tibia assembly.

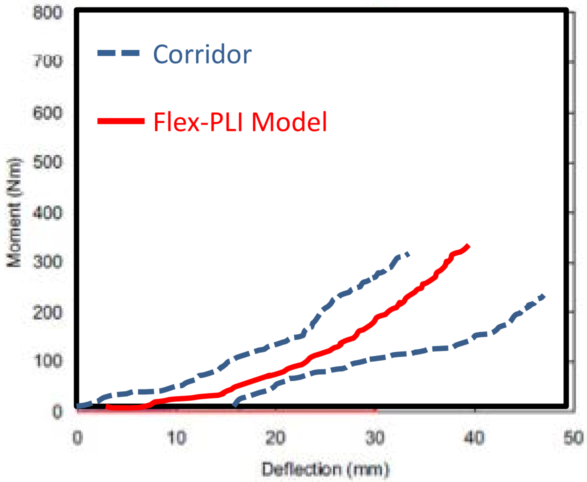


Figure 39. Biofidelity of the Flex-PLI tibia assembly.

A three-point bending qualification test (without flesh) was adapted from this biofidelity test condition (GTR9-4-07e), and the VRTC Flex-PLI was found to meet the qualification criteria for this test (Figure 40).

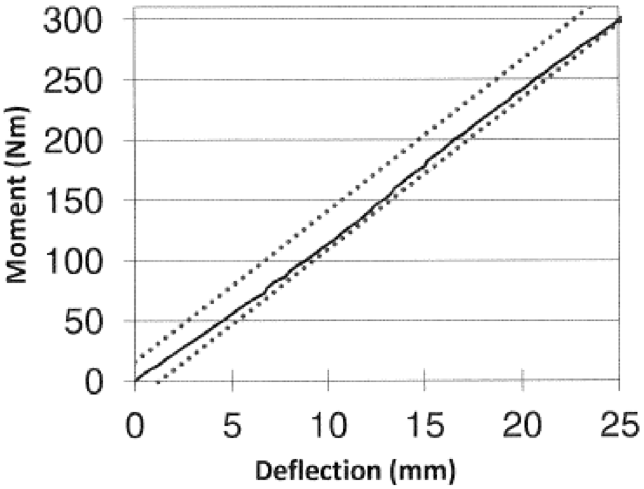


Figure 40. VRTC Flex-PLI tibia meets qualification corridor (dashed) derived from biofidelity test.

Figure 41 shows both the biofidelity of the Flex-PLI knee assembly and the improvements with respect to the EEVC legform. The Flex-PLI showed moments much more consistent with the human corridor.

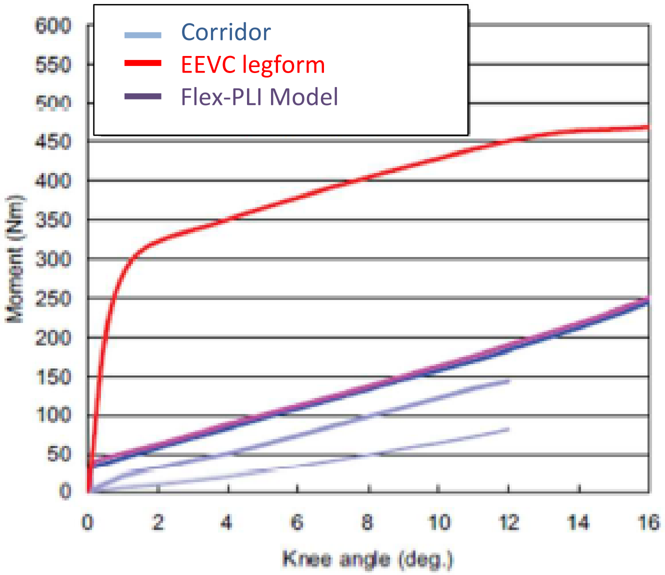


Figure 41. Biofidelity of the Flex-PLI knee assembly.

A three-point bending qualification test (without flesh) was adapted from this biofidelity test condition (GTR9-4-07e). The knee angle was related to the ligament elongations through modeling studies (ref GTR documents) and the VRTC Flex-PLI was found to meet the qualification criteria for this test (Figure 42).

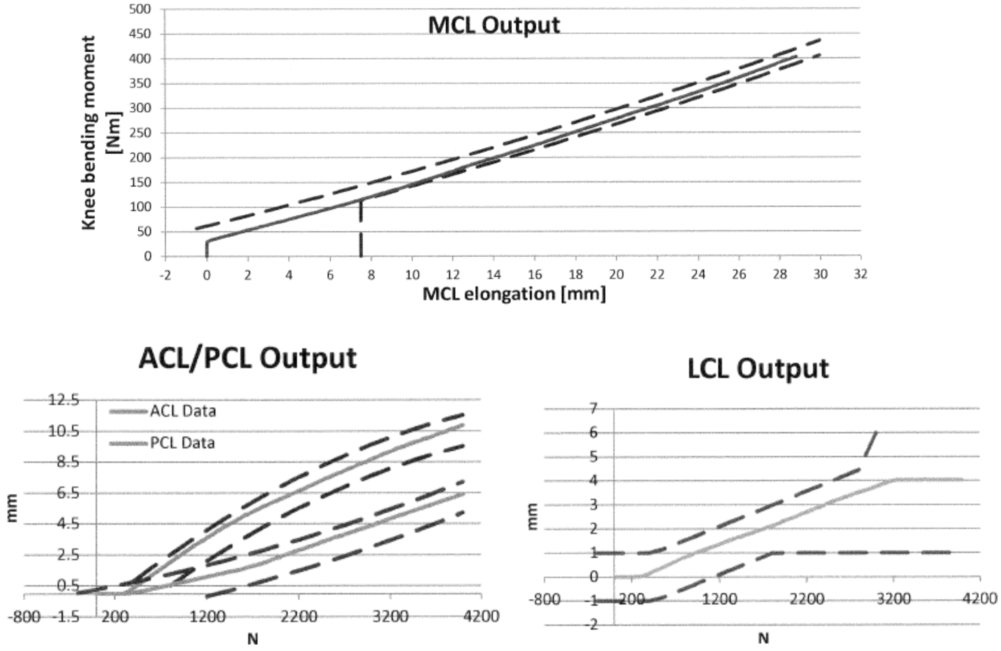


Figure 42. VRTC Flex-PLI knee meets qualification corridors (dashed) derived from biofidelity test.

The VRTC Flex-PLI also met the femur component-level qualification requirements (Figure 43).

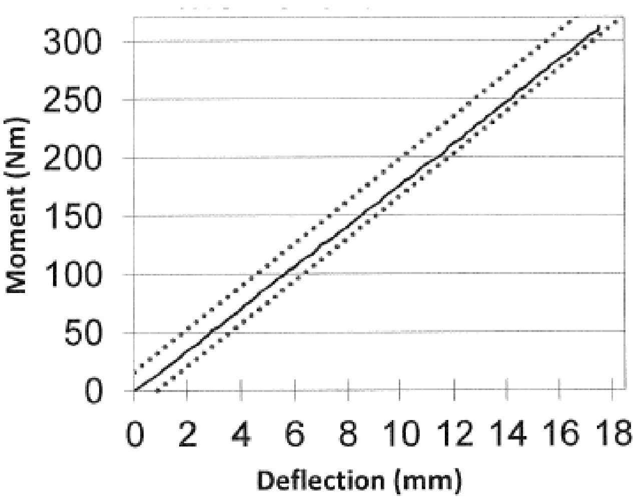


Figure 43. VRTC Flex-PLI femur meets qualification corridor (dashed) derived from biofidelity test.

3.3.2. Full Assembly Biofidelity

For the full leg response, it was determined in the CAE correlation study (GTR9-1-05r1) that the Flex-PLI response is consistent with the human full body leg response, while Konosu et al. (2009) showed that the EEVC upper tibia acceleration did not correlate with the human model tibia bending moment (Figure 44).

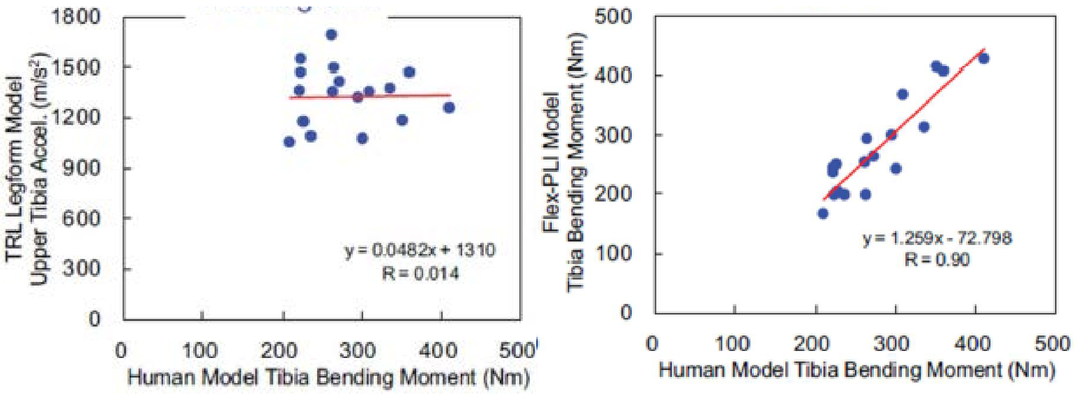


Figure 44. Flex-PLI and EEVC measurement correlation with human tibia bending moments.

Both the Flex-PLI MCL elongation and EEVC knee bending angles showed good correlation with the human model MCL elongations (Figure 45).

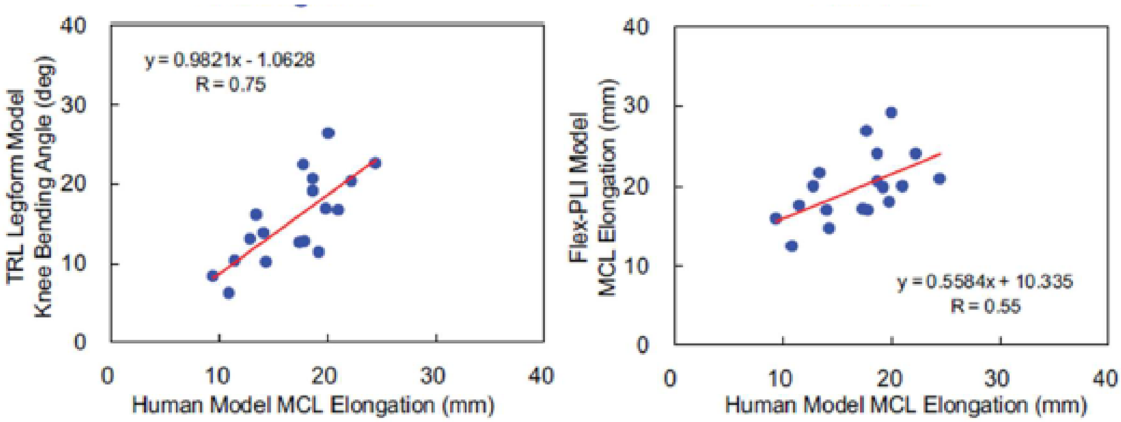


Figure 45. Flex-PLI and EEVC measurement correlation with human MCL elongation.

The Flex-PLI ACL elongation showed good correlation with the human model ACL elongations (Figure 46), while the EEVC shear displacement did not correlate well.

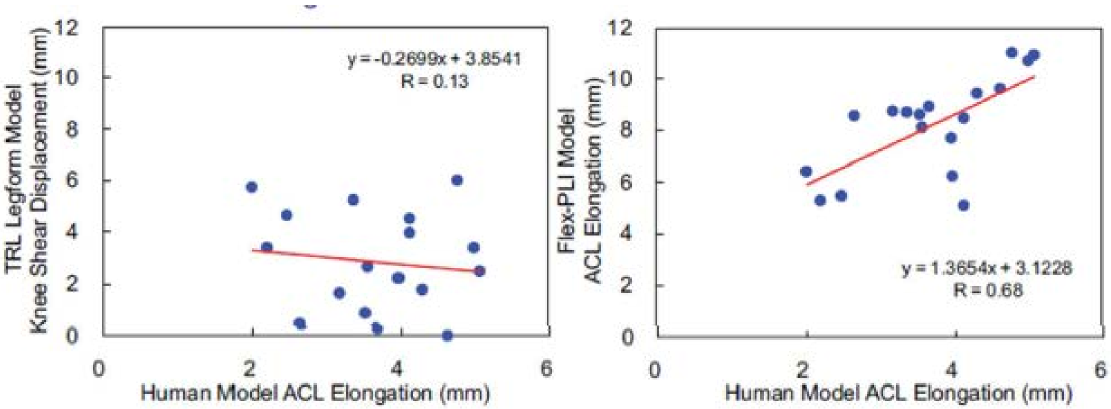


Figure 46. Flex-PLI and EEVC measurement correlation with human ACL elongation.

The Flex-PLI legforms were found to consistently meet the pendulum qualification requirements throughout vehicle tests presented in this report. Pendulum qualification data can be found in section 5.3 later in this report.

3.4. Analysis & Discussion: Biofidelity

As described in the Methods section, data from a significant number of biomechanical studies have been used to develop the Flex-PLI. Component-level tibia and knee assembly bending tests on adult PMHS were used to derive biomechanical response requirements for the Flex-PLI. Subsequently, qualification tests were developed to simulate the biomechanical test conditions. These tests are used to assure that the Flex-PLI maintains humanlike response characteristics.

To evaluate the biofidelity of the VRTC Flex-PLI legform, these component-level and full leg (pendulum) qualification tests were conducted at various times throughout the vehicle tests described in this report. The legform consistently met the qualification requirements, indicating biofidelic performance in the vehicle tests.

The biofidelity of the Flex-PLI has been compared with that of the EEVC legform. The Flex-PLI legform has exhibited consistency with a validated human body lower extremity FE model in bending moment, ACL elongation, and MCL elongation. While the EEVC legform bending angle did correlate well with the Flex-PLI MCL elongation, the EEVC tibia acceleration and shear displacement did not correlate well with the human bending moment or human ACL elongation, respectively. The Flex-PLI can capture the combined knee loading that is common in pedestrian collisions (Takahashi et al. 2001). Knee ligaments tend to elongate in combined bending and shearing motions. The EEVC legform on the other hand could have diminished injury prediction, simply because the shear displacement and bending angle are separately measured (Figure 47).

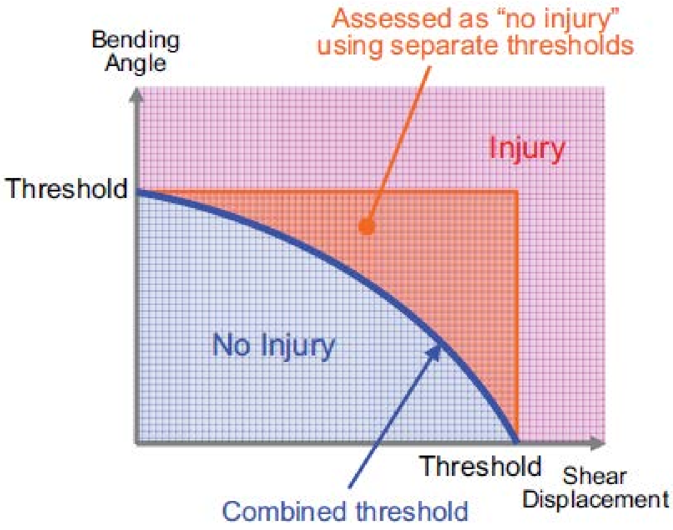


Figure 47. Flex-PLI ligament elongations capture combined shear and bending mechanisms (from Takahashi et al 2001).

The VRTC Flex-PLI femur assembly also met its required corridors, but there is some debate about the validity of the femur measurements in vehicle tests. This is mainly due to the influence of the upper body on the femur kinematics (Zander et al. 2009, Mallory et al 2010). It has been recognized that the lack of an upper body has an effect on the femur/thigh measurements in the Flex-PLI. This is the primary reason that there is no currently proposed injury assessment value for the femur.

4. Flex-PLI SENSITIVITY TO BUMPER DESIGN

It is important for a test tool to (1) make measurements that are sensitive to small differences in performance of the type of systems that it is being used to evaluate, (2) improve upon the mitigation of injury provided by existing test tools, (3) provide valid feedback on how vehicle designs would have to change to comply with safety requirements, (4) have the instrumentation and response characteristics to provide adequate coverage of the injuries that are present in the field, and (5) possess injury assessment values that are feasible to meet in light of other regulatory constraints.

The Flex-PLI should be effective at discriminating between pedestrian friendly and aggressive bumper designs. To evaluate this aspect, the Flex-PLI was (1) compared with the EEVC legform in ranking a set of vehicles, (2) compared with earlier prototypes for discerning poor from very poor designs, (3) tested against GTR-compliant and non-GTR-compliant bumpers, and (4) evaluated versus bumper performance in low speed Part 581-type pendulum tests.

4.1. Flex-PLI vs. EEVC Legform Comparison

Testing on six vehicles was performed according to the basic procedures outlined in Amendment 1 of the Proposal for a Global Technical Regulation (GTR) for the Protection of Pedestrians [GRSP, 2010] at NHTSA’s Vehicle Research and Test Center (VRTC) using the EEVC and Flex-PLI legforms (Figures 48 and 49). Both legforms were launched under the same conditions with the exception of legform height. For Flex-PLI testing, the Flex Technical Evaluation Group (TEG) recommended a nominal height of 75 mm between the bottom of the legform and the ground reference level (GRL) at the time of impact such that the knee was 572 mm above ground level. This height requirement was followed in all Flex-PLI impacts. For the EEVC leg, the nominal height was 25 mm between the bottom of the legform and the GRL such that the knee was 519 mm above ground level.

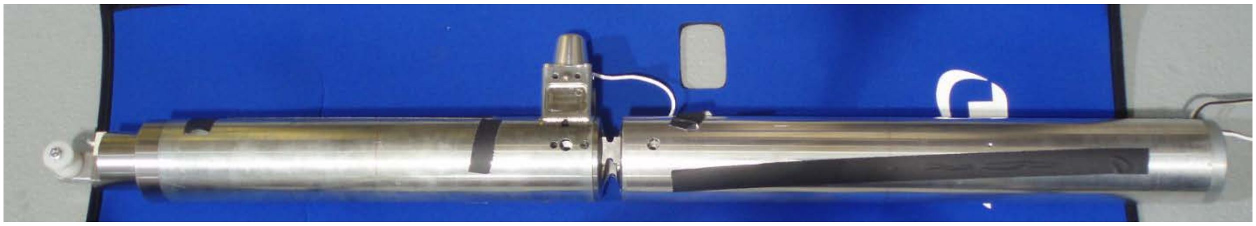


Figure 48. EEVC legform.

Figure 49. Flex-PLI legform.

EEVC tests were performed on the Silverado, Equinox, and Civic so that the resulting EEVC data can be used in combination with previous EEVC data (Miata, Passat, and Pilot were previously tested) to rank the vehicles in order of increasing severity for Flex-PLI testing. Due to uncertainty about the durability of the Flex-PLI legform, it was important to test the vehicles in order of increasing severity in order to acquire as much data as possible before damage. Injury measures from each legform were compared across vehicles to show the differences expected for a given injury measure by using one legform versus the other.

The EEVC legform was instrumented as specified in the GTR. A uniaxial accelerometer (Endevco, Model 7264-2000) was mounted on the non-impact side of the upper tibia. The legform was equipped with potentiometers (Contelec, Type GL 60) located in the upper tibia and lower femur. The potentiometers are standard EEVC transducers to measure knee bending angle and knee shear displacement. Knee bending angle and shear displacement are calculated based on the potentiometer angles and length of the potentiometer rod connecting the two potentiometers as specified in the EEVC legform user's manual (EEVC, 2007). Temperature and humidity were maintained within GTR-defined corridors during pre-test soaking and during testing. Pre-test temperature and humidity conditions were maintained by storing the legform in a climate-controlled chamber with a dehumidifier and thermostat-controlled air conditioner for four hours. To further maintain proper temperature and humidity conditions, the chamber was placed in a climate-controlled room, which was less humid than outside or test area conditions.

The Flex-PLI legform was instrumented with strain gages, displacement potentiometers, and accelerometers as a means to assess injuries and for monitoring purposes. Seven strain gages (three in the femur and four in the tibia) were used to measure the bending moment of the femur and tibia. The knee of the Flex-PLI was instrumented with three displacement potentiometers to measure the elongation of the anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), and medial collateral ligament (MCL). A fourth displacement potentiometer was mounted in the Flex-PLI to measure the elongation of the lateral collateral ligament (LCL). Lastly, one accelerometer was mounted in the tibia to measure leg acceleration during impact.

The EEVC legform's instrumentation wires exited from the bottom of the legform and were connected directly to the data acquisition system. Therefore, the instrumentation cables were positioned on the floor so that they would not influence the leg's flight (Figure 50). The Flex-PLI legform was equipped with a DTS onboard SLICE Nano data acquisition system. The system was connected to the data acquisition system computer via a cable that disconnected at the beginning of the launch motion (Figures 7-9). The cable was anchored to the stationary hydraulic impactor so that disconnect occurred immediately after the launch plate moved forward. After disconnect and throughout the flight of the legform, the onboard SLICE system was powered by a super capacitor. After reconnecting the legform to the data acquisition computer, test data was downloaded and the super capacitor recharged.

Figure 50. Test setup with the EEVC legform. The instrumentation wires exit from the bottom of leg.

The legforms were launched into free-flight using a hydraulic cylinder. A launch plate with a horizontal top-mounted pin cradled the suspended legform on the front of the actuator. Two different plate designs were used, one for the EEVC and another for the Flex-PLI legforms. The launch plate was mounted so that the actuator was aligned with the approximate height of the legform's center of gravity. The legforms were suspended by a launch guide that was rested on the plate's horizontal pin (Figure 51). The actuator was fired at a pressure of 9500 psi (EEVC) and 9030 psi (Flex-PLI) and after approximately 400 mm of travel, the actuator's motion was braked, allowing for the legform to move forward in free-flight toward the vehicle. According to GTR specifications, impact speed was 11.1 m/s (± 0.2 m/s). Impact speed was measured using high speed video analysis using TEMA v.3.5. When available, speeds were confirmed with an Aries laser speed meter (Model SM-2BL/F) with emitter and receiver modules positioned perpendicular to the flight of the legform, immediately before the bumper impact point. Velocity measurements were confirmed to be similar amongst the speed meter and high speed video analysis as there was an average difference of approximately 0.05 m/s between the two measurements.

Both the Flex-PLI and EEVC legforms were certified for the test series. The Flex-PLI qualification data can be found in both sections 5 and 6. The EEVC legform qualification data is in the Appendix.

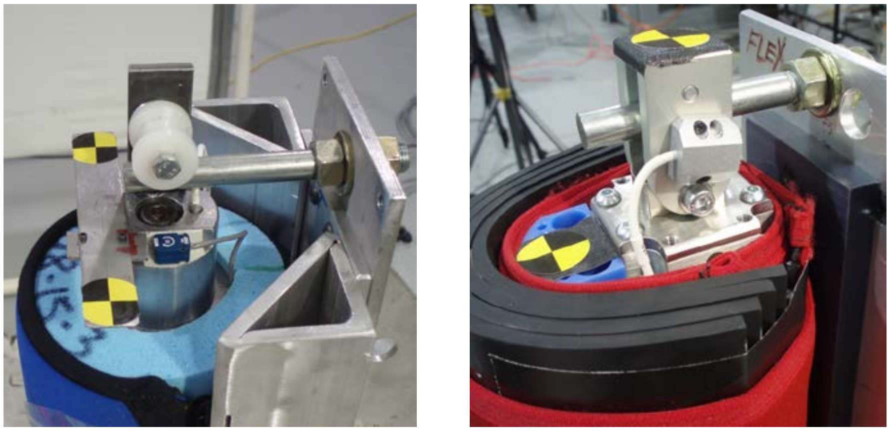


Figure 51. (Left) EEVC launch plate and guide; (right) Flex-PLI launch plate and guide.

Table 3 summarizes the vehicle impact locations performed with each legform.

Table 3. Summary of vehicle impact locations.

	EEVC		**Flex-PLI**	
	Center	**Outboard**	**Center**	**Outboard**
Passat		X	X	X
Miata		X	X	X
Civic		X	X	X
Pilot	X		X	
Silverado	X		X	
Equinox	X		X	

4.1.1. Results

EEVC legform results for each vehicle are presented in section 4.1.1.1, followed by Flex-PLI results in section 4.1.1.2. Static and dynamic qualification results and vehicle test photographs of the EEVC legform are presented in the Appendix. A laser speed meter was used for a limited number of tests. Unless mentioned otherwise, video analysis of the legforms from overhead and lateral video was utilized and showed that the legforms were within the impact speed range of the GTR in all tests. For EEVC legform tests, time zero is the time of first contact of the legform with the vehicle. For Flex-PLI tests, the time of first contact is marked by a vertical line.

4.1.1.1. EEVC

According to the GTR, acceptance levels for the EEVC lower legform test are set as follows:

- Maximum lateral knee bending angle ≤ 19 degrees
- Maximum lateral knee shearing displacement ≤ 6.0 mm
- Maximum lateral tibia acceleration ≤ 170 g except for manufacturer defined relaxation zone where maximum lateral tibia acceleration ≤ 250 g

The 264 mm relaxation zone, equivalent to two leg-widths, was assumed for all vehicles in this test series to be over the bumper bar support brackets (or frame rails in some cases) based on results of previous EEVC test experience. Vehicles must meet all of the above requirements to comply with the GTR.

2006 Volkswagen Passat (Outboard)

Peak injury measures for the Passat test are listed in Table 4 and time histories are shown in Figure 52. The Passat exceeded all three GTR limits in the outboard impact.

Table 4. Peak values for knee bending angle, knee shear displacement, and tibia acceleration for the Volkswagen Passat.

Injury Measurement	**Injury Reference Value (GTR)**	**Volkswagen Passat (Passat 1004)**
Impact Location		Outboard
Peak Bending Angle (deg)	19 deg	31.1
Peak Shear Displacement (mm)	6 mm	8.1
Peak Tibia Acceleration (g)	*250 g	307
*Outboard impacts evaluated relative to the relaxation zone limit		

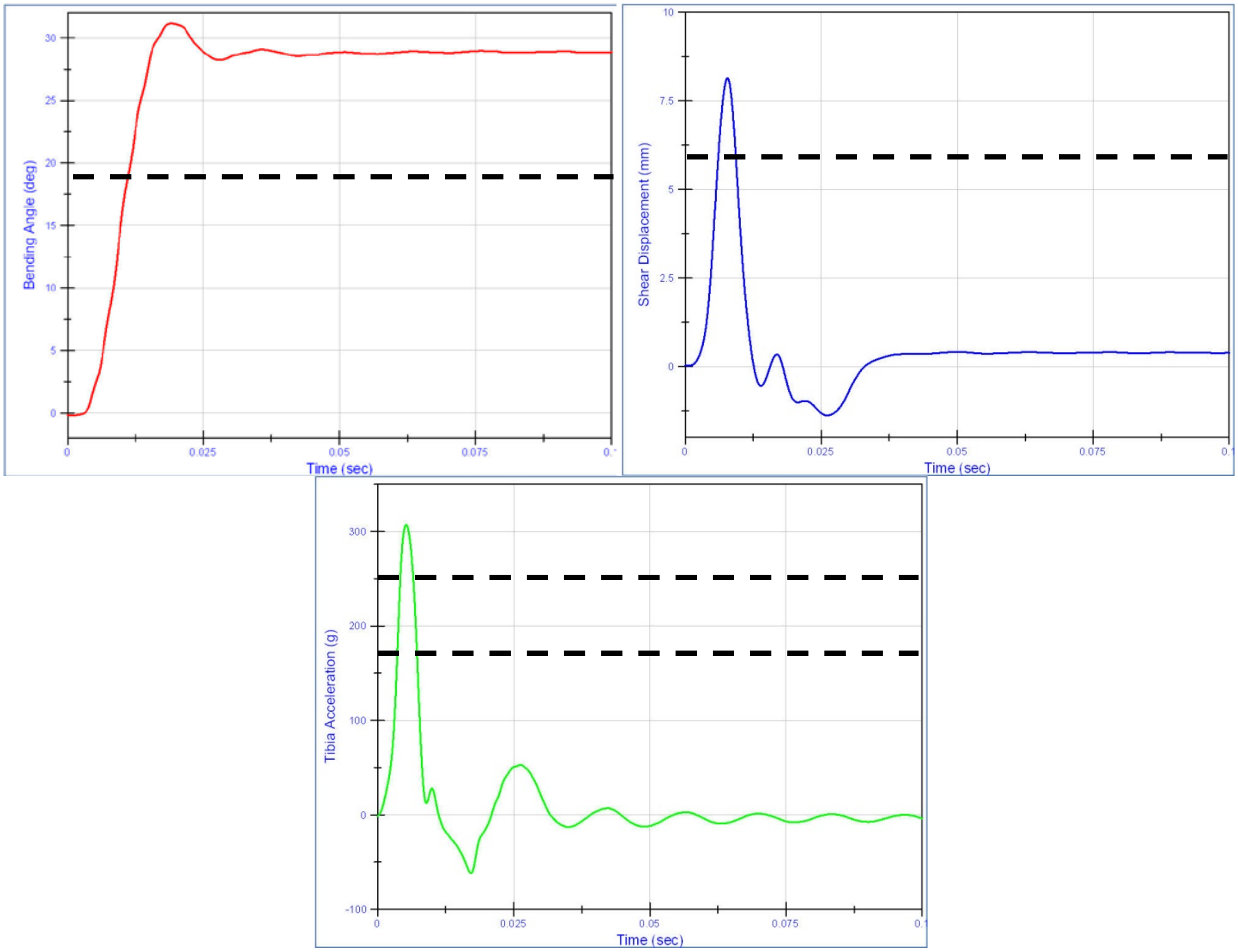


Figure 52. Time histories for knee bending angle, knee shear displacement, and tibia acceleration for the Volkswagen Passat. GTR limits are shown in black.

2002 Mazda Miata (Outboard)

Peak injury measures for the Miata test are listed in Table 5 and time histories are shown in Figure 53. The Miata exceeded all three GTR limits in the outboard impact.

Table 5. Peak values for knee bending angle, knee shear displacement, and tibia acceleration for the Mazda Miata.

Injury Measurement	Injury Reference Value (GTR)	Mazda Miata (Miata 1004)
Impact Location		Outboard
Peak Bending Angle (deg)	19 deg	26.5
Peak Shear Displacement (mm)	6 mm	8.9
Peak Tibia Acceleration (g)	*250 g	402
*Outboard impacts evaluated relative to the relaxation zone limit		

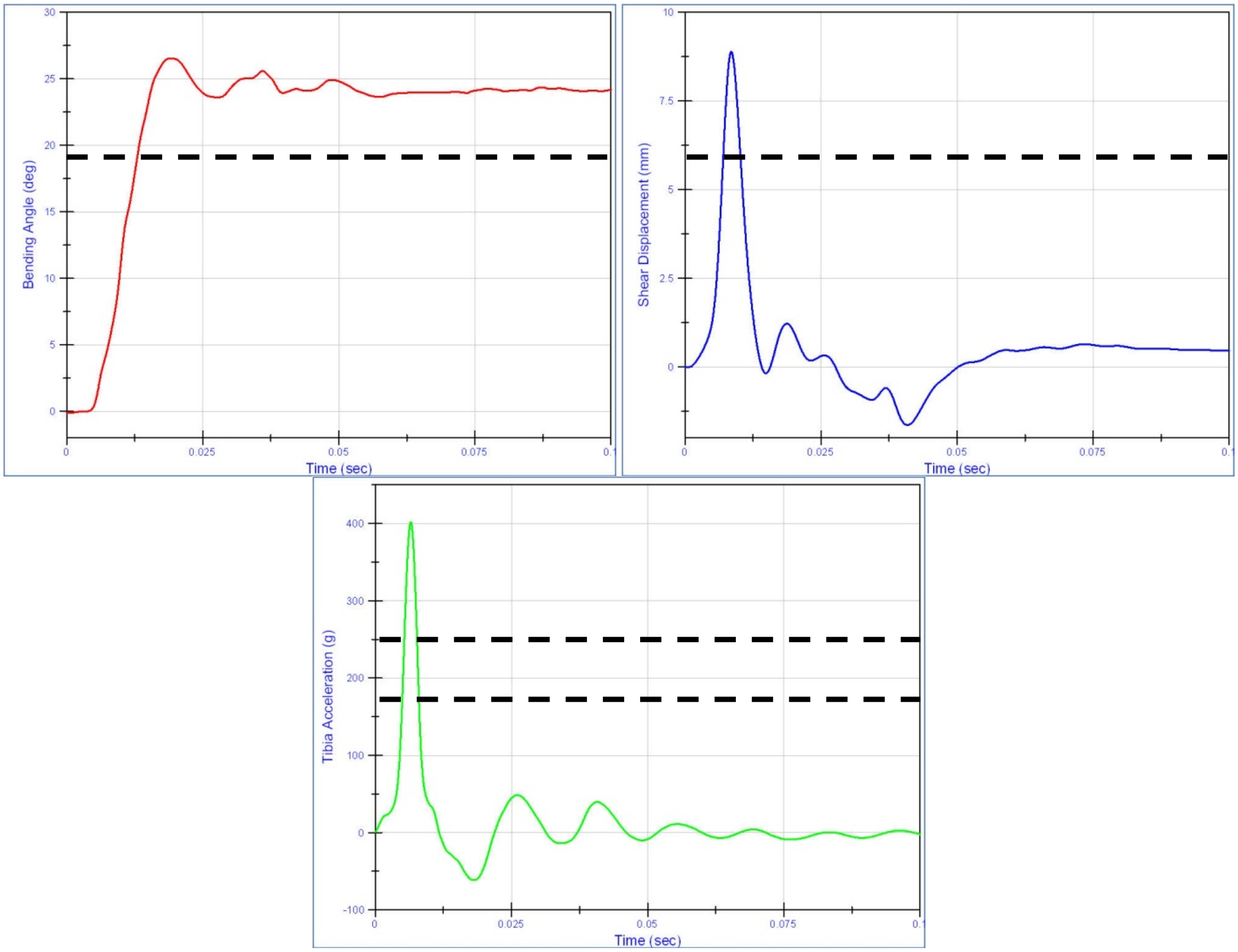


Figure 53. Time histories for knee bending angle, knee shear displacement, and tibia acceleration for the Mazda Miata. GTR limits are shown in black.

2002 Honda Civic (Outboard)

Peak injury measures for the Civic test are listed in Table 6 and time histories are shown in Figure 54. The Civic exceeded all three GTR limits in the outboard impact.

Table 6. Peak values for knee bending angle, knee shear displacement, and tibia acceleration for the Honda Civic.

Injury Measurement	Injury Reference Value (GTR)	Honda Civic (Civic EEVC/TRL 1001)
Impact Location		Outboard
Peak Bending Angle (deg)	19 deg	33
Peak Shear Displacement (mm)	6 mm	8.9
Peak Tibia Acceleration (g)	*250 g	326
*Outboard impacts evaluated relative to the relaxation zone limit		

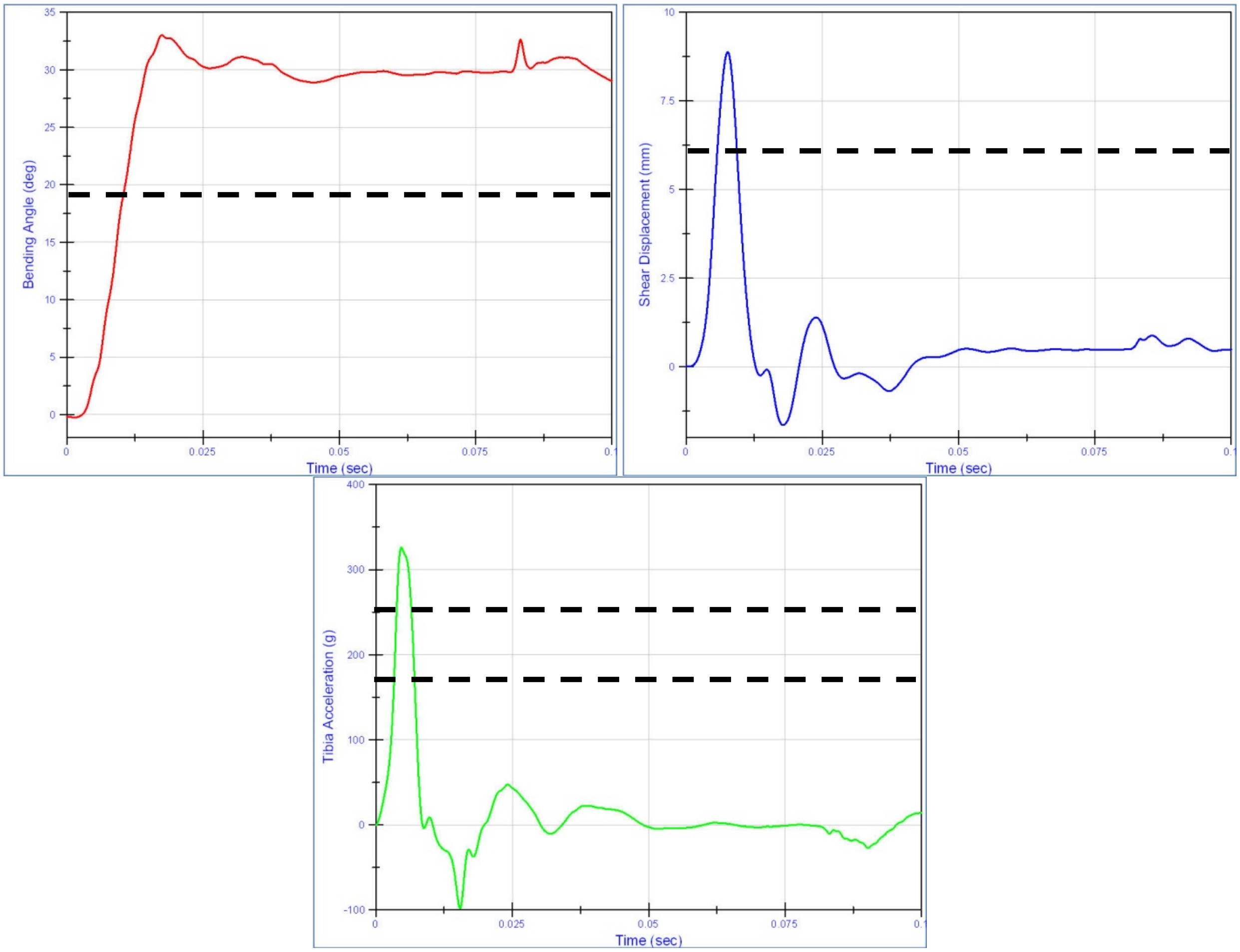


Figure 54. Time histories for knee bending angle, knee shear displacement, and tibia acceleration for the Honda Civic. GTR limits are shown in black.

2003 Honda Pilot (Center)

Peak injury measures for the Pilot test are listed in Table 7 and time histories are shown in Figure 55. The Pilot exceeded all three GTR limits in the center impact.

Table 7. Peak values for knee bending angle, knee shear displacement, and tibia acceleration for the Honda Pilot.

Injury Measurement	Injury Reference Value (GTR)	Honda Pilot (Pilot 0901)
Impact Location		Center
Peak Bending Angle (deg)	19 deg	33
Peak Shear Displacement (mm)	6 mm	-6.8
Peak Tibia Acceleration (g)	*170 g	401
*Center impacts evaluated relative to the 170 g limit		
Note: A negative shear displacement indicates that the tibia moved forward relative to the femur		

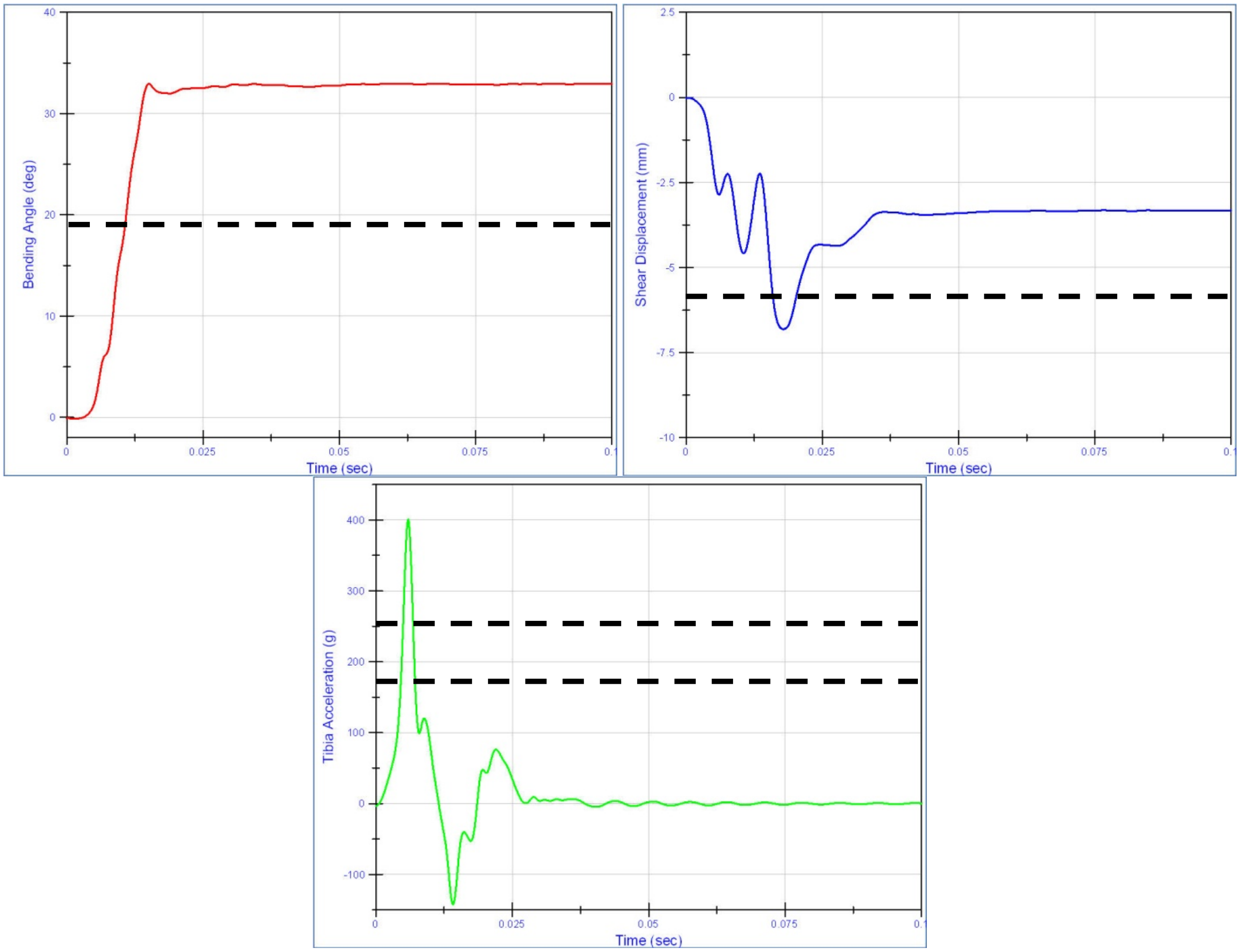


Figure 55. Time histories for knee bending angle, knee shear displacement, and tibia acceleration for the Honda Pilot. GTR limits are shown in black.

2007 Chevrolet Silverado (Center)

Peak injury measures for the Silverado test are listed in Table 8 and time histories are shown in Figure 56. The Silverado exceeded all three GTR limits in the center impact.

Table 8. Peak values for knee bending angle, knee shear displacement, and tibia acceleration for the Chevrolet Silverado.

Injury Measurement	Injury Reference Value (GTR)	Chevrolet Silverado (Silverado EEVC/TRL 1001)
Impact Location		Center
Peak Bending Angle (deg)	19 deg	26.5
Peak Shear Displacement (mm)	6 mm	-8.3
Peak Tibia Acceleration (g)	*170 g	353
*Center impacts evaluated relative to the 170 g limit		
Note: A negative shear displacement indicated that the tibia moved forward relative to the femur		

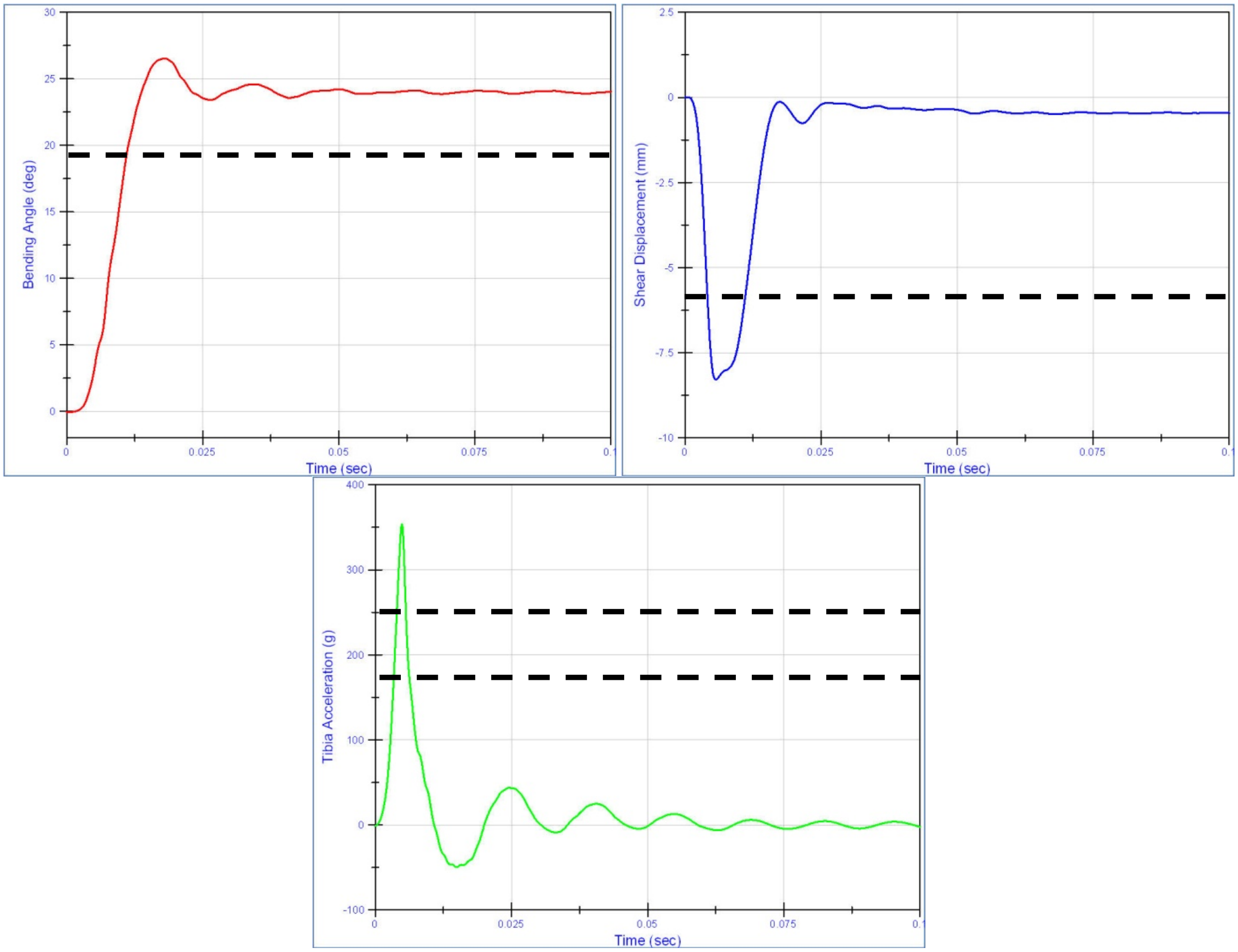


Figure 56. Time histories for knee bending angle, knee shear displacement, and tibia acceleration for the Chevrolet Silverado. GTR limits are shown in black.

2009 Chevrolet Equinox (Center)

Peak injury measures for the Equinox test are listed in Table 9 and time histories are shown in Figure 57. The Equinox exceeded all three GTR limits in the center impact.

Table 9. Peak values for knee bending angle, knee shear displacement, and tibia acceleration for the Chevrolet Equinox.

Injury Measurement	Injury Reference Value (GTR)	Chevrolet Equinox (Equinox EEVC/TRL 1001)
Impact Location		Center
Peak Bending Angle (deg)	19 deg	33.1
Peak Shear Displacement (mm)	6 mm	-7.5
Peak Tibia Acceleration (g)	*170 g	183
*Center impacts evaluated relative to the 170 g limit		
Note: A negative shear displacement indicated that the tibia moved forward relative to the femur		

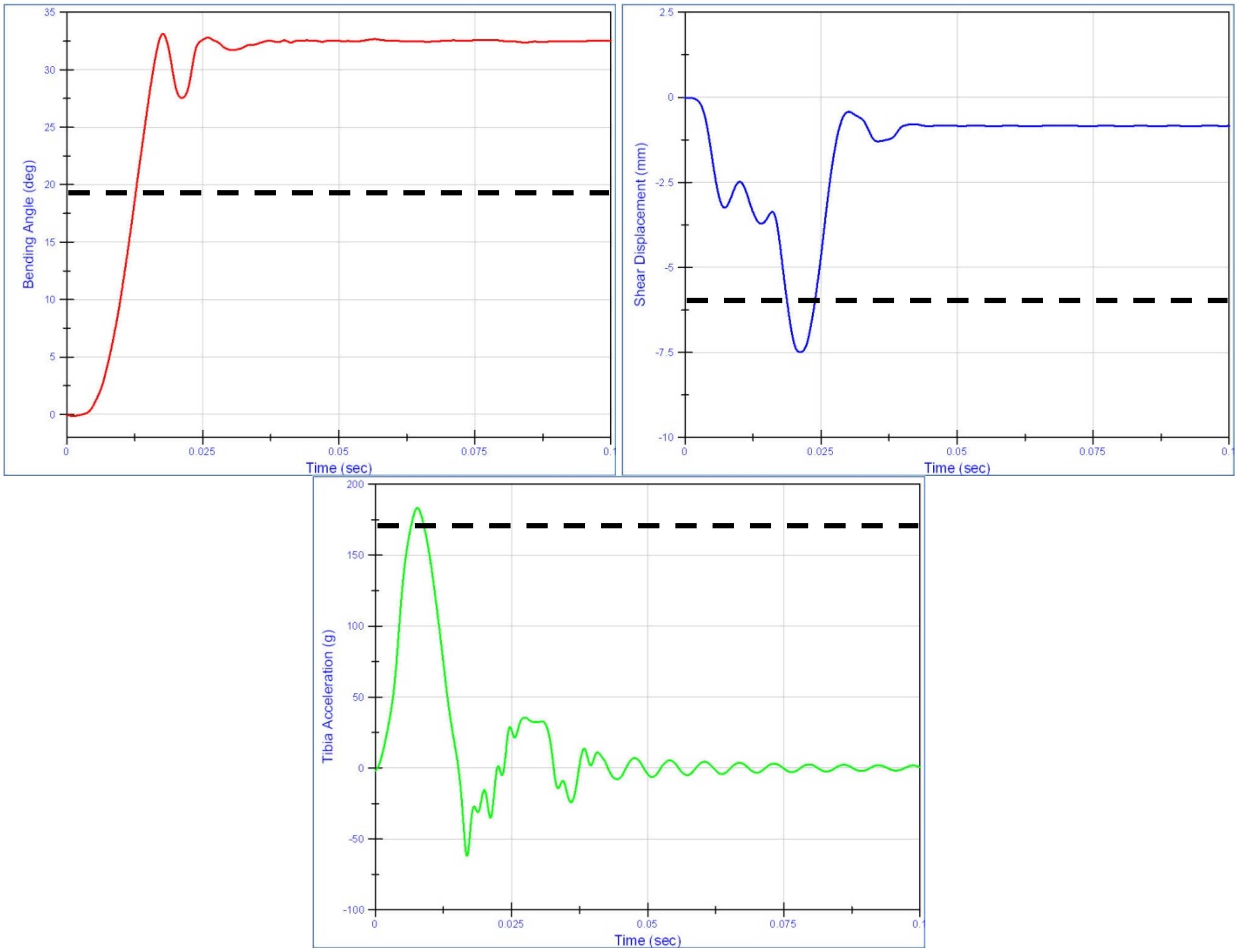


Figure 57. Time histories for knee bending angle, knee shear displacement, and tibia acceleration for the Chevrolet Equinox. GTR limits are shown in black.

The EEVC results were used to rank the vehicles in order of increasing severity for Flex testing due to concerns with the durability of the Flex-PLI legform against the aggressive US vehicle fleet. In particular, the Flex-PLI legform was expected to be damaged when subjected to very large knee shear displacements. Therefore, with this in mind, the EEVC shear displacement was used as the primary measurement in ranking the vehicles in order of increasing severity for Flex testing (Table 10). If the EEVC legform happened to measure the same amount of shear in more than one vehicle, the bending angle measurement was looked at as well. Looking at the EEVC results in Table 10 below, the vehicles were ranked from least severe to most severe for Flex testing as follows: Honda Pilot (least severe), Chevrolet Equinox, Volkswagen Passat, Chevrolet Silverado, Mazda Miata, Honda Civic (most severe). This was the order used when testing the Flex-PLI legform.

Table 10. EEVC legform results for each injury measure

EEVC Legform Results

	Location	Peak Bending Angle	Peak Shear Displacement	Peak Tibia Acceleration
		(19 Deg)	(6 mm)	(170g, 250g)
Mazda Miata	Outboard	🟥 26.5	🟥 8.90	🟥 402
Honda Civic	Outboard	🟥 33.0	🟥 8.90	🟥 326
Volkswagen Passat	Outboard	🟥 31.1	🟥 8.10	🟥 307
Honda Pilot	Center	🟥 33.0	🟥 6.80	🟥 401
Chevrolet Equinox	Center	🟥 33.1	🟥 7.50	🟨 183*
Chevrolet Silverado	Center	🟥 26.5	🟥 8.30	🟥 353

🟩 Passed IARV
🟨 Marginal
🟥 Failed IARV

*Passes relaxed GTR requirement

4.1.1.2. Flex-PLI

According to the GTR, acceptance levels for the Flex-PLI lower legform test are set as follows:

- Maximum MCL elongation ≤ 22 mm
- Maximum ACL/PCL elongation ≤ 13 mm
- Maximum tibia bending moment ≤ 340 N-m except for manufacturer defined relaxation zone where maximum lateral tibia acceleration ≤ 380 N-m

The 264 mm relaxation zone, equivalent to two leg-widths, was assumed for all vehicles in this test series to be over the bumper bar support brackets (or frame rails in some cases) based on results of previous EEVC test experience. Vehicles must meet all of the above requirements to comply with the GTR.

2009 Chevrolet Equinox (Center)

Figure 58 shows screen captures at time of first contact and at maximum legform bending. Peak values for the 2009 Chevrolet Equinox tests are listed in Table 11 and time histories are shown in Figure 59. The Chevrolet Equinox exceeded the Tibia Moment and MCL GTR limits.

Figure 58. 2009 Chevrolet Equinox impact at times of first contact (left) and maximum deflection (right).

Table 11. Flex-PLI peak injury measures for the 2009 Chevrolet Equinox; Center Impact.

Injury Measurement		**Injury Reference Value (FlexTEG)**	**Chevrolet Equinox**
Femur Moment (Nm)	**Femur 3 (Upper)**	N/A	90
	Femur 2 (Middle)		219
	Femur 1 (Lower)		273
Tibia Moment (Nm)	**Tibia 1 (Upper)**	340 N-m (380 N-m)	378
	Tibia 2 (Mid Upper)		312
	Tibia 3 (Mid Lower)		216
	Tibia 4 (Lower)		98
MCL Elongation (mm)		22 mm	34.4
ACL Elongation (mm)		13 mm	11.9
PCL Elongation (mm)		13 mm	8.4
LCL Elongation (mm)		N/A	-3.7
Tibia Acceleration (g)		N/A	-37

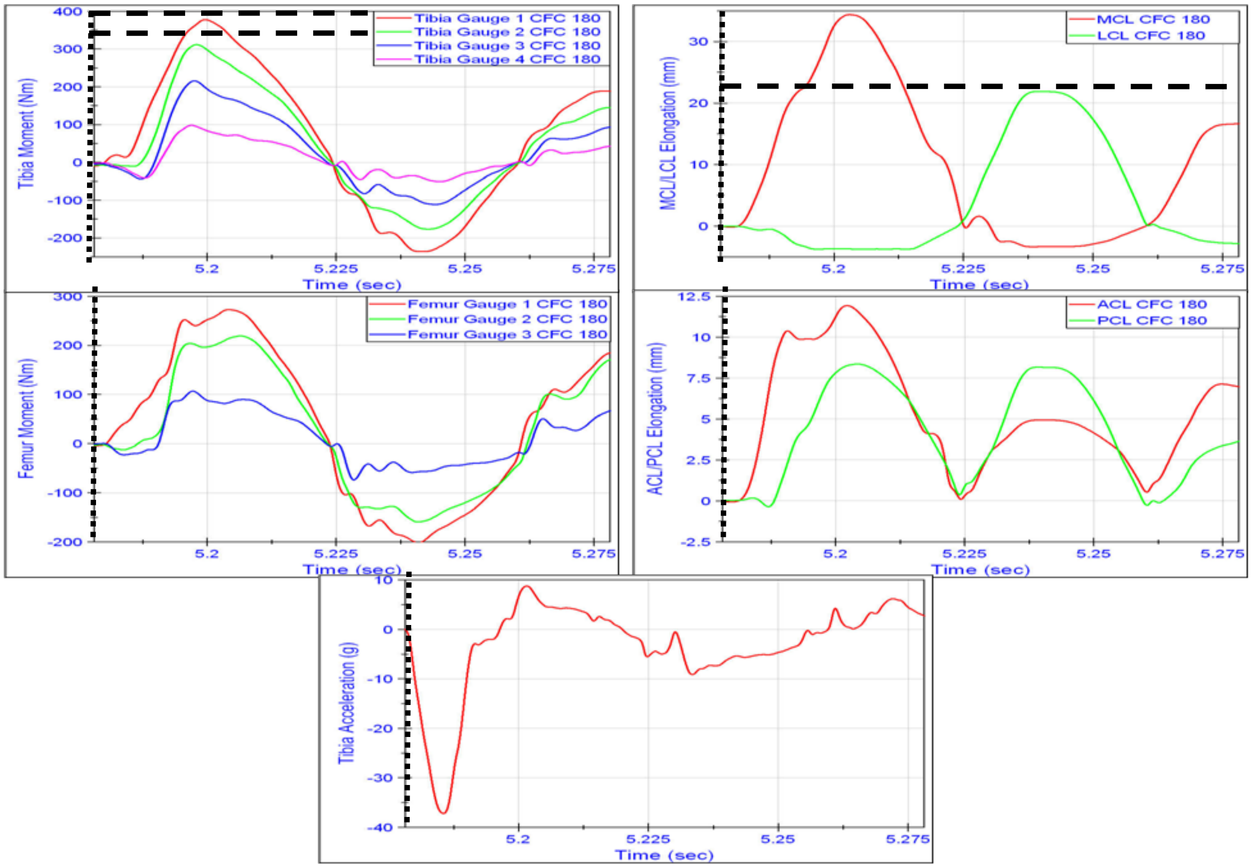


Figure 59. Flex-PLI time histories of the injury measures for the 2009 Chevrolet Equinox. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

2007 Chevrolet Silverado (Center)

Figure 60 shows screen captures at time of first contact and at maximum legform bending. Peak values for the 2007 Chevrolet Silverado tests are listed in Table 12 and time histories are shown in Figure 61. The Chevrolet Silverado exceeded the MCL elongation limit.

Figure 60. 2007 Chevrolet Silverado impact at times of first contact (left) and maximum deflection (right)

Table 12. Flex-PLI peak injury measures for the 2007 Chevrolet Silverado; Center Impact.

Injury Measurement		**Injury Reference Value (FlexTEG)**	**Chevrolet Silverado**
Femur Moment (Nm)	**Femur 3 (Upper)**	N/A	77
	Femur 2 (Middle)		139
	Femur 1 (Lower)		246
Tibia Moment (Nm)	**Tibia 1 (Upper)**	340 N-m (380 N-m)	333
	Tibia 2 (Mid Upper)		320
	Tibia 3 (Mid Lower)		237
	Tibia 4 (Lower)		108
MCL Elongation (mm)		22 mm	22.3
ACL Elongation (mm)		13 mm	7.9
PCL Elongation (mm)		13 mm	5.6
LCL Elongation (mm)		N/A	-3.8
Tibia Acceleration (g)		N/A	-59

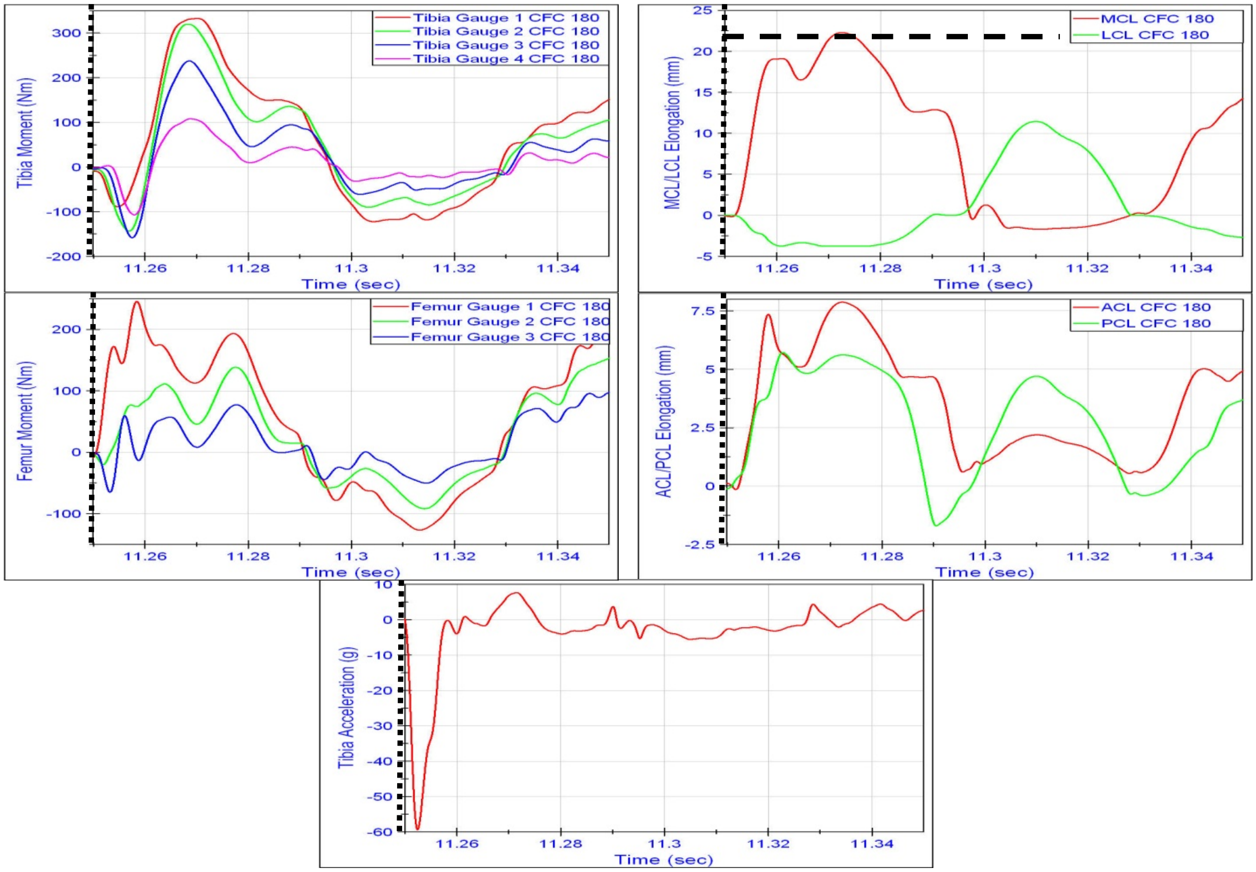


Figure 61. Flex-PLI time histories of the injury measures for the 2007 Chevrolet Silverado. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

2002 Honda Civic (Outboard)

Figure 62 shows screen captures at time of first contact and at maximum legform bending. Peak values for the 2002 Honda Civic tests are listed in Table 13 and time histories are shown in Figure 63. The Honda Civic exceeded the Tibia Moment, MCL, and ACL GTR limits.

Figure 62. 2002 Honda Civic impact at times of first contact (left) and maximum deflection (right).

Table 13. Flex-PLI peak injury measures for the 2002 Honda Civic; Outboard Impact.

Injury Measurement		Injury Reference Value (FlexTEG)	Honda Civic
Femur Moment (Nm)	**Femur 3 (Upper)**	N/A	122
	Femur 2 (Middle)		N/A*
	Femur 1 (Lower)		266
Tibia Moment (Nm)	**Tibia 1 (Upper)**	340 N-m (380 N-m)	475
	Tibia 2 (Mid Upper)		423
	Tibia 3 (Mid Lower)		266
	Tibia 4 (Lower)		127
MCL Elongation (mm)		22 mm	27.0
ACL Elongation (mm)		13 mm	14.8
PCL Elongation (mm)		13 mm	7.2
LCL Elongation (mm)		N/A	6.1
Tibia Acceleration (g)		N/A	-72

*Bad strain gauge

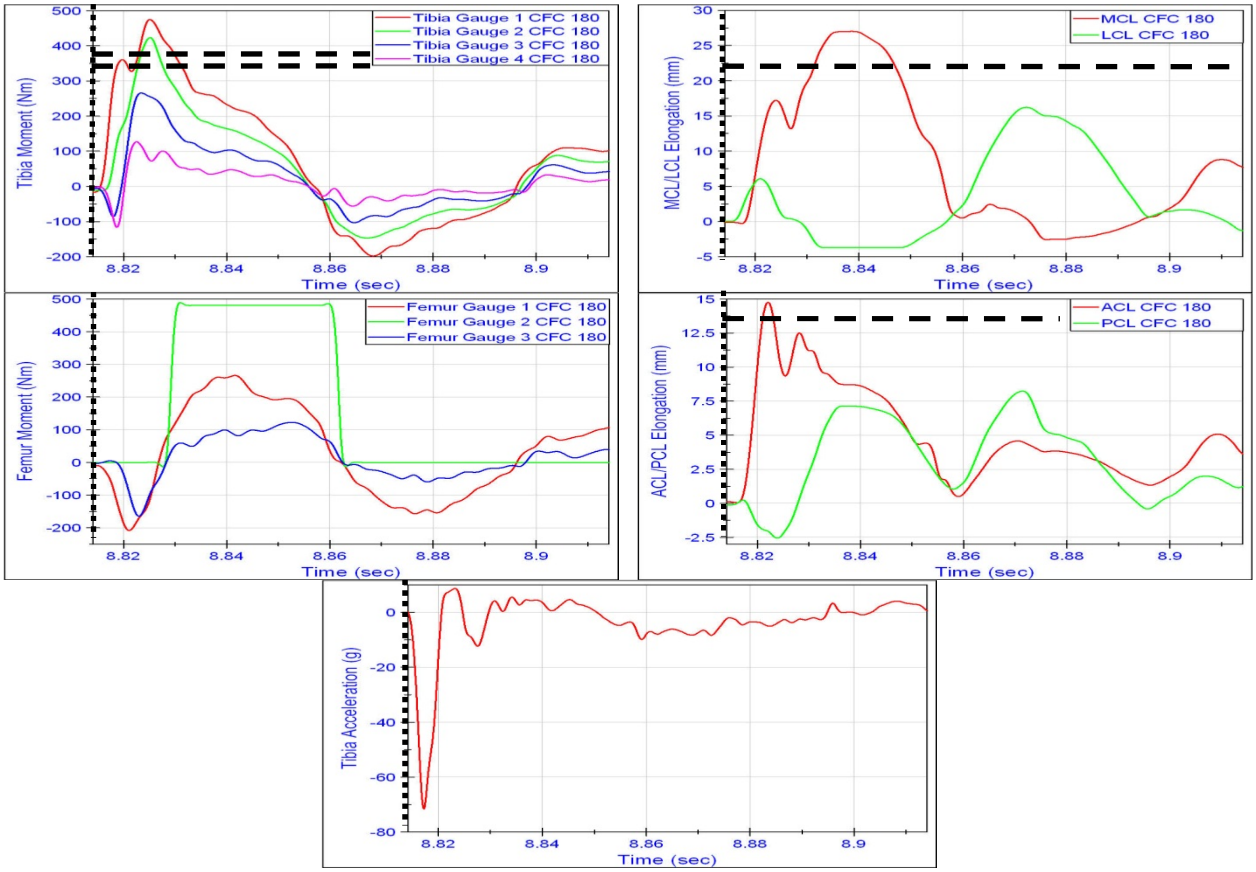


Figure 63. Flex-PLI time histories of the injury measures for the 2002 Honda Civic. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

2003 Honda Pilot (Center)

Figure 64 shows screen captures at time of first contact and at maximum legform bending. Peak values for the 2003 Honda Pilot tests are listed in Table 14 and time histories are shown in Figure 65. The Pilot exceeded the Tibia Moment, MCL, and ACL GTR limits.

Figure 64. 2003 Honda Pilot impact at times of first contact (left) and maximum deflection (right).

Table 14. Flex-PLI peak injury measures for the 2003 Honda Pilot; Center Impact.

Injury Measurement		**Injury Reference Value (FlexTEG)**	**Honda Pilot**
Femur Moment (Nm)	**Femur 3 (Upper)**	N/A	105
	Femur 2 (Middle)		198
	Femur 1 (Lower)		287
Tibia Moment (Nm)	**Tibia 1 (Upper)**	340 N-m (380 N-m)	402
	Tibia 2 (Mid Upper)		344
	Tibia 3 (Mid Lower)		256
	Tibia 4 (Lower)		124
MCL Elongation (mm)		22 mm	32.1
ACL Elongation (mm)		13 mm	15.5
PCL Elongation (mm)		13 mm	7.1
LCL Elongation (mm)		N/A	-3.7
Tibia Acceleration (g)		N/A	-67

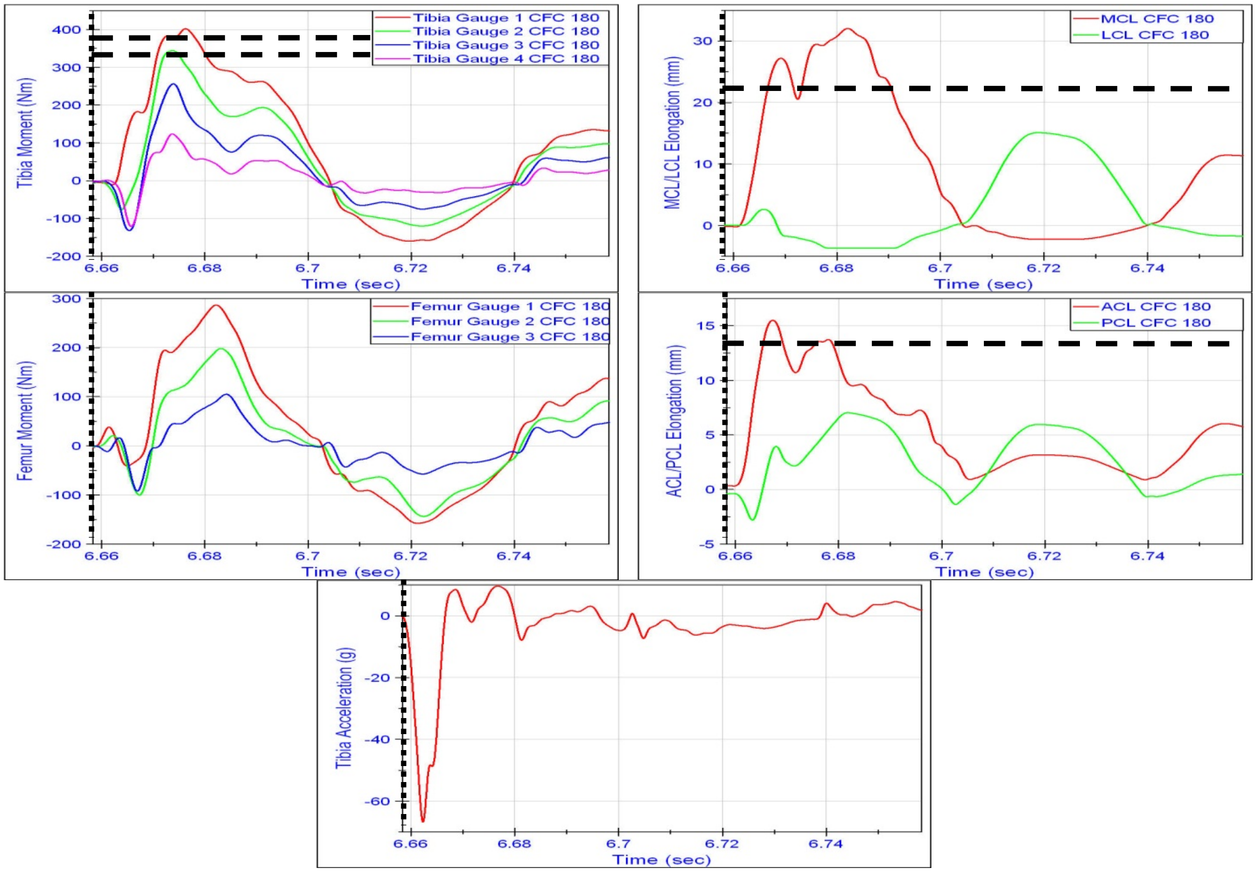


Figure 65. Flex-PLI time histories of the injury measures for the 2003 Honda Pilot. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

2002 Mazda Miata (Outboard)

Figure 66 shows screen captures at time of first contact and at maximum legform bending. Peak values for the 2002 Mazda Miata tests are listed in Table 15 and time histories are shown in Figure 67. The Mazda Miata exceeded the Tibia Moment, MCL, and ACL GTR limits.

Figure 66. 2002 Mazda Miata impact at times of first contact (left) and maximum deflection (right).

Table 15. Flex-PLI peak injury measures for the 2002 Mazda Miata; Outboard Impact.

Injury Measurement		**Injury Reference Value (FlexTEG)**	**Mazda Miata**
Femur Moment (Nm)	**Femur 3 (Upper)**	N/A	-153
	Femur 2 (Middle)		N/A*
	Femur 1 (Lower)		226
Tibia Moment (Nm)	**Tibia 1 (Upper)**	340 N-m (380 N-m)	460
	Tibia 2 (Mid Upper)		383
	Tibia 3 (Mid Lower)		299
	Tibia 4 (Lower)		163
MCL Elongation (mm)		22 mm	24.1
ACL Elongation (mm)		13 mm	14.3
PCL Elongation (mm)		13 mm	6.4
LCL Elongation (mm)		N/A	7.0
Tibia Acceleration (g)		N/A	-60

*Bad strain gauge

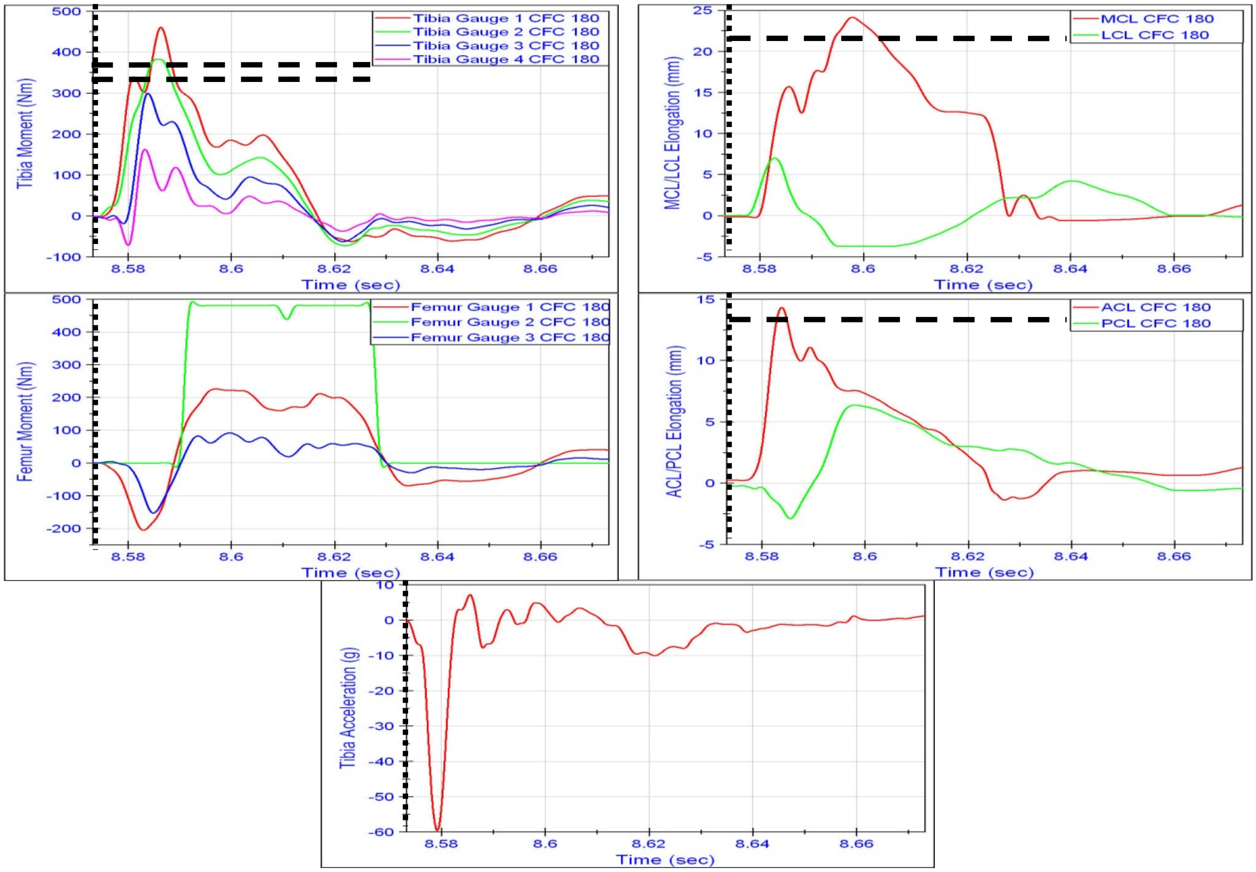


Figure 67. Flex-PLI time histories of the injury measures for the 2002 Mazda Miata. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

2006 Volkswagen Passat (Outboard)

Figure 68 shows screen captures at time of first contact and at maximum legform bending. Peak values for the 2006 Volkswagen Passat tests are listed in Table 16 and time histories are shown in Figure 69. The Volkswagen Passat exceeded the Tibia Moment, MCL, and ACL GTR limits.

Figure 68. 2006 Volkswagen Passat impact at times of first contact (left) and maximum deflection (right).

Table 16. Flex-PLI peak injury measures for the 2006 Volkswagen Passat; Outboard Impact.

Injury Measurement		**Injury Reference Value (FlexTEG)**	**Volkswagen Passat**
Femur Moment (Nm)	**Femur 3 (Upper)**	N/A	189
	Femur 2 (Middle)		382
	Femur 1 (Lower)		324
Tibia Moment (Nm)	**Tibia 1 (Upper)**	340 N-m (380 N-m)	428
	Tibia 2 (Mid Upper)		368
	Tibia 3 (Mid Lower)		277
	Tibia 4 (Lower)		156
MCL Elongation (mm)		22 mm	28.2
ACL Elongation (mm)		13 mm	13.9
PCL Elongation (mm)		13 mm	7.9
LCL Elongation (mm)		N/A	-3.8
Tibia Acceleration (g)		N/A	-84

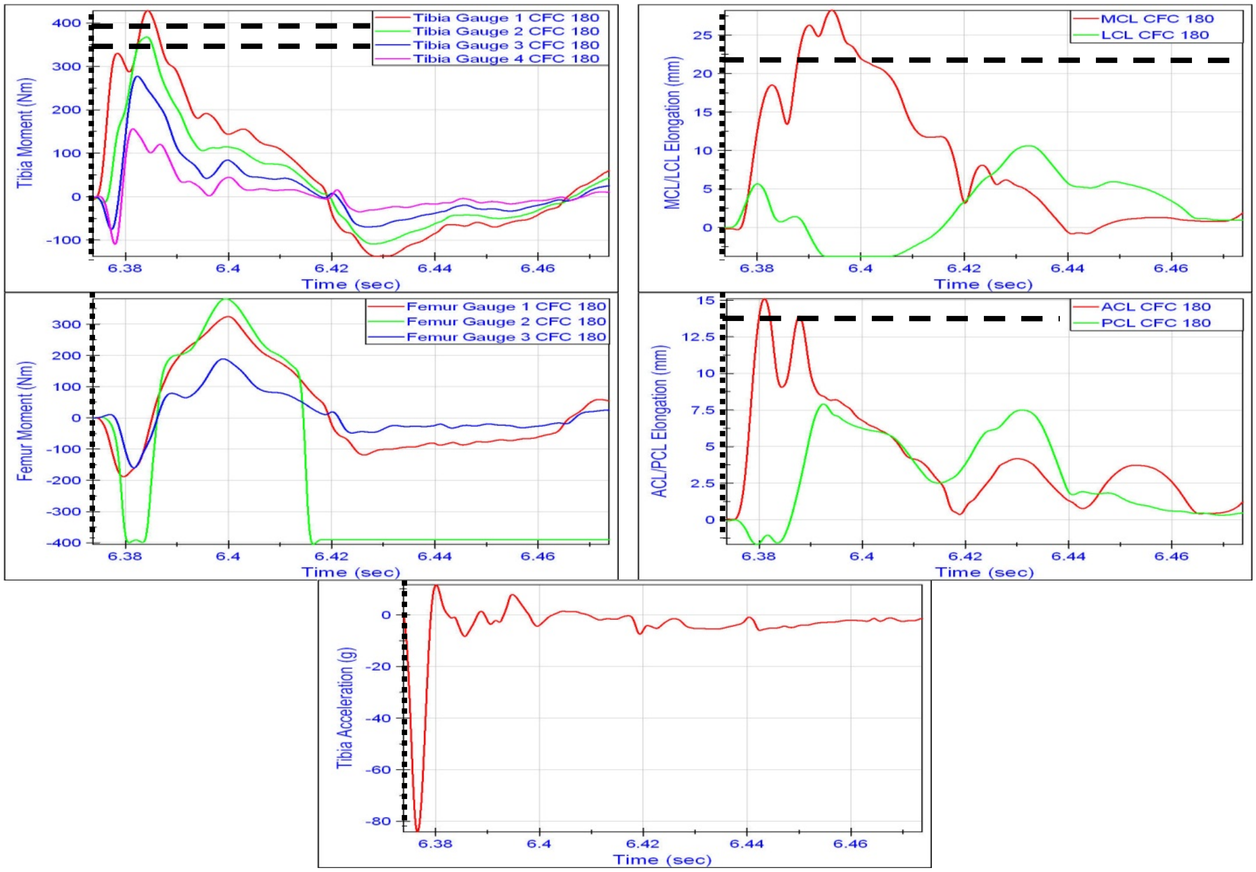
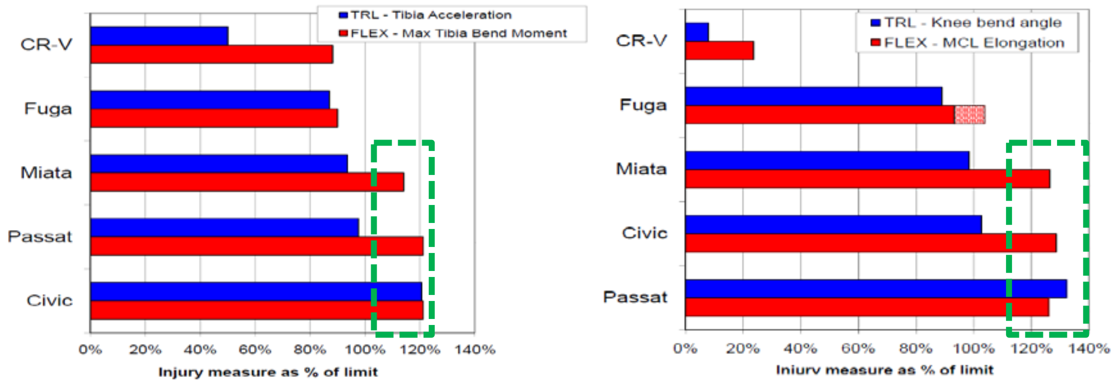


Figure 69. Flex-PLI time histories of the injury measures for the 2006 Volkswagen Passat. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

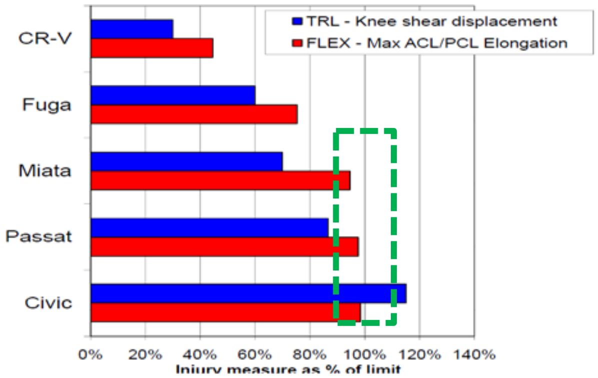
4.2. Flex-PLI Sensitivity for Non-GTR bumpers

In 2010, Mallory tested the centers of five vehicles with an early prototype version of the Flex-PLI that included the 2002 Miata, 2006 Passat, and 2002 Civic. The results of those tests are shown in Figure 70 below. Highlighted in green are the results for the Miata, Passat, and Civic. Notice that with the Flex-PLI (red bars), the three vehicles performed poorly and that the results for each vehicle are similar and seemed to reach a limit. For this reason, Mallory suggested that the instrumentation or allowable range of motion in the Flex-PLI may have been topping out and that the legform may not be able to distinguish marginally poor performing vehicles from poor performing vehicles. It is important for the Flex to discriminate between marginally poor and poor vehicle designs (be more sensitive) so that critical bumper design parameters can be identified for improving performance with respect to the legform injury limits. A comparison was made between Mallory's results and the results of the current series of testing to determine if the earlier Flex prototype had a topping out issue that has since been resolved or if the three vehicles just happened to be similar.



Fracture

Bend



Shear

Figure 70. Fracture, bend, and shear injury measure results of Mallory's 2010 testing.

The results of the additional testing on the bumper centers of the Passat, Miata, and Civic are presented in Figures 71-73. Bar plots for fracture injury measures, bending injury measures, and shear injury measures are shown and are plotted as a percentage of the Flex-PLI's injury limits. Notice that the resulting trends of the additional tests are similar to those of Mallory's 2010 results. The injury measures appear very similar among the three vehicles.

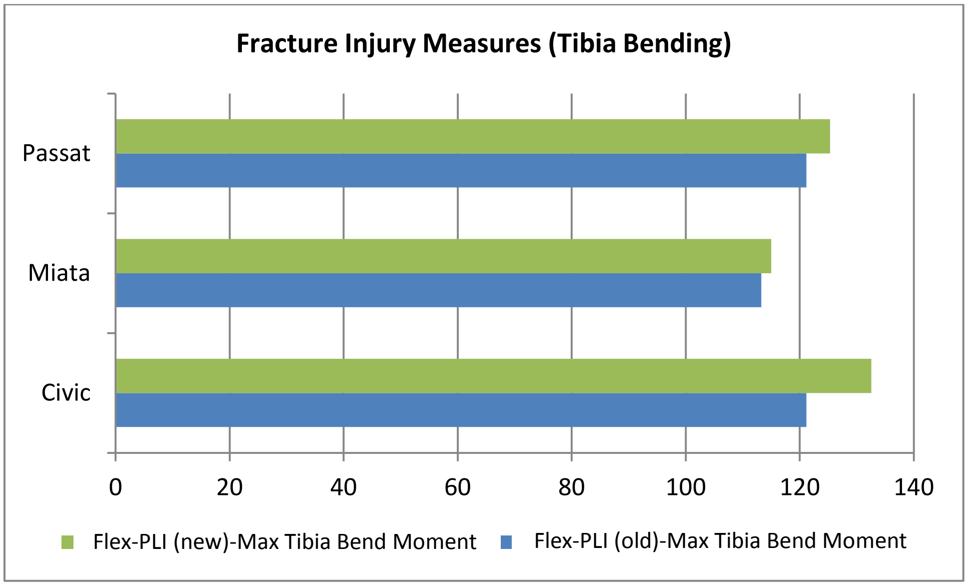


Figure 71. A comparison of fracture injury measures (tibia bending) with the Flex-PLI for the Passat, Miata, and Civic of the current test series (new) and Mallory's 2010 series (old) as a percentage of proposed GTR injury limit.

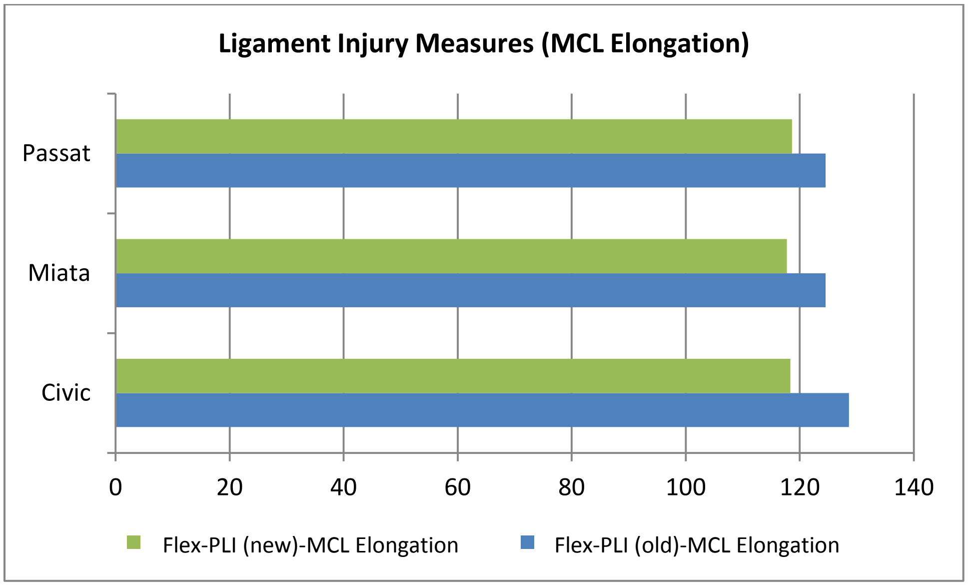


Figure 72. A comparison of ligament injury measures due to bending at the knee (MCL elongation) with the Flex-PLI for the Passat, Miata, and Civic of the current test series (new) and Mallory's 2010 series (old) as a percentage of proposed GTR injury limit.

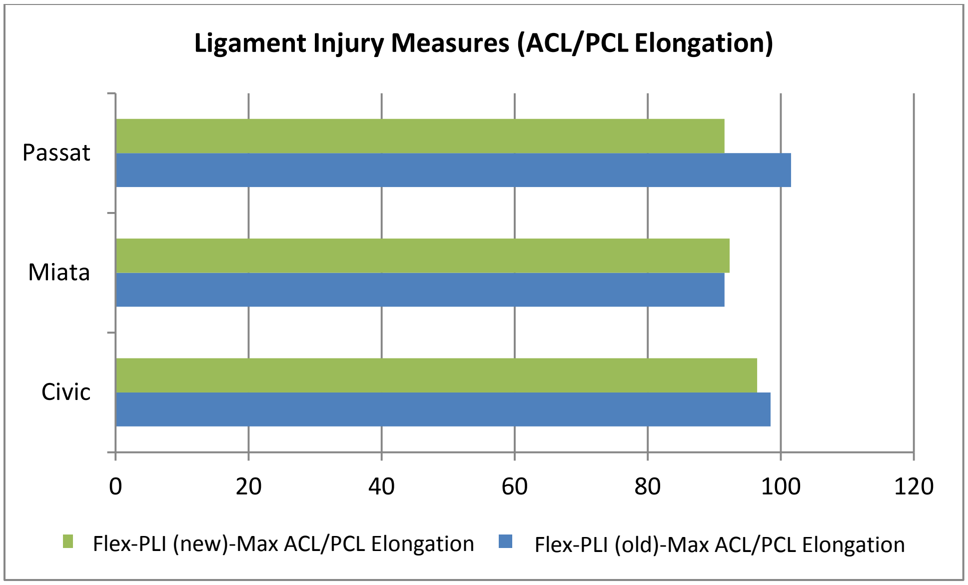


Figure 73. A comparison of ligament injury measures due to shearing at the knee (ACL/PCL elongation) with the Flex-PLI for the Passat, Miata, and Civic of the current test series (new) and Mallory's 2010 series (old) as a percentage of proposed GTR injury limit.

However, the results presented earlier in this study (center impacts on the larger vehicles and outboard passenger car impacts) show that the Flex-PLI can measure injury risk beyond what is shown in Figures 71 to 73. The Flex-PLI can measure up to at least 150% in bending injury (Equinox) and 120% in shear injury (Pilot). Therefore, it can be concluded that Mallory's testing and the current testing did not top out the Flex-PLI's measurement capabilities. Instead, the Miata, Passat, and Civic just happened to be vehicles that performed similarly at their bumper centers.

Mallory's 2010 tests used an earlier prototype of the Flex-PLI legform. The most up to date version of the Flex-PLI legform was used in the current series of tests. The only major difference between the two legforms is shown in Figure 74 below. Along the four edges of the tibia and femur are cables that span the length of the segment and prevent over-bending of the leg. A cable stop gap, which is highlighted in yellow in Figure 74, is specified in the Flex-PLI user manual. The stop gap distances for the latest version of the legform are 9.1 mm and 10.3 mm for the femur and tibia, respectively. The stop gap distance in the older version of the legform, the one used by Mallory, was 8 mm and 9 mm for the femur and tibia, respectively. Therefore, the cable stop gap has increased from the older version of the legform to the current version. It is believed that a stiffer bone core was introduced to add durability to the latest version of the Flex-PLI so an increased cable gap was applied to allow for more flex in the leg to counteract the stiffer core. The better discrimination of poorly performing impact points in the newer design is attributed to this increase in flexibility due to the cable gap revision.

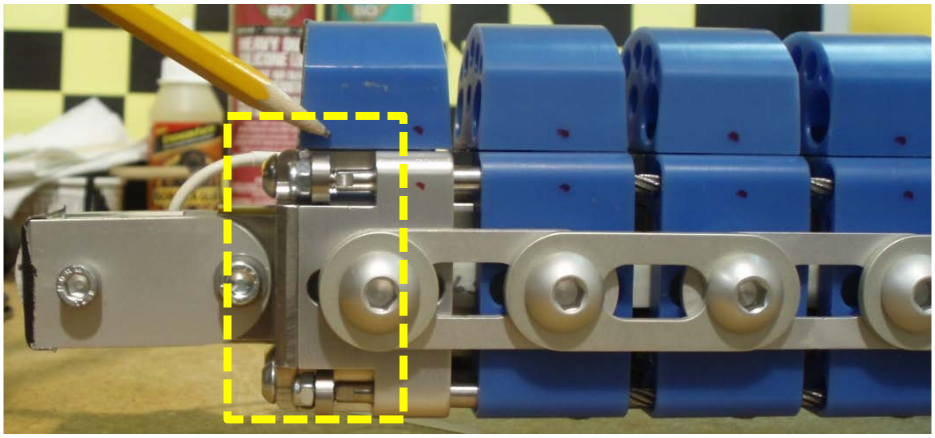


Figure 74. Cable stop gap on the femur portion of the Flex-PLI.

4.2.1.1. EEVC and Flex-PLI Comparison

Although the two legforms do not measure the same parameters, the different parameters are intended to measure similar injury risks. The tibia bending moment of the Flex-PLI and the tibia acceleration of the EEVC legform both correspond to fracture risk. Likewise, MCL elongation of the Flex-PLI and bending angle of the EEVC legform correspond to a collateral ligament injury risk due to bending of the knee. Lastly, the ACL/PCL elongation of the Flex-PLI and shear displacement of the EEVC legform correspond to a cruciate ligament injury risk due to shear loading of the knee. The same comparisons were made by Mallory et al. 2010. Bar plots for fracture injury measures and ligamentous injury measures due to lateral knee flexion and knee shear displacement are shown below in Figures 75 - 77 and are plotted as a percentage of the legforms' injury limits.

Primary type of Injury	Flex-PLI	Proposed IARV	EEVC	Proposed IARV
Tibia (bone) fracture	Tibia bending moment	340 Nm	Tibia acceleration	170 G
Ligamentous due to lateral knee flexion	MCL elongation	22 mm	Knee bending angle	19 deg
Ligamentous due to knee shear displacement	ACL/PCL elongation	13 mm	Knee shear displacement	6 mm

For fracture injury risk (Figure 75), the Silverado had the lowest injury measurement with the Flex-PLI, but the Equinox was the only vehicle to fall below the injury limits of both legforms. In all vehicles but the Equinox, the EEVC predicted a higher injury risk, relative to the limits, than the Flex-PLI. In addition, the two legforms rank the vehicles differently in terms of fracture protection.

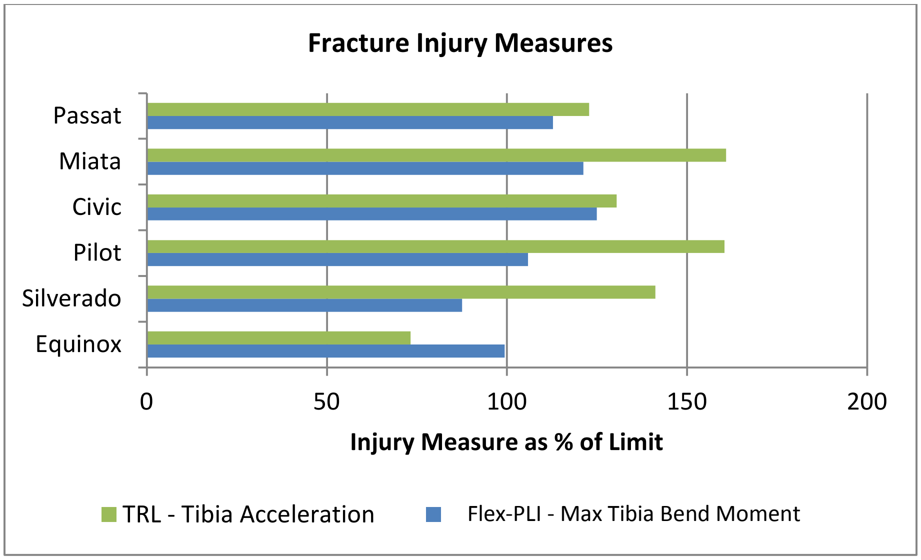


Figure 75. Fracture injury measures for each vehicle by both legforms as a percentage of proposed GTR injury limit.

For ligamentous injury risk due to lateral knee flexion (Figure 76), all vehicles exceeded the injury limits of both legs, although the Silverado was close at 101%. In all vehicles, the EEVC predicted a much higher injury risk, relative to the limits, than the Flex-PLI. Again, the two legforms rank the vehicles differently in terms of bending performance.

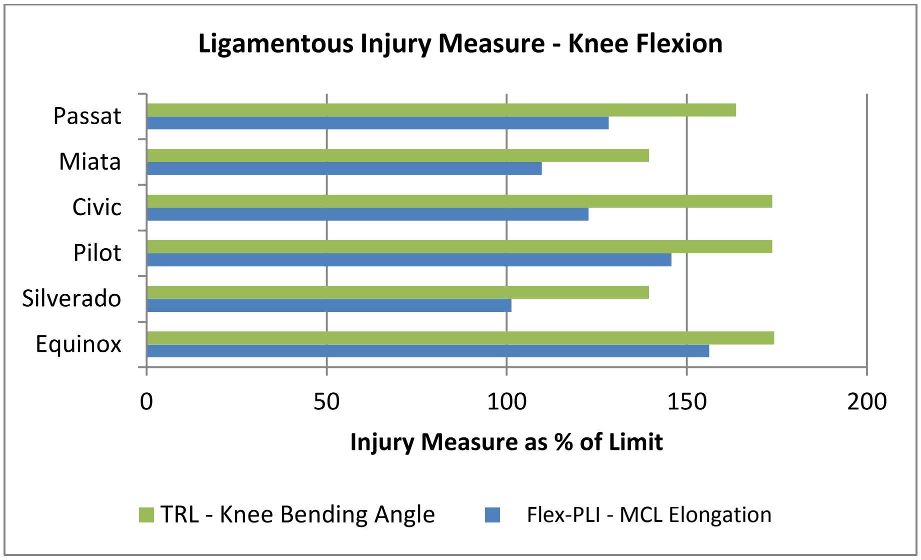


Figure 76. Bending injury measures for each vehicle by both legforms as a percentage of proposed GTR injury limit.

Lastly, for ligamentous injury risk due to shear displacement of the knee (Figure 77), all vehicles exceed the injury limits with the EEVC, but fell below the injury limits with the Silverado and Equinox with Flex-PLI. At 60%, the Silverado was much lower with the Flex-PLI than the other vehicles. As with the previous measures, the EEVC predicted a much higher injury risk than the Flex-PLI and the two legforms rank the vehicles differently.

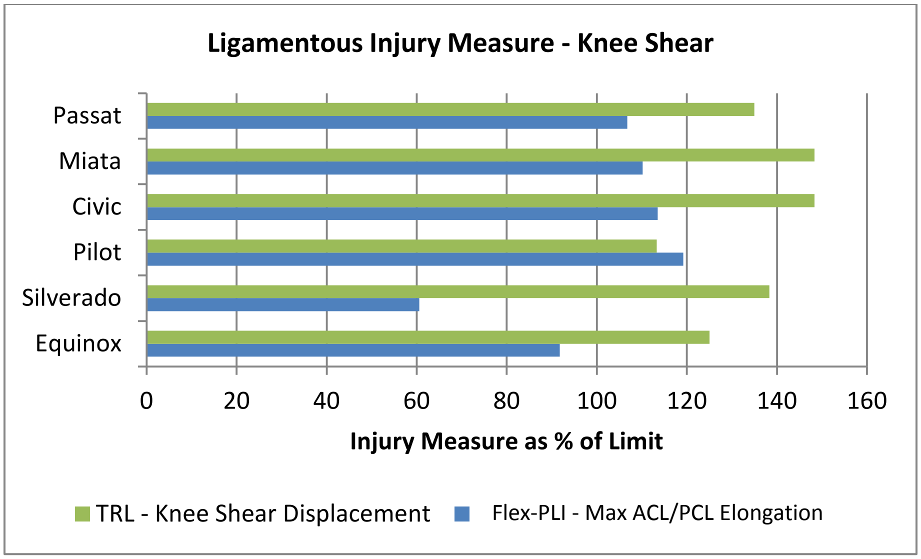


Figure 77. Shear injury measures for each vehicle by both legforms as a percentage of proposed GTR injury limit.

Flex-PLI results versus the EEVC results as a percentage of their respective injury limits are shown in Figures 78 to 80. If both legforms measured the same percentage of injury for a given vehicle, the data would lie along the diagonal. However, the results of this series of tests do not. In fact, a majority of the data points lie to the right of the diagonal, which indicates that the EEVC legform predicted greater injury risk than the Flex-PLI. The plots can also be used to determine vehicle rank as predicted by two legforms. From left to right, along the x-axis, are the least severe to most severe vehicles as predicted by the EEVC. From bottom to top, along the y-axis, are the least severe to most severe vehicles as predicted by the Flex-PLI. Note that each legform on its own ranks the vehicles differently depending on the injury measure.

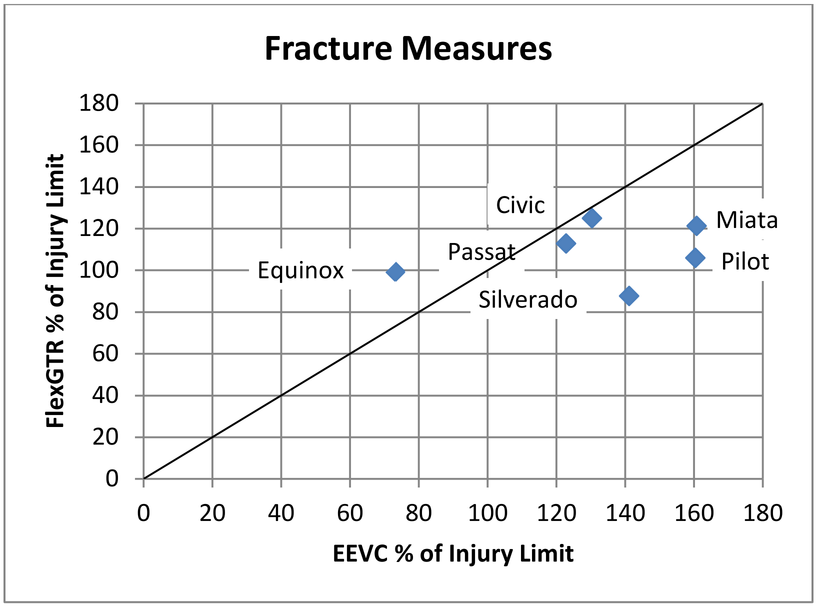


Figure 78. Flex-PLI versus EEVC as a percentage of the injury limit for fracture injury measures.

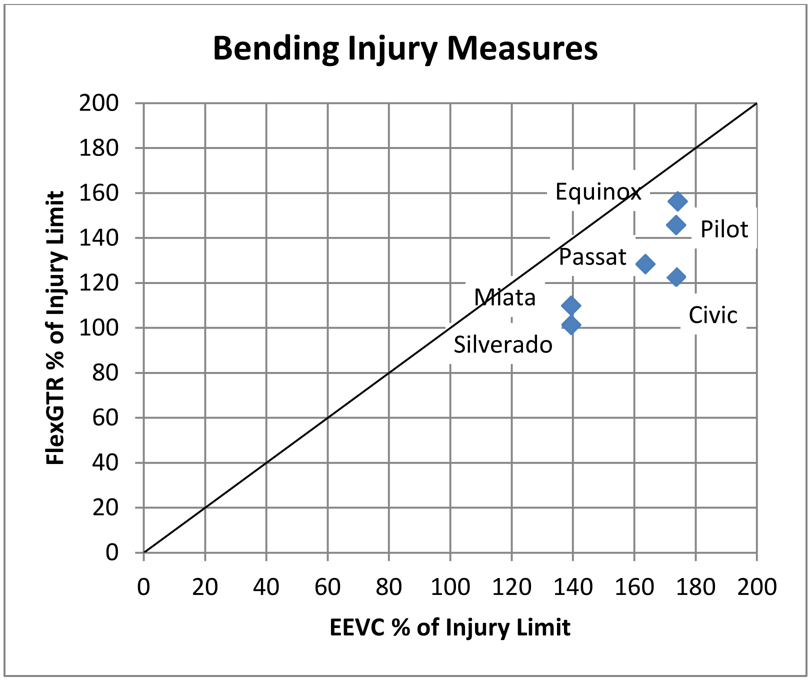


Figure 79. Flex-PLI versus EEVC as a percentage of the injury limit for bending injury measures.

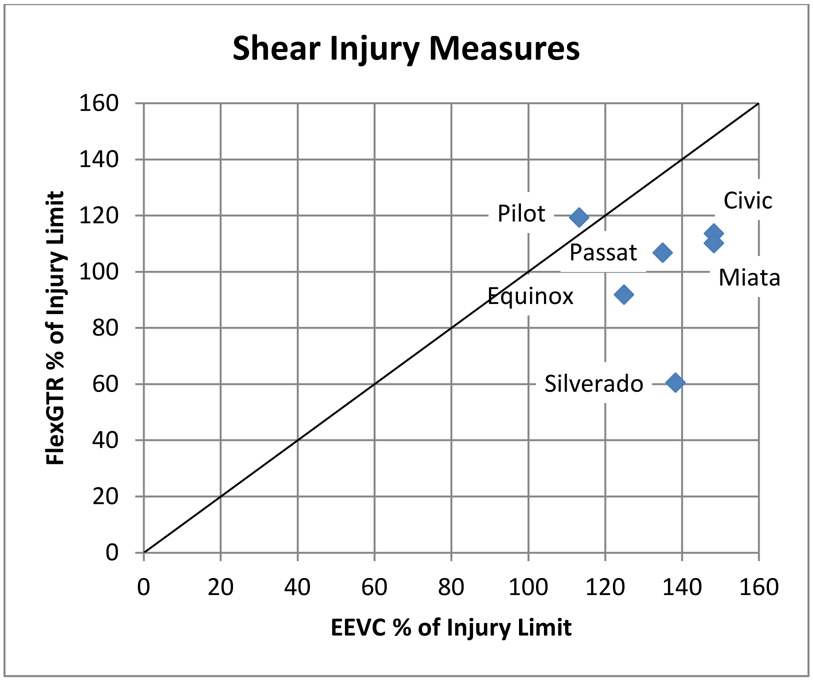


Figure 80. Flex-PLI versus EEVC as a percentage of the injury limit for shear injury measures.

To summarize, the EEVC and Flex-PLI legforms rank the vehicles differently in terms of performance, which is likely a result of differences in biofidelity and also what is measured in each legform. Since the legforms measure different parameters, it is unclear whether this comparison can be made. It was also observed that, with a few exceptions, the EEVC predicted a higher injury risk than the Flex-PLI. However, the Flex-PLI may be able to better differentiate marginally poor performing vehicles from poor performing vehicles based on the wider range of results than the EEVC legform.

4.3. Flex-PLI Identification of GTR-Compliant Bumper Systems

To better understand the bumper design factors associated with good pedestrian performance, “global platform” vehicles were identified in the U.S. fleet for testing with the Flex-PLI. These vehicles have identical external bumper areas and are sold in both U.S. and overseas markets; the differences lie in the internal components which are designed to meet (a) pedestrian protection requirements overseas, (b) bumper damageability requirements in North America, or (c) both of those requirements in a single bumper system.

The following vehicles were identified as candidates for testing:

- MY 2006 Volkswagen Passat
- MY 2011 Chevrolet Cruze
- MY 2012 Ford Focus
- MY 2013 Ford Fusion
- MY 2010 Toyota Yaris
- MY 2011 Jeep Grand Cherokee
- MY 2011 Honda Odyssey

All of the vehicles on this list with the exception of the Odyssey were identified as “global platform” vehicles where different bumper configurations could be tested. The Odyssey was tested to evaluate how a minivan bumper system is configured, and the Grand Cherokee was included as a high bumper vehicle. Only the passenger cars on this list are required to meet Part 581 damageability criteria.

Testing was conducted on various bumper configurations for the vehicles listed above using standard GTR9 test conditions. Those bumper configurations included (1) the North American market configuration (denoted as “NA”) that generally included a stiff energy absorber and a less prevalent undertray component, (2) an overseas market configuration (denoted as “EU”) with a softer energy absorber and load bearing undertray to help distribute pedestrian legform loading, and (3) a hybrid system that included both NA and EU lower bumper stiffener (LBS) components (denoted as “NA w/EU LBS”) in an effort to develop a system that could perform well in both pedestrian GTR and Part 581 damageability test conditions. The test matrix is shown in Table 17 below:

Table 17. Test Matrix.

Vehicle	Bumper System	Bumper Location
2006 Volkswagen Passat	NA (3 legforms)	Center
	EU	Center
	NA w/EU LBS	Center
2011 Chevrolet Cruze	NA	Center
	EU	Center
	NA w/EU LBS	Center
2013 Ford Fusion	NA	Center
	NA	Passenger Outboard
	NA	Driver Outboard
2012 Ford Focus	NA	Center
	EU	Center
2010 Toyota Yaris	NA	Center
	EU	Center
	NA w/EU LBS	Center
2011 Jeep Grand Cherokee	NA (3 repeats)	Center
	NA w/EU LBS	Center
2011 Honda Odyssey	NA	Center
	NA w/EU LBS*	Center
"Center" refers to vehicle longitudinal centerline		
"Outboard" refers to extreme edge of bumper test area		
*Lower bumper stiffener for the Odyssey was from a Citroen, since no EU version of the Odyssey LBS		

4.3.1. Results: Flex-PLI Testing on EU, NA, & hybrid bumper systems

4.3.1.1. NA Only

2013 Ford Fusion

The 2013 North American Ford Fusion contained a modular energy absorber along with an undertray that resembled many of the EU lower leg support systems for good pedestrian performance (Figure 81). Figures 82 and 83 show screen captures at time of first contact and at maximum legform bending, in center and outboard impacts. Table 18 shows the measurements in each of those impact locations. Figures 84 - 86 show the time history data from the Fusion tests.

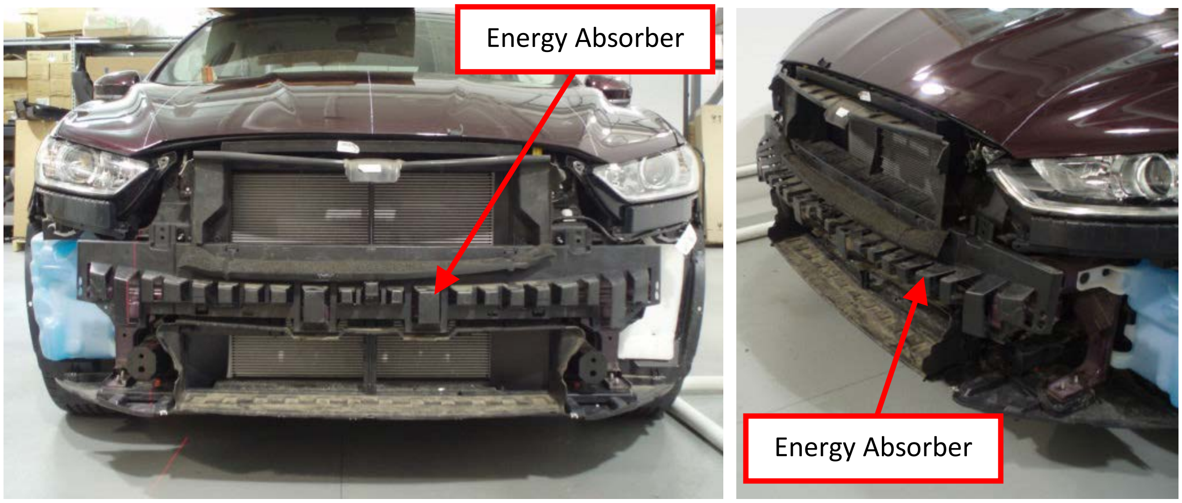


Figure 81. Views of the 2013 Ford Fusion with North American front bumper components.

Figure 82. 2013 Ford Fusion center impact at times of first contact (left) and maximum deflection (right).

Figure 83. 2013 Ford Fusion outboard impact at times of first contact (left) and maximum deflection (right).

Table 18. Flex-PLI peak injury measures for the 2013 North American Ford Fusion center and outboard impacts.

Injury Measurement		Injury Reference Value (FlexTEG)	Bumper Configuration		
			NA - Center	NA – Outboard (Passenger)	NA – Outboard (Driver)
Femur Moment (Nm)	Femur 3 (Upper)	N/A	190	152	161
	Femur 2 (Middle)		251	213	232
	Femur 1 (Lower)		217	189	200
Tibia Moment (Nm)	Tibia 1 (Upper)	340 N-m (380 N-m)	250	177	184
	Tibia 2 (Mid Upper)		223	151	135
	Tibia 3 (Mid Lower)		162	118	105
	Tibia 4 (Lower)		104	81	80
MCL Elongation (mm)		22 mm	18.0	14.6	15.1
ACL Elongation (mm)		13 mm	7.2	6.7	7.4
PCL Elongation (mm)		13 mm	6.3	4.5	--*
LCL Elongation (mm)		N/A	14.7	13.7	12.4
Tibia Acceleration (g)		N/A	132	117	117
*An error occurred in the PCL measurement of the driver side outboard impact					

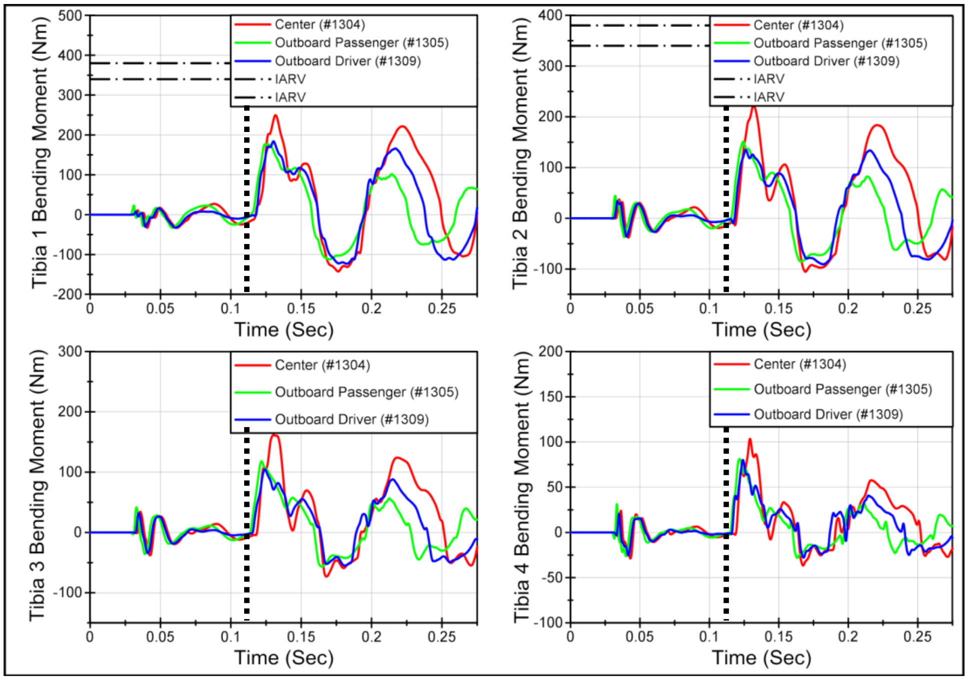


Figure 84. Tibia bending moment time histories for the 2013 North American Ford Fusion center (red), outboard passenger side (green), and outboard driver side (blue) impacts. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

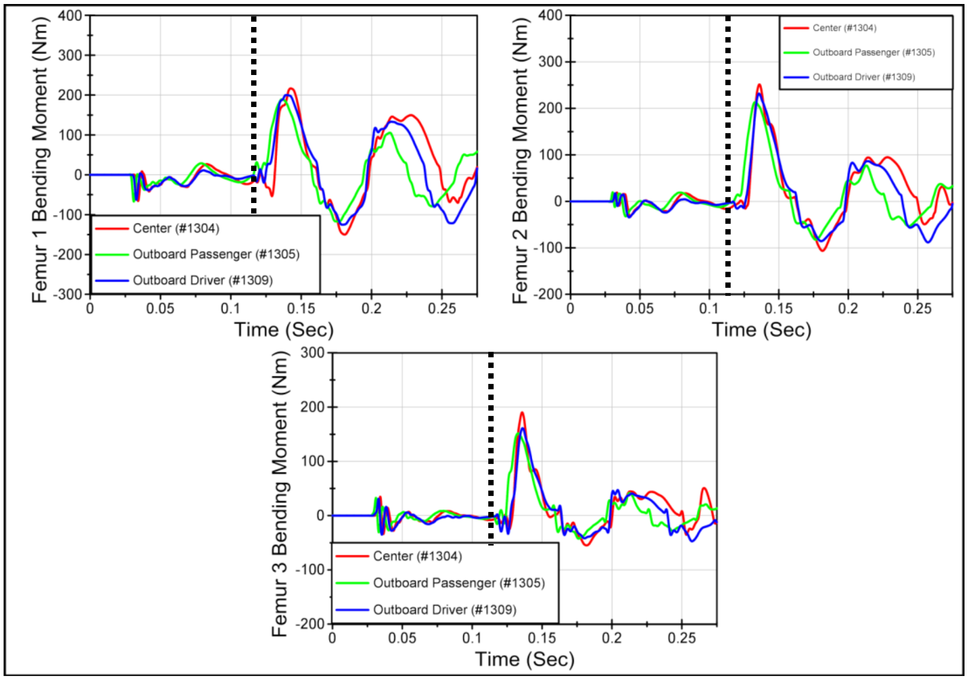


Figure 85. Femur bending moment time histories for the 2013 North American Ford Fusion center (red) and outboard (green) impacts. Dotted vertical lines show the time of first contact.

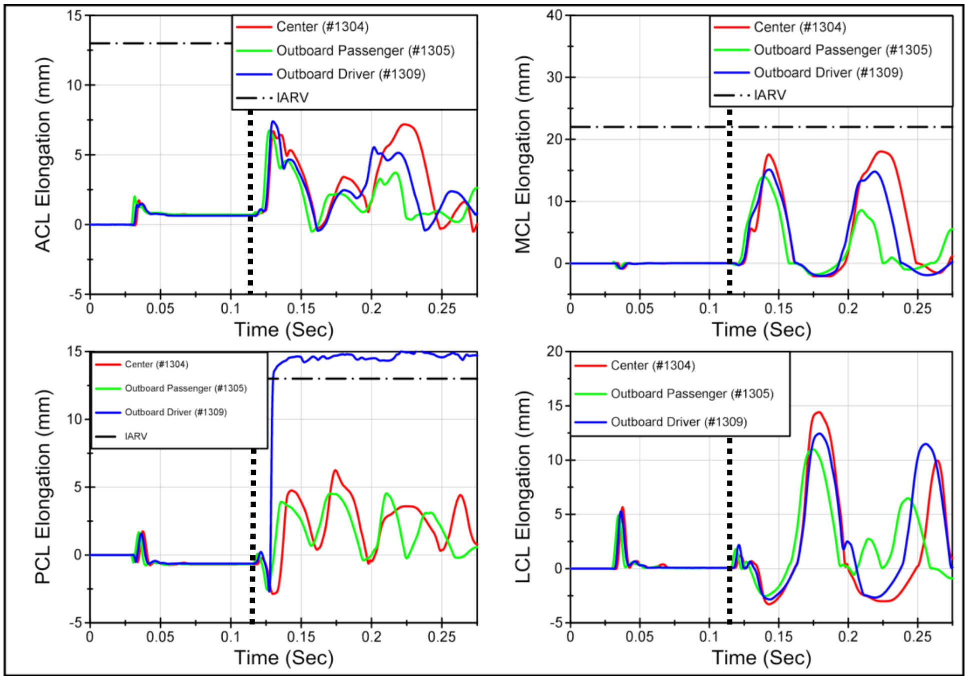


Figure 86. Ligament elongation time histories for the 2013 North American Ford Fusion center (red) and outboard (green) impacts. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

4.3.1.2. NA vs EU vs Hybrid

2011 Chevrolet Cruze

The 2011 Chevrolet Cruze NA system contained a foam energy absorber, the EU system contained a softer energy absorber along with lower bumper stiffener, and the “hybrid” system utilized the NA absorber with the EU lower bumper stiffener (Figures 87-88). Figures 89-91 show screen captures at time of first contact and at maximum legform bending, in the center bumper location. Table 19 shows the Flex-PLI results, and Figures 92-94 show the time histories of each bumper version. The NA and EU versions of the Chevrolet Cruze were tested by Shape Corp. (Grand Haven, MI) as part of a cooperative agreement.

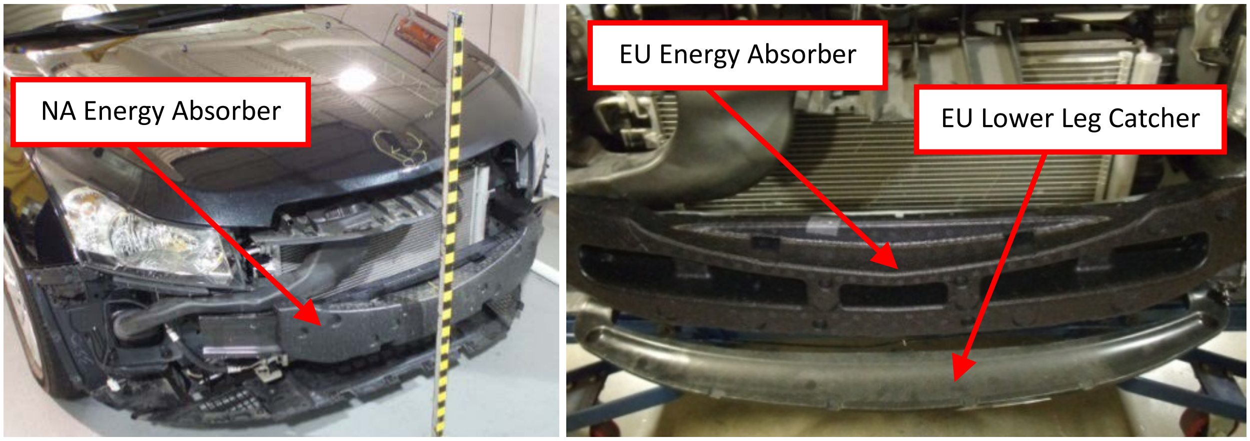


Figure 87. Views of the 2011 Chevrolet Cruze with North American front bumper components (left) and European front bumper components (right).

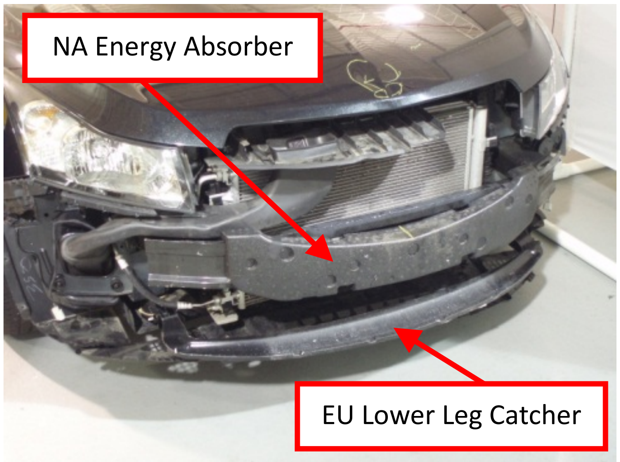


Figure 88. View of the “hybrid” 2011 Chevrolet Cruze with a North American energy absorber and European lower bumper stiffener.

Figure 89. 2011 North American Chevrolet Cruze impact at times of first contact (left) and maximum deflection (right). The NA Chevrolet Cruze was tested by Shape Corp. (Grand Haven, MI).

Figure 90. 2011 European Chevrolet Cruze impact at times of first contact (left) and maximum deflection (right). The EU Chevrolet Cruze was tested by Shape Corp. (Grand Haven, MI).

Figure 91. 2011 Hybrid Chevrolet Cruze impact at times of first contact (left) and maximum deflection (right). The Hybrid Chevrolet Cruze was tested at VRTC.

Table 19. Flex-PLI peak injury measures for the 2011 North American, European, and “Hybrid” Chevrolet Cruze.

Injury Measurement		**Injury Reference Value (FlexTEG)**	**Bumper Configuration**		
			NA	**EU**	**Hybrid**
Femur Moment (Nm)	**Femur 3 (Upper)**	N/A	192	152	220
	Femur 2 (Middle)		328	291	313
	Femur 1 (Lower)		305	274	297
Tibia Moment (Nm)	**Tibia 1 (Upper)**	340 N-m (380 N-m)	336	197	297
	Tibia 2 (Mid Upper)		360	208	336
	Tibia 3 (Mid Lower)		276	208	284
	Tibia 4 (Lower)		198	192	136
MCL Elongation (mm)		22 mm	13.9	11.2	15.0
ACL Elongation (mm)		13 mm	6.0	3.7	8.9
PCL Elongation (mm)		13 mm	4.9	3.9	4.5
LCL Elongation (mm)		N/A	9.1	7.8	13.8
Tibia Acceleration (g)		N/A	167	115	209

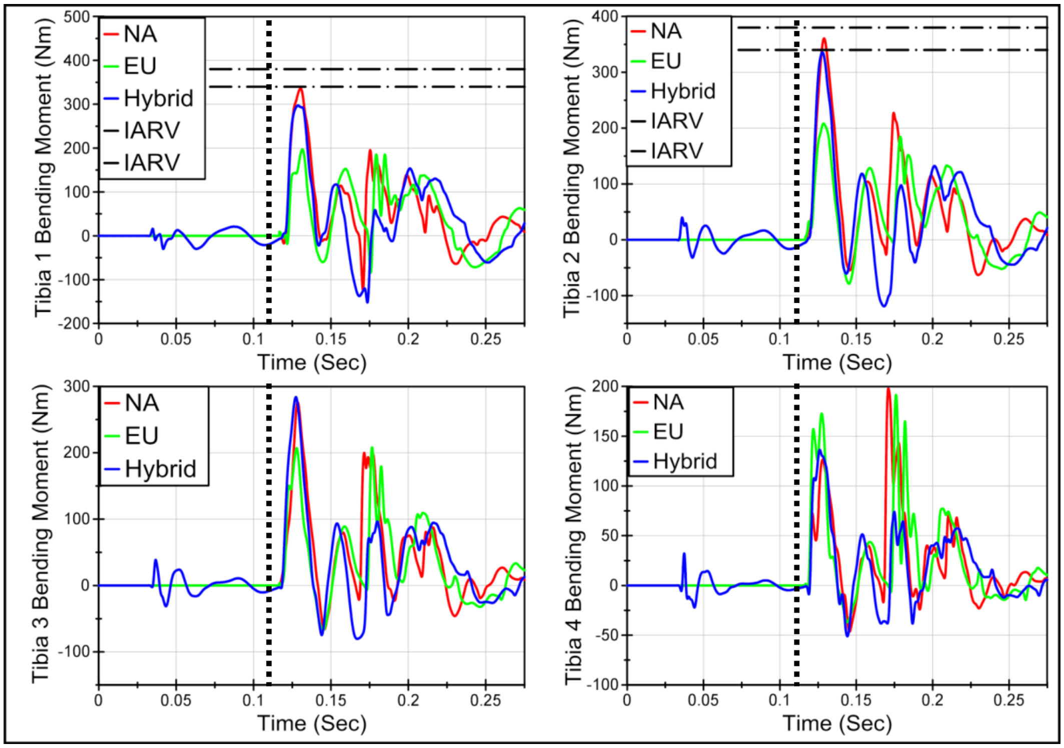


Figure 92. Tibia bending moment time histories for the 2011 Chevrolet Cruze with North American (red), European (green), and hybrid (blue) bumper components. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

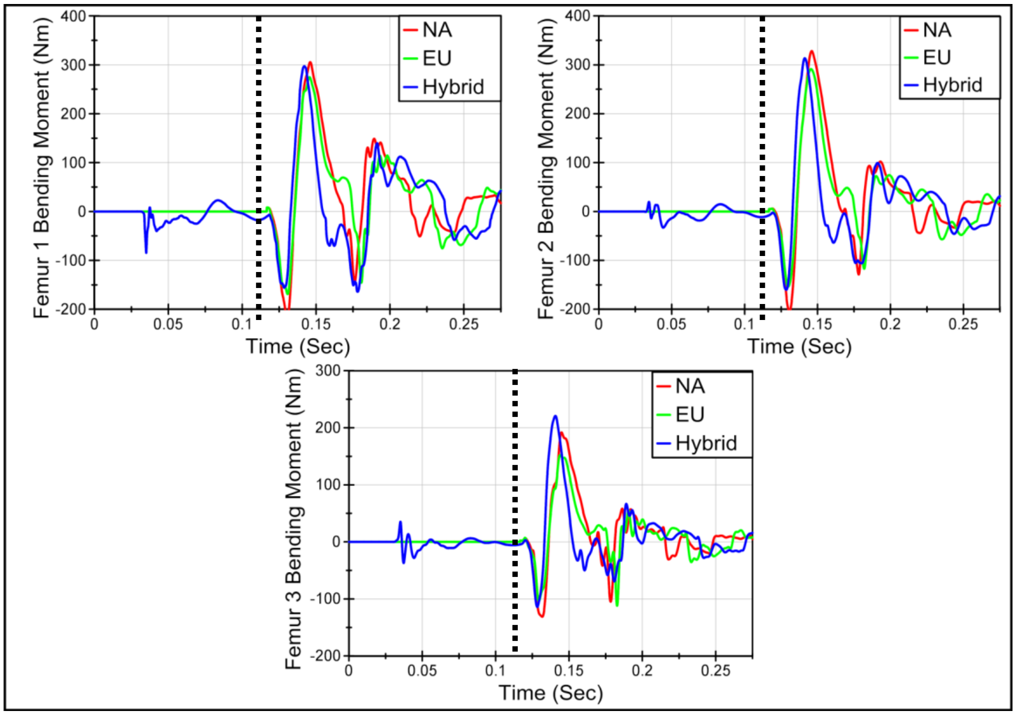


Figure 93. Femur bending moment time histories for the 2011 Chevrolet Cruze with North American (red), European (green), and hybrid (blue) bumper components. Dotted vertical lines show the time of first contact.

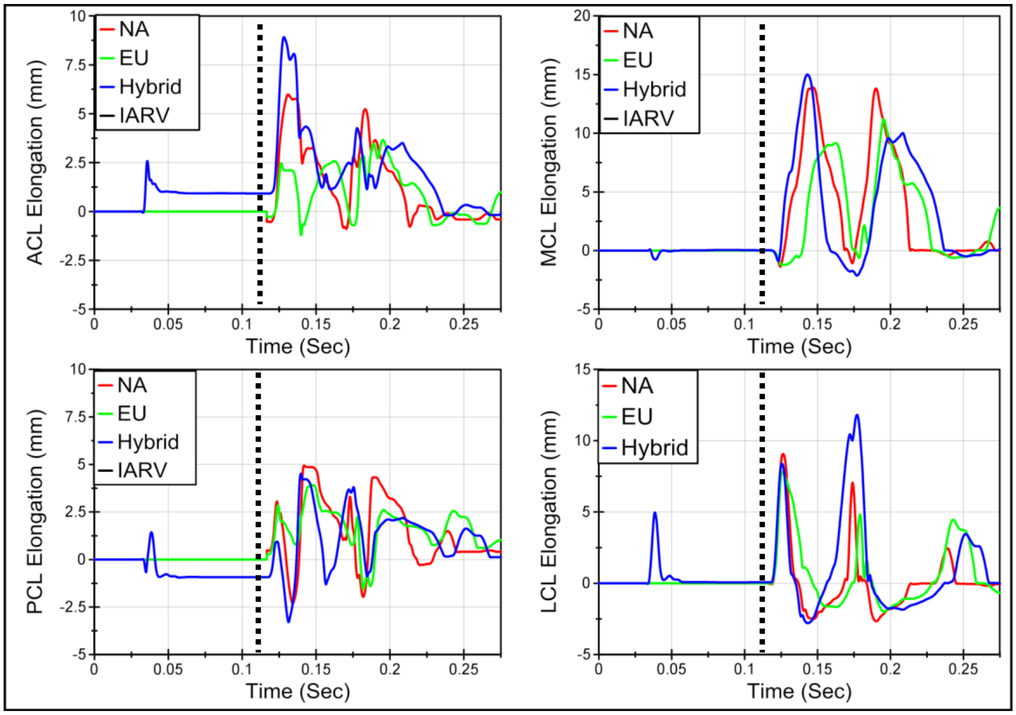


Figure 94. Ligament elongation time histories for the 2011 Chevrolet Cruze with North American (red), European (green), and hybrid (blue) bumper components. Dotted vertical lines show the time of first contact.

2010 Toyota Yaris

The 2010 Toyota Yaris NA system contained no energy absorber, the EU system contained a softer bumper beam structure along with lower bumper stiffener, and the "hybrid" system utilized the NA beam with the EU lower bumper stiffener (Figures 95-96). Figures 97-99 show screen captures at time of first contact and at maximum legform bending, in the center bumper location. Table 20 shows the Flex-PLI results, and Figures 100-102 show the time histories of each bumper version.

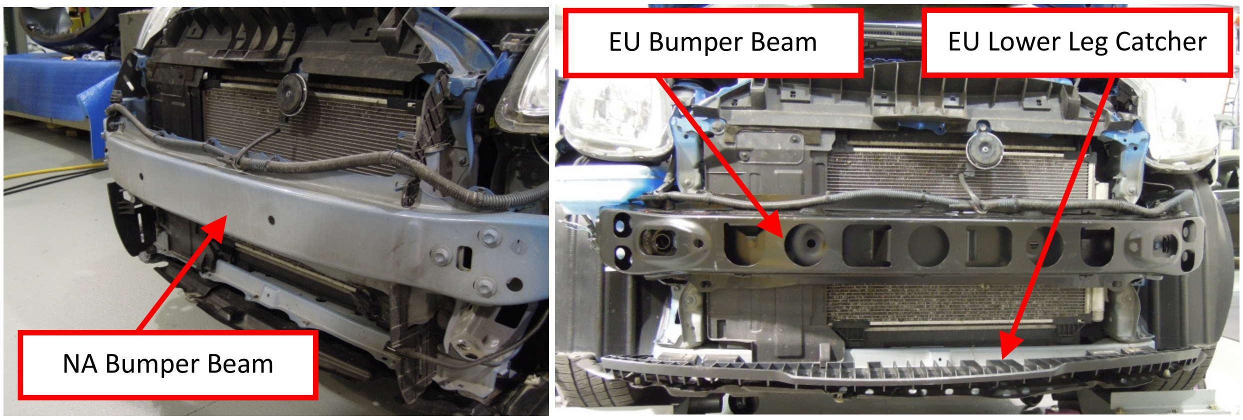


Figure 95. Views of the 2010 Toyota Yaris with North American front bumper components (left) and European front bumper components (right).

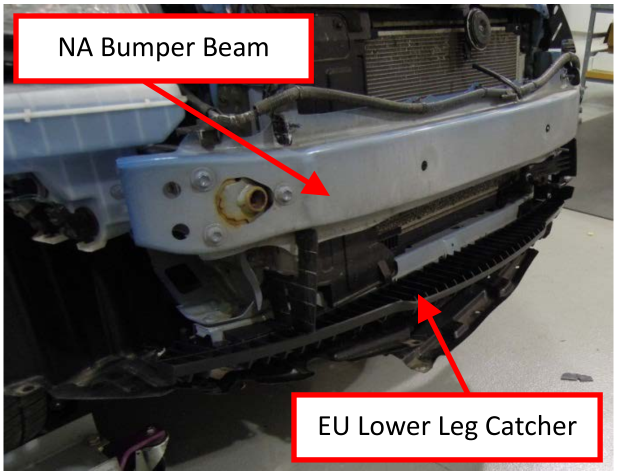


Figure 96. View of the "hybrid" 2010 Toyota Yaris with a North American bumper beam and European lower bumper stiffener.

Figure 97. 2010 North American Toyota Yaris impact at times of first contact (left) and maximum deflection (right).

Figure 98. 2010 European Toyota Yaris impact at times of first contact (left) and maximum deflection (right).

Figure 99. 2010 Hybrid Toyota Yaris impact at times of first contact (left) and maximum deflection (right).

Table 20. Flex-PLI peak injury measures for the 2010 North American, European, and “Hybrid” Toyota Yaris.

Injury Measurement		**Injury Reference Value (FlexTEG)**	**Bumper Configuration**		
			NA	**EU**	**Hybrid**
Femur Moment (Nm)	**Femur 3 (Upper)**	N/A	220	164	203
	Femur 2 (Middle)		328	215	309
	Femur 1 (Lower)		362	245	342
Tibia Moment (Nm)	**Tibia 1 (Upper)**	340 N-m (380 N-m)	407	258	348
	Tibia 2 (Mid Upper)		370	225	266
	Tibia 3 (Mid Lower)		249	171	200
	Tibia 4 (Lower)		139	118	135
MCL Elongation (mm)		22 mm	32.9	18.6	25.5
ACL Elongation (mm)		13 mm	14.0	7.8	12.9
PCL Elongation (mm)		13 mm	8.2	6.3	6.5
LCL Elongation (mm)		N/A	22.6	16.6	17.5
Tibia Acceleration (g)		N/A	337	168	334

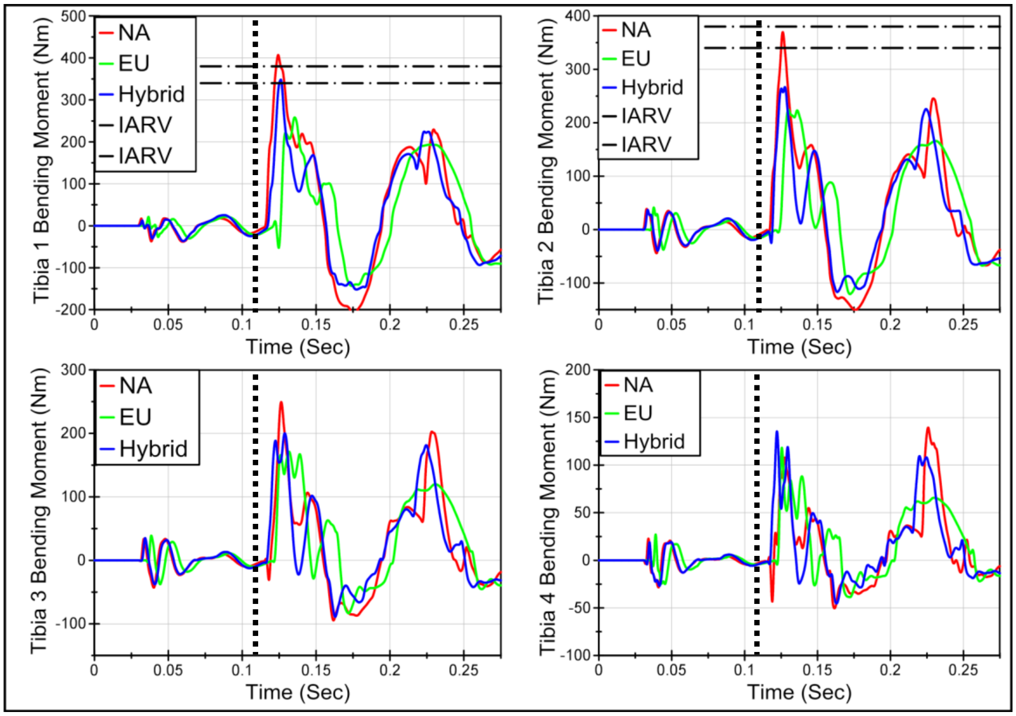


Figure 100. Tibia bending moment time histories for the 2010 Toyota Yaris with North American (red), European (green), and hybrid (blue) bumper components. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

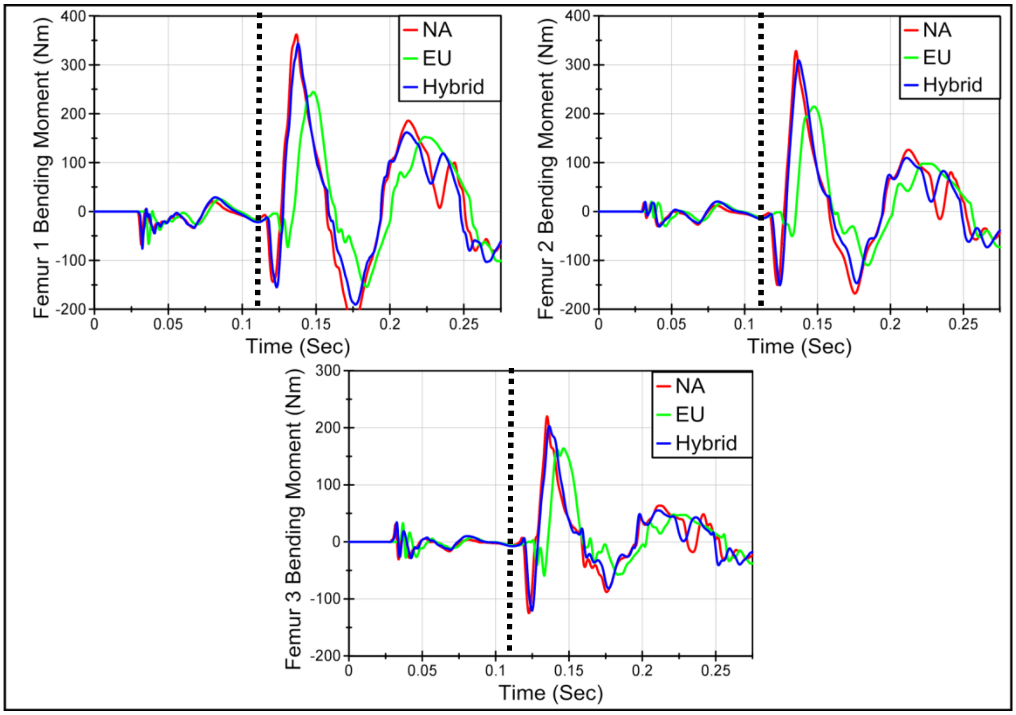


Figure 101. Femur bending moment time histories for the 2010 Toyota Yaris with North American (red), European (green), and hybrid (blue) bumper components. Dotted vertical lines show the time of first contact.

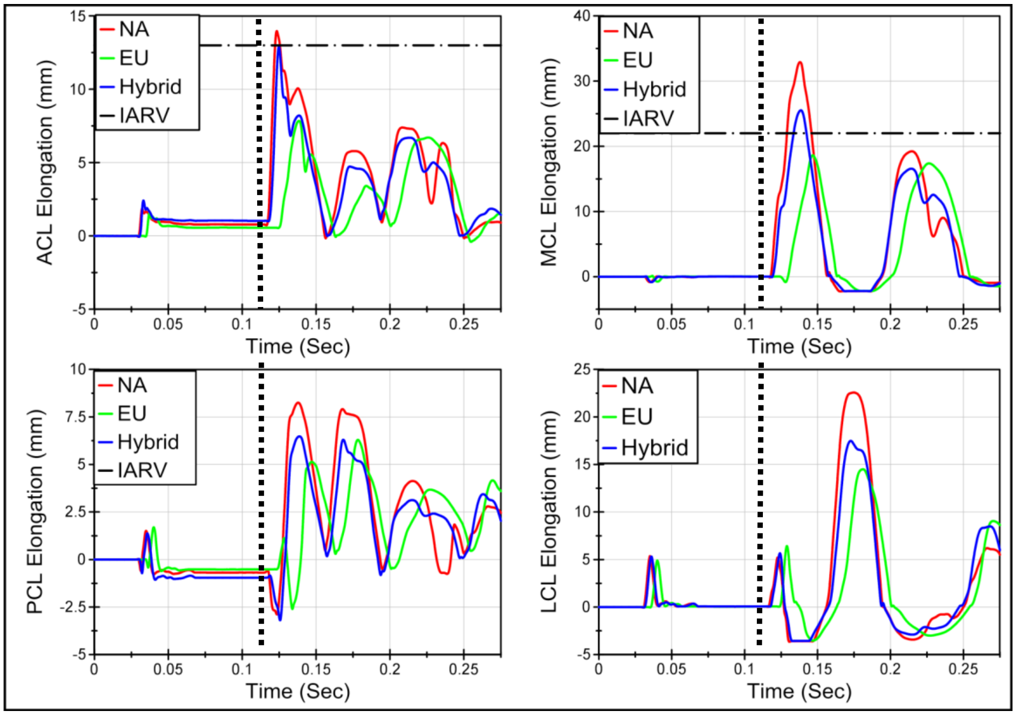


Figure 102. Ligament elongation time histories for the 2010 Toyota Yaris with North American (red), European (green), and hybrid (blue) bumper components. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

2006 Volkswagen Passat

The 2006 Volkswagen Passat NA system contained a stiff foam energy absorber, the EU system contained a softer energy absorber along with lower bumper stiffener, and the “hybrid” system utilized the NA foam with the EU lower bumper stiffener (Figures 103-104). Figures 105-107 show screen captures at time of first contact and at maximum legform bending, in the center bumper location. Table 21 shows the Flex-PLI results, and Figures 108-109 show the time histories of each bumper version.

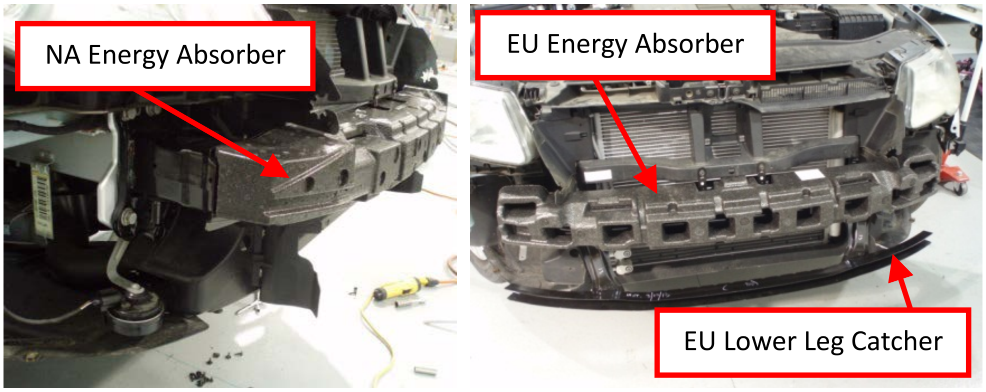


Figure 103. Views of the 2006 Volkswagen Passat with North American front bumper components (left) and European front bumper components (right).

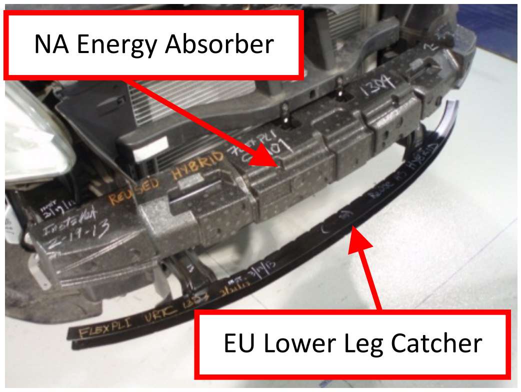


Figure 104. View of the “hybrid” 2006 Volkswagen Passat with a North American energy absorber and European lower bumper stiffener. The European bumper beam was used in the “hybrid” setup due to the addition of attachment points for the lower bumper stiffener.

Figure 105. 2006 North American Volkswagen Passat impact at times of first contact (left) and maximum deflection (right).

Figure 106. 2006 European Volkswagen Passat impact at times of first contact (left) and maximum deflection (right).

Figure 107. 2006 Hybrid Volkswagen Passat impact at times of first contact (left) and maximum deflection (right).

Table 21. Flex-PLI peak injury measures for the 2006 North American, European, and "Hybrid" Volkswagen Passat.

Injury Measurement		Injury Reference Value (FlexTEG)	Bumper Configuration		
			NA	**EU**	**Hybrid**
Femur Moment (Nm)	**Femur 3 (Upper)**	N/A	207	201	190
	Femur 2 (Middle)		484	328	309
	Femur 1 (Lower)		377	319	305
Tibia Moment (Nm)	**Tibia 1 (Upper)**	340 N-m (380 N-m)	426	232	354
	Tibia 2 (Mid Upper)		379	225	304
	Tibia 3 (Mid Lower)		251	209	230
	Tibia 4 (Lower)		111	149	134
MCL Elongation (mm)		22 mm	26.1	16.8	21.3
ACL Elongation (mm)		13 mm	11.9	8.9	13.1
PCL Elongation (mm)		13 mm	6.8	4.9	5.9
LCL Elongation (mm)		N/A	19.3	11.0	12.7
Tibia Acceleration (g)		N/A	50	153	251

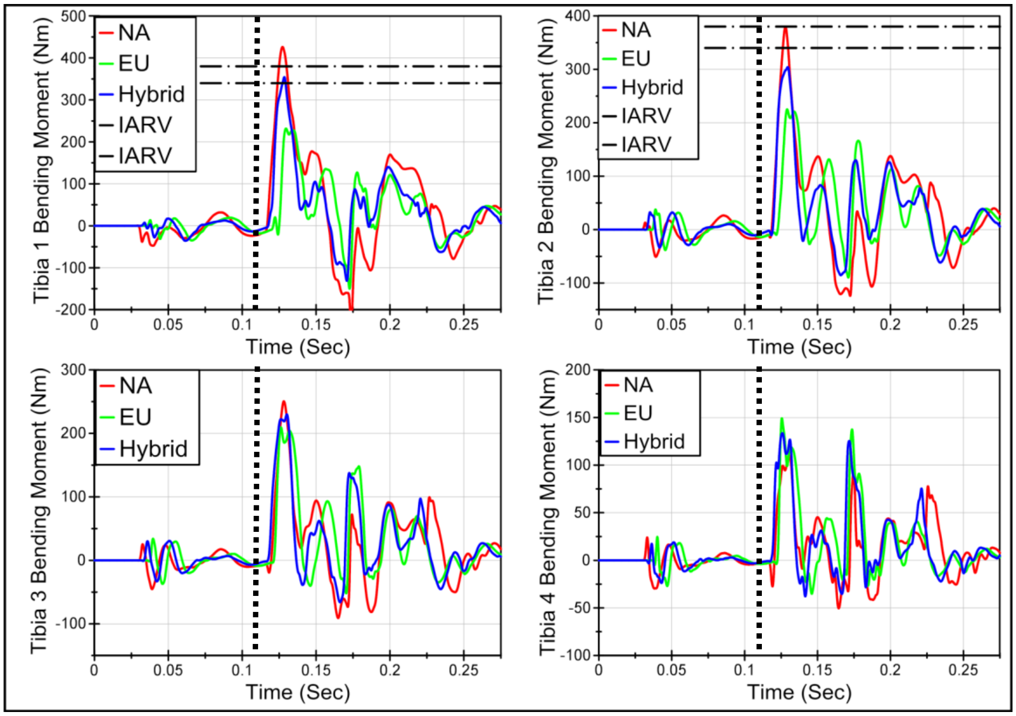


Figure 108. Tibia bending moment time histories for the 2006 Volkswagen Passat with North American (red), European (green), and hybrid (blue) bumper components. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

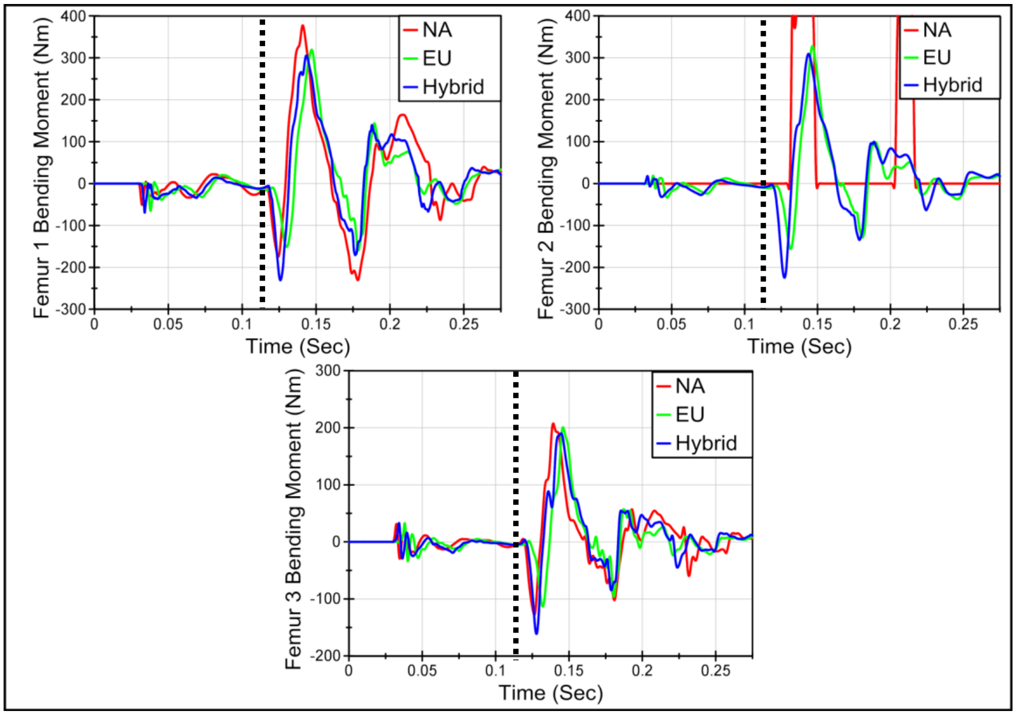


Figure 109. Femur bending moment time histories for the 2006 Volkswagen Passat with North American (red), European (green), and hybrid (blue) bumper components. Dotted vertical lines show the time of first contact.

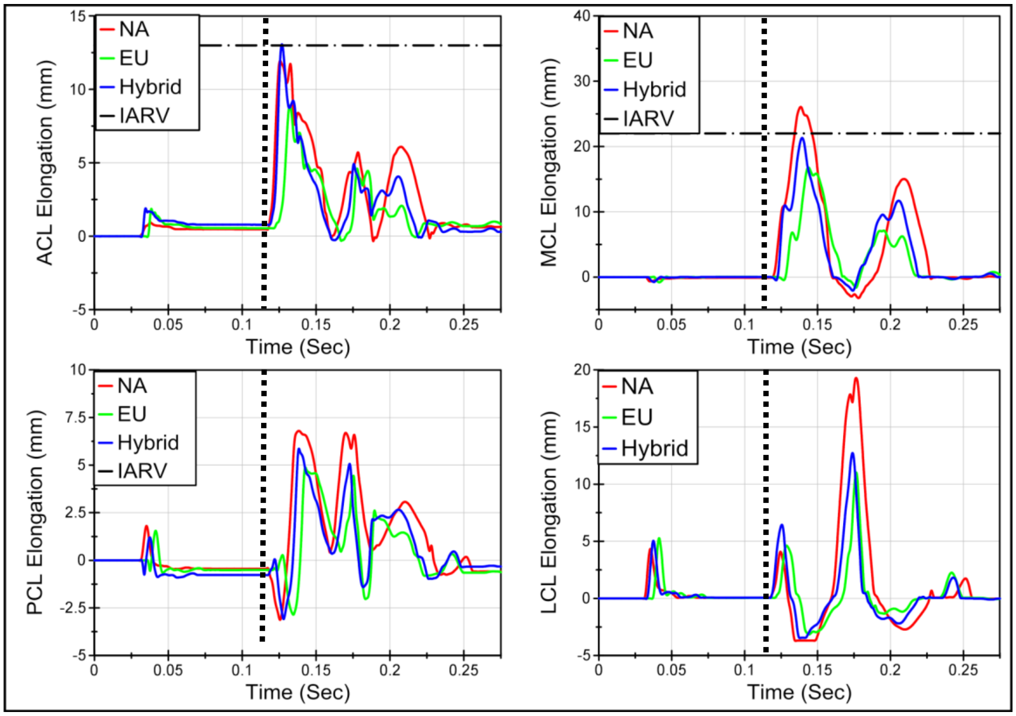


Figure 110. Ligament elongation time histories for the 2006 Volkswagen Passat with North American (red), European (green), and hybrid (blue) bumper components. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

4.3.1.3. NA vs EU

2013 Ford Focus

The 2012 Ford Focus NA system contained a stiff foam energy absorber, and the EU system contained a softer energy absorber (Figure 111). Figures 112 - 113 show screen captures at time of first contact and at maximum legform bending, in the center bumper location. Table 22 shows the Flex-PLI results, and Figures 114-116 show the time histories of each bumper version. The Ford Focus was tested by Shape Corp. (Grand Haven, MI) as part of a cooperative agreement.

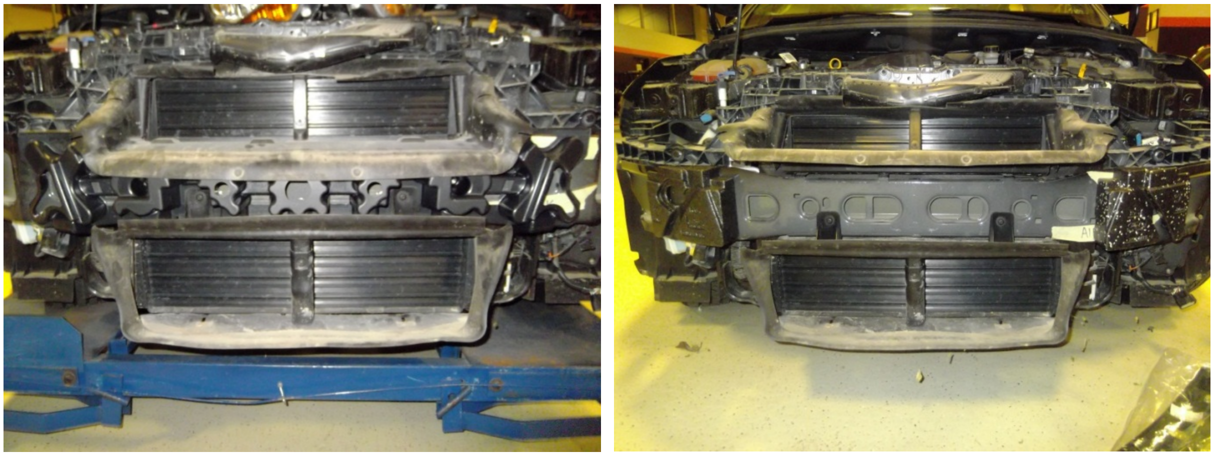


Figure 111. Profile views of the 2013 North American (left) and European (right) Ford Focus.

Figure 112. 2013 North American Ford Focus impact at times of first contact (left) and maximum deflection (right). The Ford Focus was tested by Shape Corp. (Grand Haven, MI).

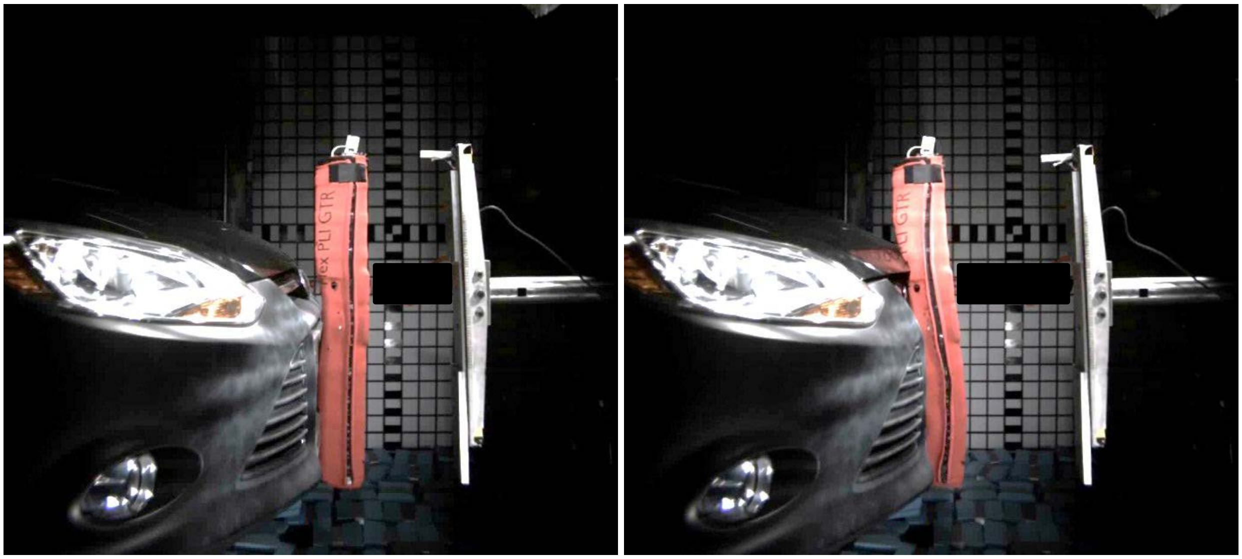


Figure 113. 2013 European Ford Focus impact at times of first contact (left) and maximum deflection (right). The Ford Focus was tested by Shape Corp. (Grand Haven, MI).

Table 22. Flex-PLI peak injury measures for the 2013 North American and European Ford Focus.

Injury Measurement		**Injury Reference Value (FlexTEG)**	**Bumper Configuration**	
			NA	**EU**
Femur Moment (Nm)	**Femur 3 (Upper)**	N/A	163	88
	Femur 2 (Middle)		291	163
	Femur 1 (Lower)		361	192
Tibia Moment (Nm)	**Tibia 1 (Upper)**	340 N-m (380 N-m)	371	147
	Tibia 2 (Mid Upper)		362	176
	Tibia 3 (Mid Lower)		261	183
	Tibia 4 (Lower)		113	153
MCL Elongation (mm)		22 mm	28.6	10.0
ACL Elongation (mm)		13 mm	10.7	4.7
PCL Elongation (mm)		13 mm	7.9	3.2
LCL Elongation (mm)		N/A	16.2	4.2
Tibia Acceleration (g)		N/A	258	118

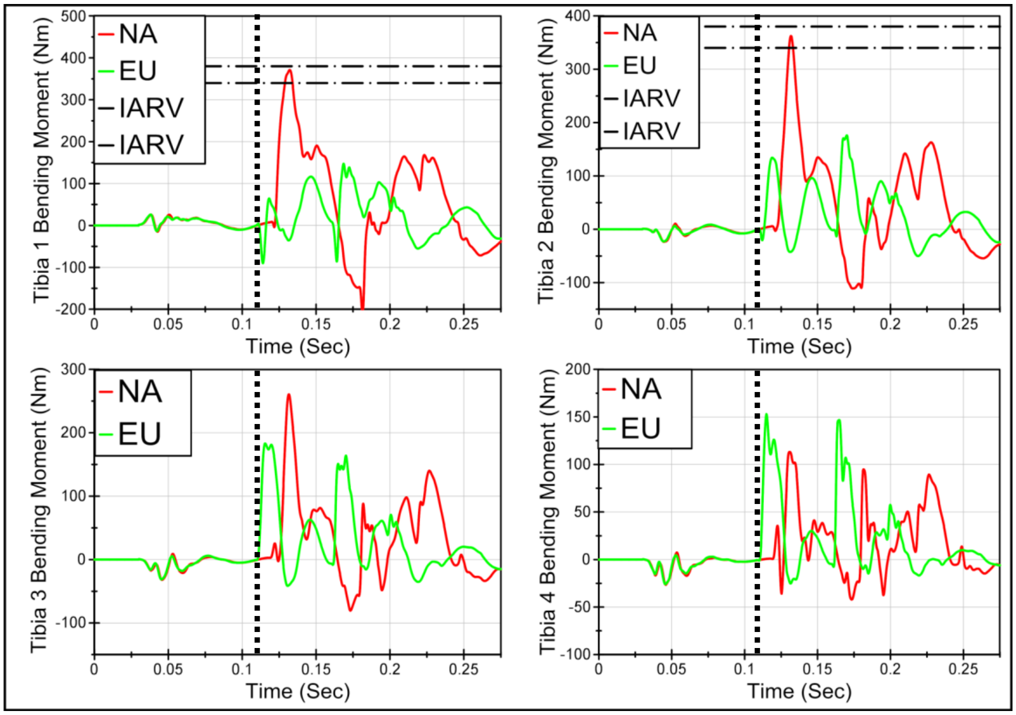


Figure 114. Tibia bending moment time histories for the 2012 Ford Focus with North American (red) and European (green) bumper components. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

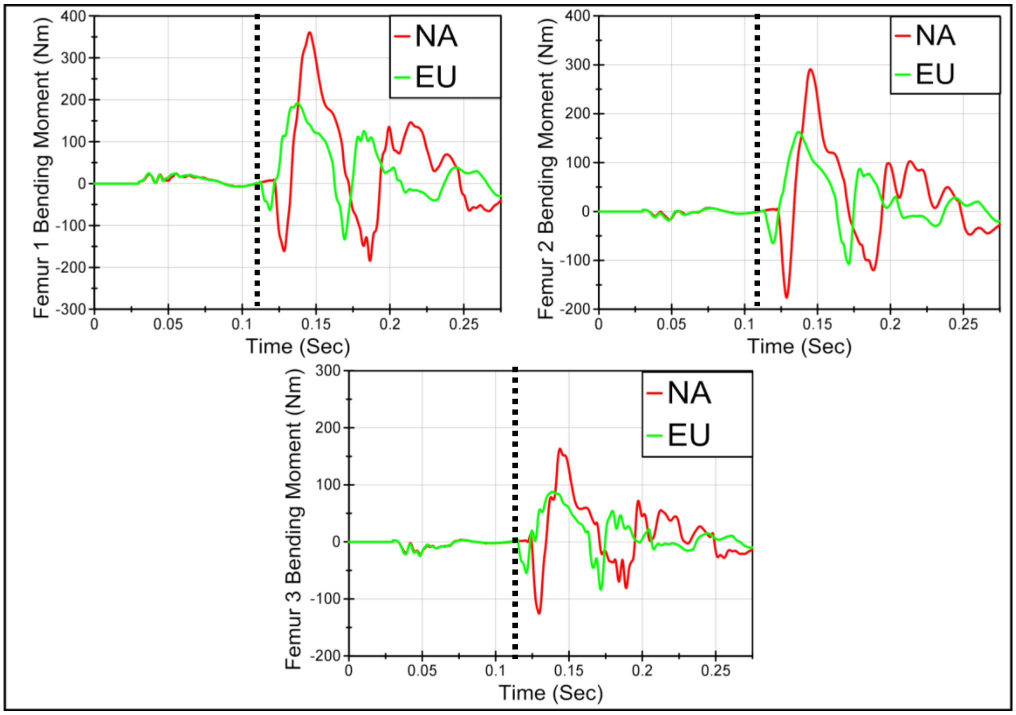


Figure 115. Femur bending moment time histories for the 2012 Ford Focus with North American (red) and European (green) bumper components. Dotted vertical lines show the time of first contact.

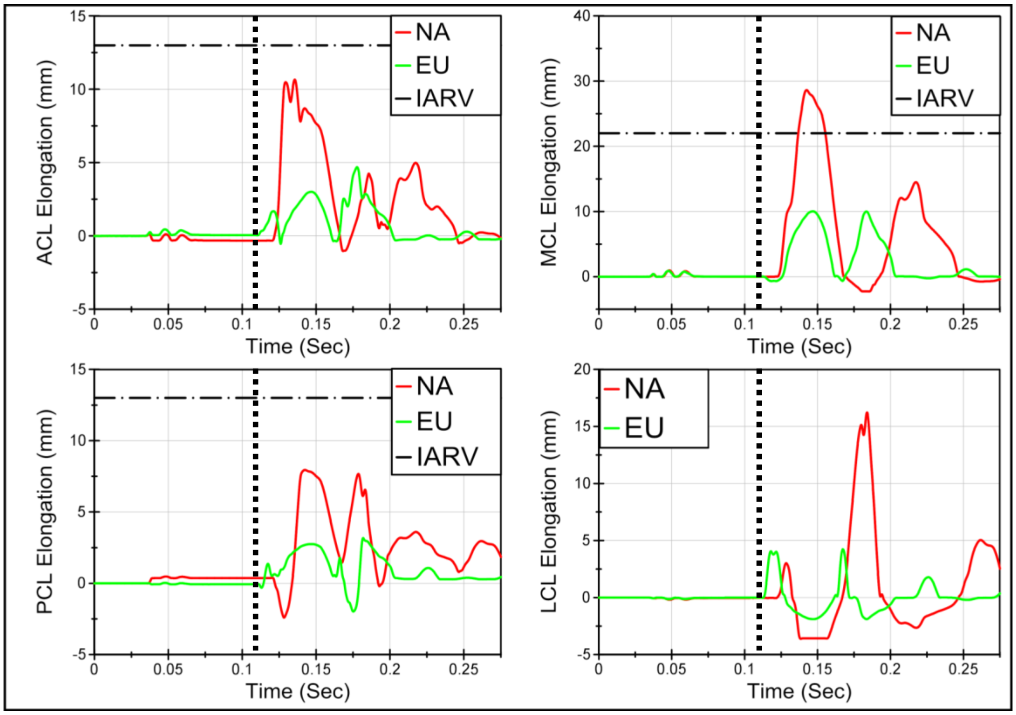


Figure 116. Knee ligament elongation time histories for the 2012 Ford Focus with North American (red) and European (green) bumper components. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

4.3.1.4. NA vs Hybrid

2011 Honda Odyssey

The 2011 Honda Odyssey NA system contained a stiff foam energy absorber, and a lower bumper stiffener from an EU bumper system from a different vehicle was added to create a "hybrid" experimental design (Figure 117). Figures 118-119 show screen captures at time of first contact and at maximum legform bending, in the center bumper location. Table 23 shows the Flex-PLI results, and Figures 120-122 show the time histories of each bumper version.

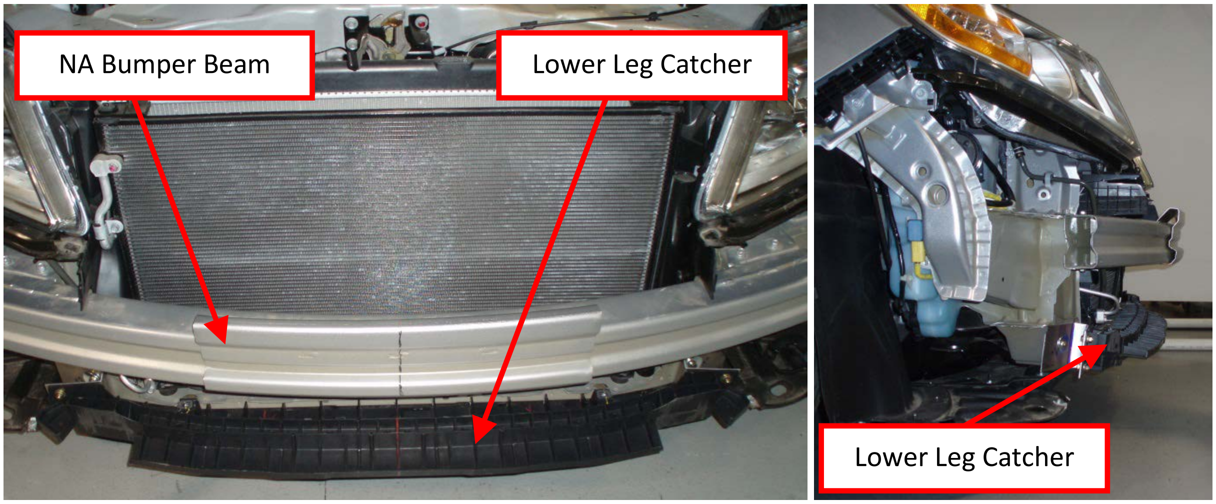


Figure 117. Front and profile views of the “hybrid” 2011 Honda Odyssey with a North American bumper beam and modified lower bumper stiffener.

Figure 118. 2011 North American Honda Odyssey impact at times of first contact (left) and maximum deflection (right).

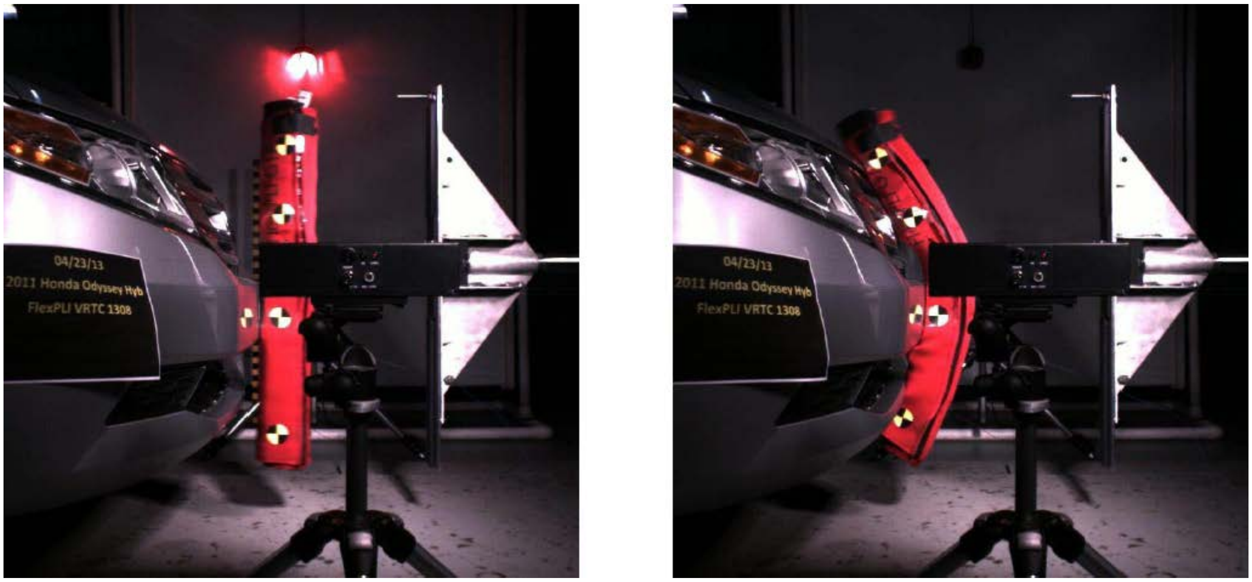


Figure 119. 2011 Hybrid Honda Odyssey impact at times of first contact (left) and maximum deflection (right).

Table 23. Flex-PLI peak injury measures for the 2011 North American and "Hybrid" Honda Odyssey.

Injury Measurement		**Injury Reference Value (FlexTEG)**	**Bumper Configuration**	
			NA	**Hybrid**
Femur Moment (Nm)	**Femur 3 (Upper)**	N/A	134	153
	Femur 2 (Middle)		207	214
	Femur 1 (Lower)		266	275
Tibia Moment (Nm)	**Tibia 1 (Upper)**	340 N-m (380 N-m)	385	390
	Tibia 2 (Mid Upper)		368	379
	Tibia 3 (Mid Lower)		262	273
	Tibia 4 (Lower)		111	108
MCL Elongation (mm)		22 mm	31.2	31.0
ACL Elongation (mm)		13 mm	14.5	15.7
PCL Elongation (mm)		13 mm	8.0	7.9
LCL Elongation (mm)		N/A	16.1	15.8
Tibia Acceleration (g)		N/A	487	480

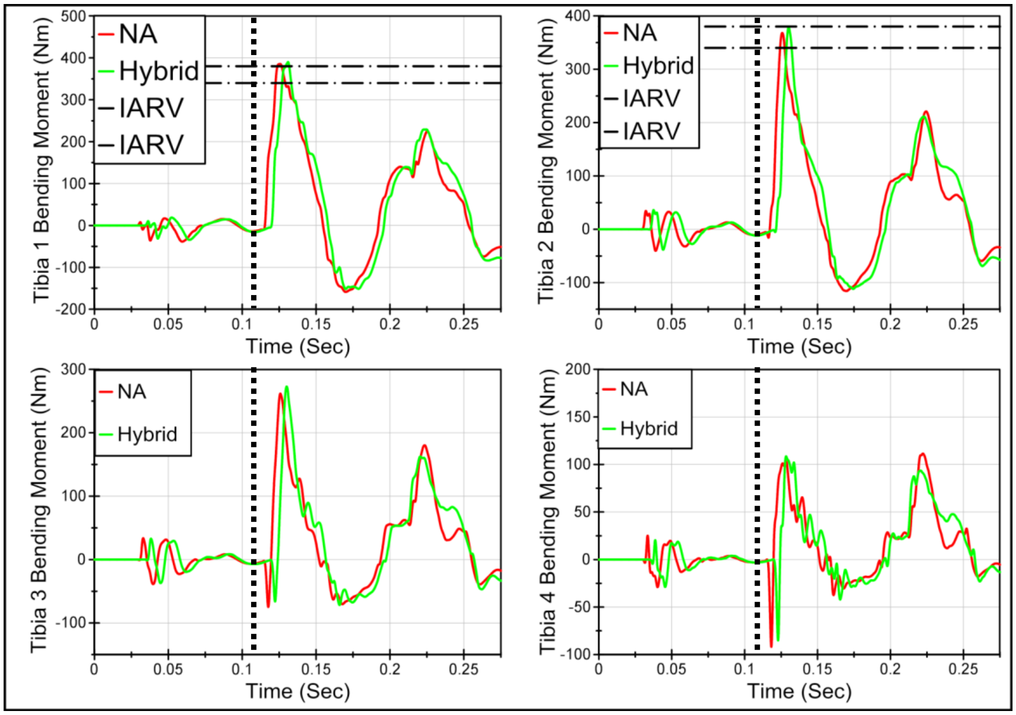


Figure 120. Tibia bending moment time histories for the 2011 Honda Odyssey with North American (red), and hybrid (green) bumper components. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

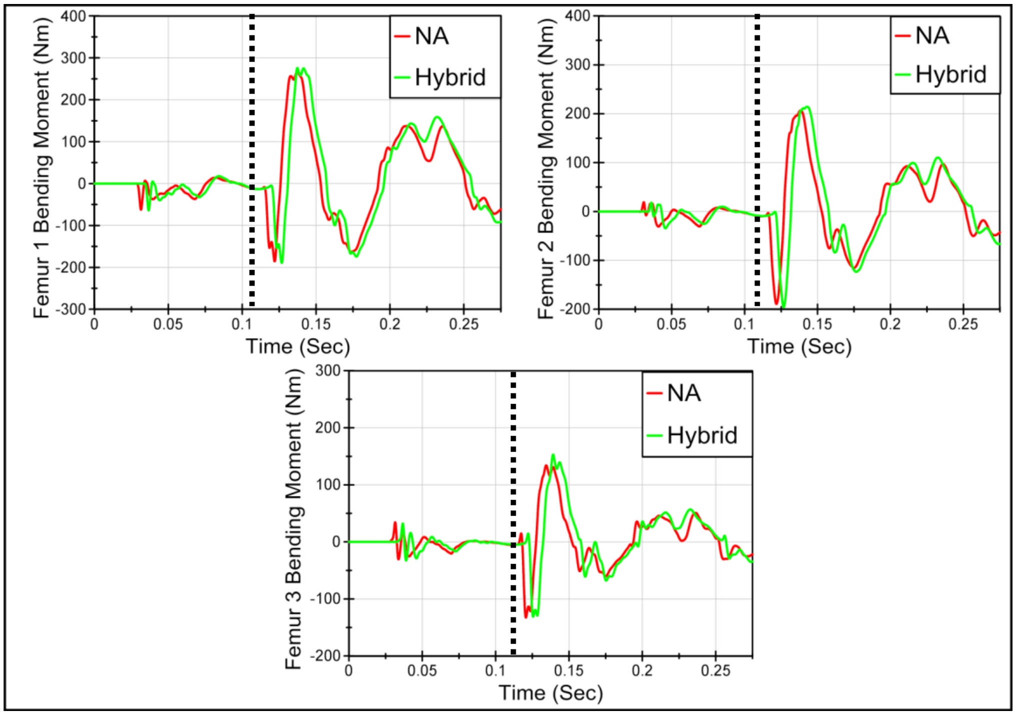


Figure 121. Femur bending moment time histories for the 2011 Honda Odyssey with North American (red), and hybrid (green) bumper components. Dotted vertical lines show the time of first contact.

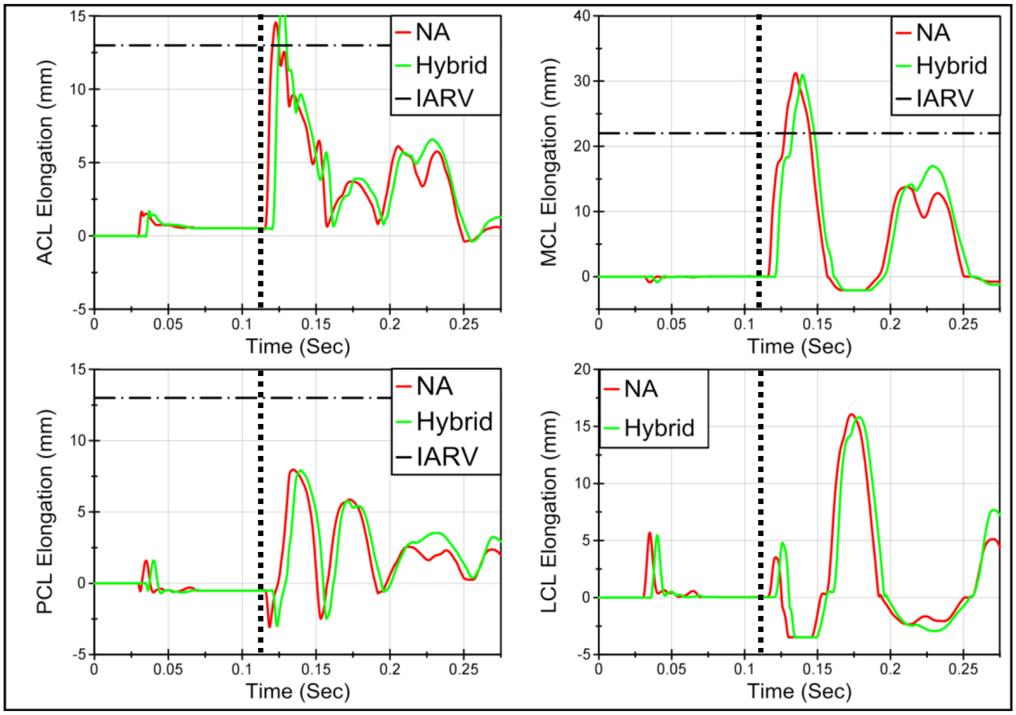


Figure 122. Ligament elongation time histories for the 2011 Honda Odyssey with North American (red), and hybrid (green) bumper components. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

2011 Jeep Grand Cherokee

The 2011 Jeep Grand Cherokee NA system contained a stiff foam energy absorber, and a lower bumper stiffener from the EU Cherokee bumper system to create a “hybrid” experimental design (Figures 123-124). Figures 125-126 show screen captures at time of first contact and at maximum legform bending, in the center bumper location. Table 24 shows the Flex-PLI results, and Figures 127-129 show the time histories of each bumper version.

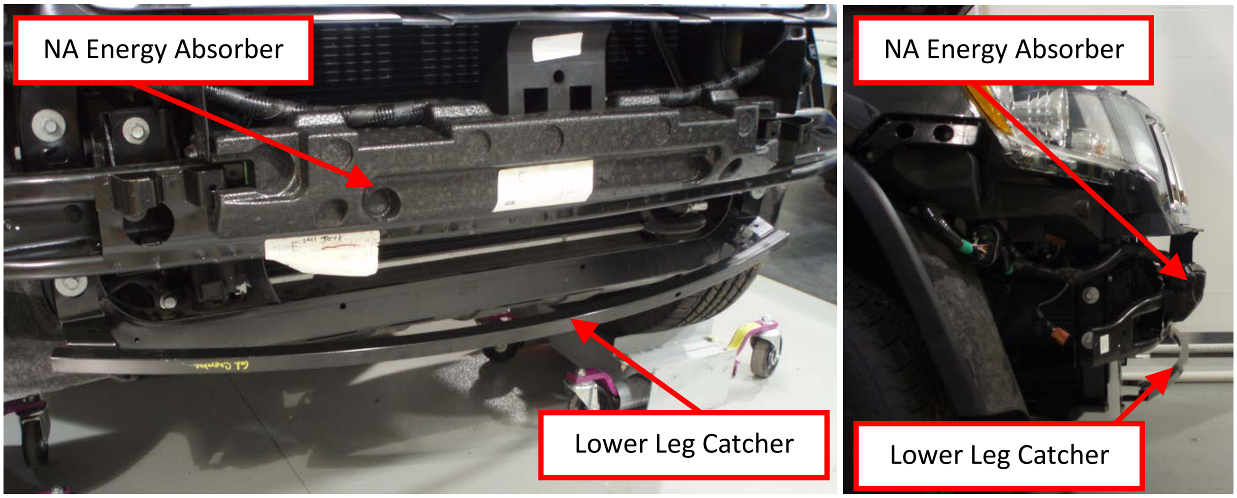


Figure 123. Front and profile views of the “hybrid” 2011 Jeep Grand Cherokee with a North American energy absorber and modified lower bumper stiffener.

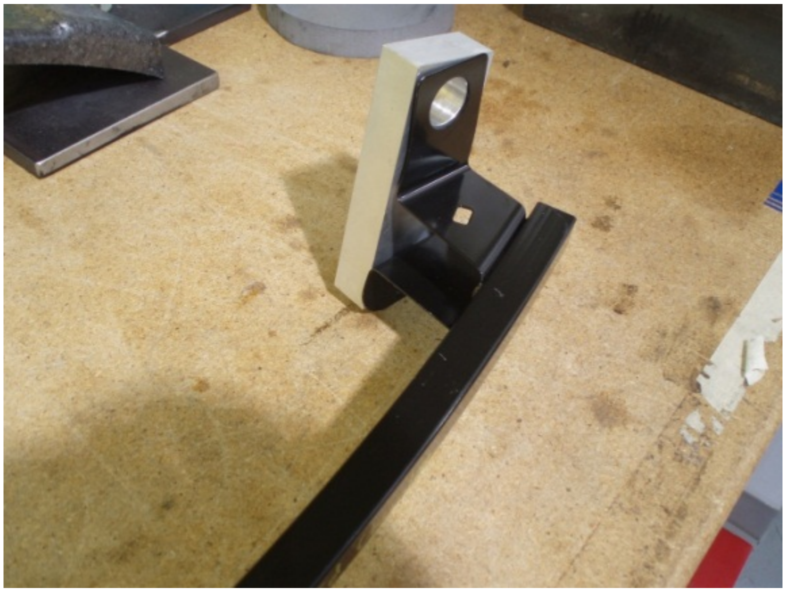


Figure 124. A close-up view of a lower bumper stiffener (LBS) for the 2011 Jeep Grand Cherokee. A spacer was fabricated to push the LBS forward so that its front edge was up against the fascia.

Figure 125. 2011 North American Jeep Grand Cherokee impact at times of first contact (left) and maximum deflection (right).

Figure 126. Figure 143. 2011 Hybrid Jeep Grand Cherokee impact at times of first contact (left) and maximum deflection (right).

Table 24. Flex-PLI peak injury measures for the 2011 North American and “Hybrid” Jeep Grand Cherokee.

Injury Measurement		**Injury Reference Value (FlexTEG)**	**Bumper Configuration**	
			NA	**Hybrid**
Femur Moment (Nm)	**Femur 3 (Upper)**	N/A	142	161
	Femur 2 (Middle)		204	173
	Femur 1 (Lower)		287	246
Tibia Moment (Nm)	**Tibia 1 (Upper)**	340 N-m (380 N-m)	422	387
	Tibia 2 (Mid Upper)		355	369
	Tibia 3 (Mid Lower)		241	249
	Tibia 4 (Lower)		104	113
MCL Elongation (mm)		22 mm	33.4	32.3
ACL Elongation (mm)		13 mm	13.6	14.3
PCL Elongation (mm)		13 mm	6.9	7.1
LCL Elongation (mm)		N/A	15.7	20.9
Tibia Acceleration (g)		N/A	395	260

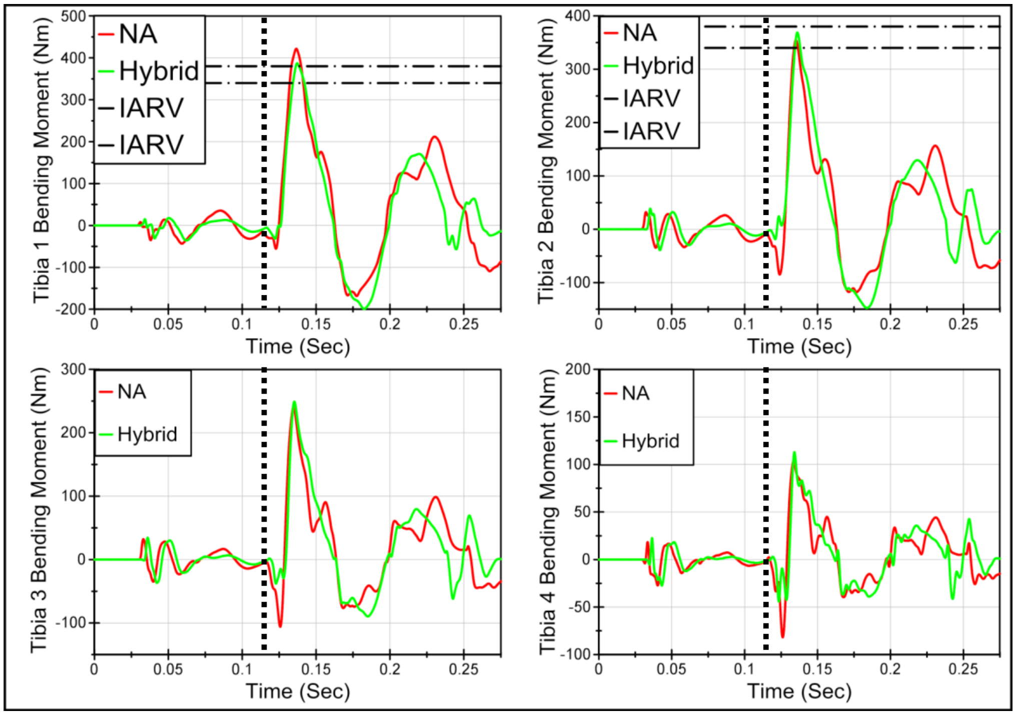


Figure 127. Tibia bending moment time histories for the 2011 Jeep Grand Cherokee with North American (red), and hybrid (green) bumper components. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

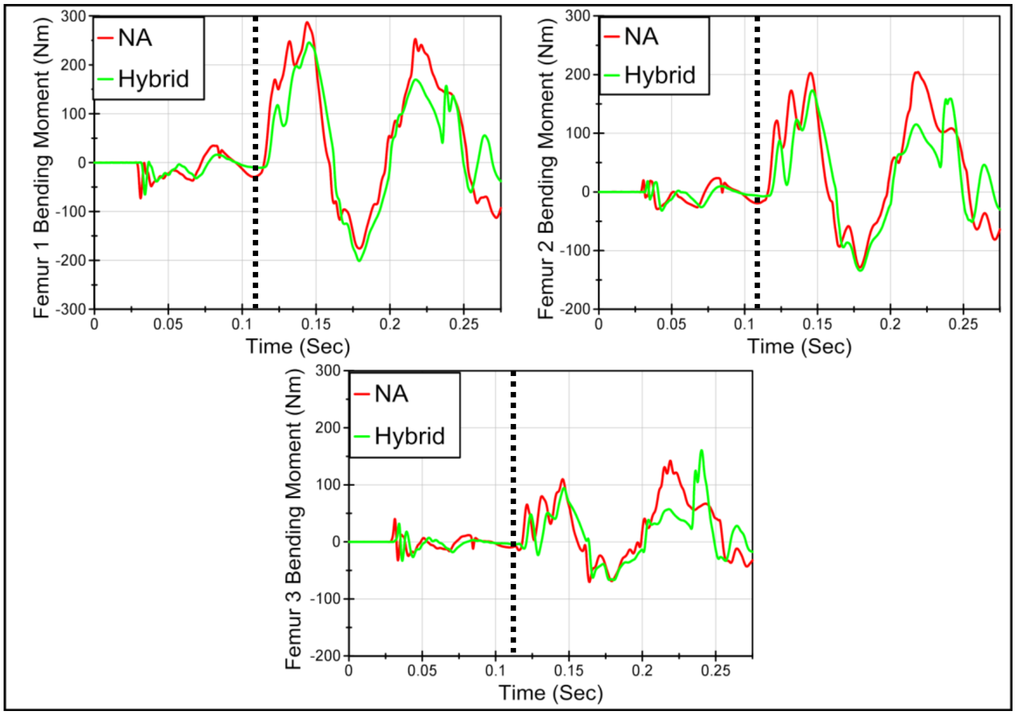


Figure 128. Femur bending moment time histories for the 2011 Jeep Grand Cherokee with North American (red), and hybrid (green) bumper components. Dotted vertical lines show the time of first contact.

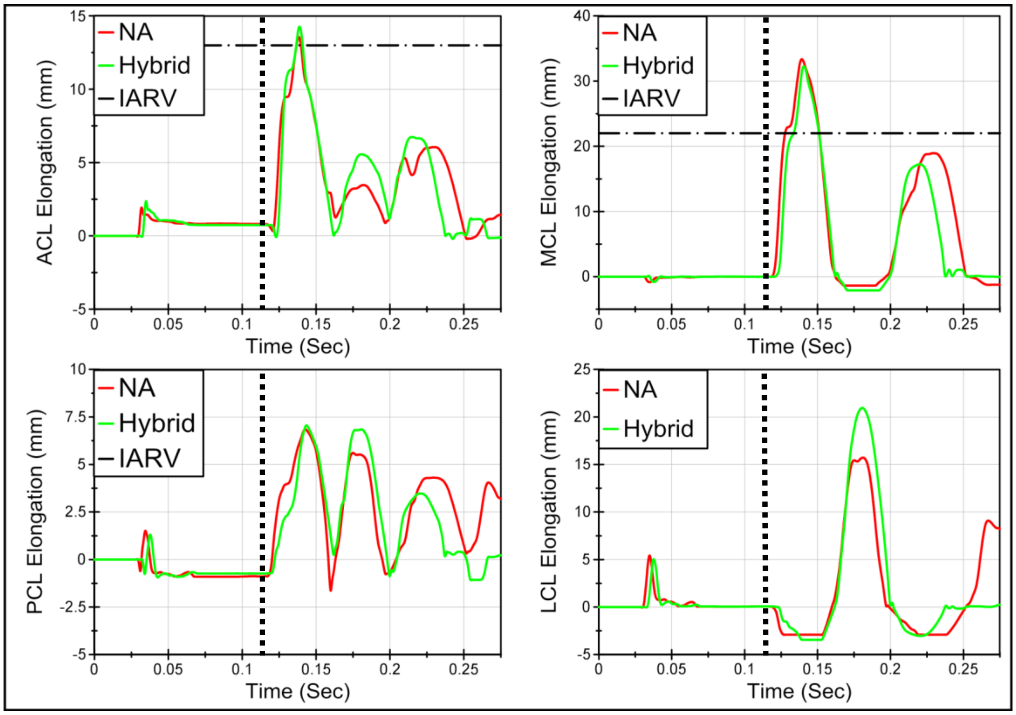


Figure 129. Ligament elongation time histories for the 2011 Jeep Grand Cherokee with North American (red), and hybrid (green) bumper components. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

4.3.2. Analysis & Discussion: Flex-PLI testing on EU, NA, and hybrid bumper systems

The four primary observations from this phase of the study were that (1) design strategies varied widely across the tested vehicles, (2) the Fusion was the only vehicle to meet the GTR proposed IARVs, and it had lower Flex-PLI measures at the outboard location than at the center, which contradicts earlier tests on other vehicles, (3) there were different trends in femur vs. tibia measurements depending on vehicle design that were not necessarily related to vehicle size, and (4) the lower bumper stiffener was found to be the most critical element for reducing Flex-PLI measurements.

- **Design strategies**

There was no pattern in the various design concepts used for the tested vehicles. The Fusion contained a modular box array that provided a soft structure in a localized impact such as the pedestrian test, but a stiffer, distributed structure for Part 581 or vehicle-vehicle contacts. The Yaris EU system had a crushable bumper bar with no energy absorber between the bar and fascia. The Cruze EU system contained a softer energy absorber in addition to a lower bumper stiffener as opposed to its NA design. The larger vehicles tended to have more substantial part changes to make them pedestrian friendly. In summary, it appears there are many different alternatives for achieving good performance when using the Flex-PLI legform. It was also evident from these tests that the under-fascia components can be made drastically different without compromising the external geometry or appearance of the vehicle.

- **Center vs. outboard performance**

The Fusion was the only vehicle to meet the GTR proposed IARVs, and it had lower Flex-PLI measures at the outboard location than at the center, which contradicts earlier tests on other vehicles. The modular box energy absorber had different depths, with a greater depth in the outboard location than at the center. The front profile of the Fusion is very flat, and there was very little lateral rebound or oblique angle in the outboard test. Therefore, it doesn't appear that this lateral component had a significant effect on the lower Flex measurements. When comparing the passenger vs. driver side outboard results, the driver side had higher femur moments but the tibia moments and ligament measures were not significantly different, even though the tibia accelerations were identical. Any driver vs. passenger side differences appear be related to some asymmetry in some of the structural components in the vehicle unrelated to pedestrian protection, given that the Flex leg is symmetric from left to right.

- **Femur vs. tibia measurements with respect to vehicle type**

There were some differences in the distribution of loading between the femur and tibia for vehicles tested. For the Silverado, the femur moment is low (F1=246 Nm) relative to the other vehicles, which was a bit surprising given the conventional wisdom that higher bumper/larger vehicles tend to be worse for the upper leg. It is also low relative to the new, global vehicles shown in the next section of the report, with the exception of the Fusion. In the Silverado test, the max femur moment occurs earlier than the tibia moment. For the sedans, femur moments occurred later. It appears that the height of the bumper has little effect on the femur moment, if the grill and front face of the vehicle above the bumper bar is flat, as is the case with the Silverado.

- **Effect of lower bumper stiffener**

At the beginning of this study, it was assumed that differences in the energy absorber would be the primary factor related to differences in Flex measurements between the compliant and non-compliant systems. During the course of testing, it became evident that, while the energy absorber did have an effect, the lower bumper stiffener present in the compliant systems was the most critical factor. In general, bending in the femur was not affected in 4 of 5 vehicles, and barely affected in the Passat. Ligament measures were not affected greatly in any of the 5 vehicles. Tibia bending was lowered for the three sedans, but not for the Odyssey or Jeep. The Odyssey was not affected at all by the addition of the apron, most likely because the stiffener attachment was very close in proximity to the bumper bar, and the stiffener used was not from a GTR-compliant Odyssey. For the Jeep, the apron only had a marginal effect. It appears that a lower stiffener is more effective when it is further from the bumper beam.

While both NA (non-GTR compliant) and EU (GTR compliant) versions of vehicles were tested to evaluate the fleet baseline performance and to assess the Flex-PLI's capacity for discriminating good vs. bad pedestrian designs, it was assumed that a bumper that could meet both GTR pedestrian protection and Part 581 damageability requirements would have to be somewhere in between those two extremes. After analyzing part differences between EU and NA systems for global platform vehicles, it was surmised that the addition of a lower bumper stiffener to the NA system would be an easy approach for evaluating a hybrid system. In most cases, this addition did provide a middle point between the EU and NA system results. For the Cruze, the hybrid system met all three proposed IARVs with the hybrid system. For the Passat, the response was improved for bending moment and MCL elongation, but the ACL elongation was actually increased from the NA result. The MCL value of 21.9 mm is marginally passing, but this value is associated with a 68% risk of MCL rupture, which seems excessively high for a passing test. For the Yaris, the tibia bending moment and MCL elongation were improved but still did not pass the GTR limits. The addition of an undertray had a negligible effect on the Grand Cherokee and Odyssey Flex-PLI results.

4.4. Feasibility of Meeting GTR and Part 581 Damageability Requirements

The objective of this portion of the Flex-PLI legform evaluation was to determine if it was possible for a single bumper design to pass both pedestrian protection and Part 581 damageability requirements by testing various bumper configurations for "global platform" vehicles in both GTR9 and Part 581 conditions. To investigate the Part 581 side of this question, both 2.5 mph longitudinal and 1.5 mph corner Part 581-type tests were conducted on the Fusion, Passat (hybrid bumper), and Cruze (hybrid bumper).

The Code of Federal Regulations (CFR) 49 Part 581 Bumper Standard establishes requirements for the impact resistance of vehicles in low speed front and rear collisions. There are nine protective criteria in the standard which must be met after a series of nine low speed impact tests (2 front corner, 2 front center, 2 rear corner, 2 rear center, and 1 fixed barrier) are conducted. Seven of these criteria require that the vehicle systems continue to work correctly after the series of nine low speed tests is completed. The other two criteria are most relevant to pedestrian protection requirements. Those are that (1) the vehicle shall not touch the test device, except on the impact ridge, with a force exceeding 2000 lbs (8896 N) on the combined surfaces of Planes A & B, and (2) the exterior surfaces shall have no visible damage on any structure except for the bumper face bar and associated components/fasteners that directly attach the bumper face bar to the chassis frame. These two criteria were evaluated in the two most relevant Part 581 test conditions: 2.5 mph front center (longitudinal) and 1.5 mph front corner impacts (Figure 130).

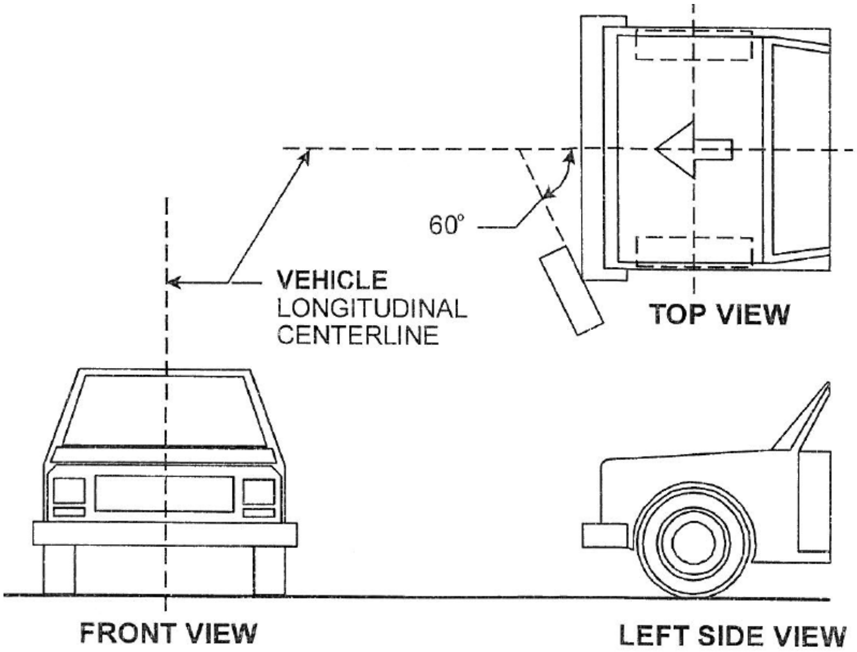


Figure 130. Vehicle setup for Part 581 tests

Three vehicles were selected for this testing: Fusion, Cruze, and Passat. The Fusion was tested as purchased, while the Cruze and Passat were tested in the as purchased configuration but with the EU lower bumper stiffener element added ("NA w/EU LBS" in Table 25). This element was added because the objective was to evaluate a bumper configuration that could come closest to meeting both GTR9 and Part 581 requirements. It was assumed that the EU system alone would not pass the Part 581 test requirements and the NA system alone would not pass the GTR9 pedestrian protection injury limits. Given the presence of the lower bumper stiffener in GTR-compliant EU systems, the unknown stiffness difference in energy absorber construction, and the ease of attaching the lower bumper stiffener to the NA system, it was deemed appropriate to use this hybrid construction as an experimental attempt to meet both GTR9 and Part 581-type test requirements.

Table 25. Test Matrix.

Vehicle	**2.5 mph Longitudinal**	**1.5 mph Corner**
2013 Ford Fusion	NA	NA
2011 Chevrolet Cruze	NA w/EU LBS	NA w/EU LBS
2006 Volkswagen Passat	NA w/EU LBS	NA w/EU LBS

For the center/corner impacts to the front of the vehicle, the pendulum mass was adjusted to match the vehicle mass per the Part 581 test procedure. Thirteen load cells were configured as shown in Figure 131 to measure the relative loads on the impact ridge and upper/lower planes.

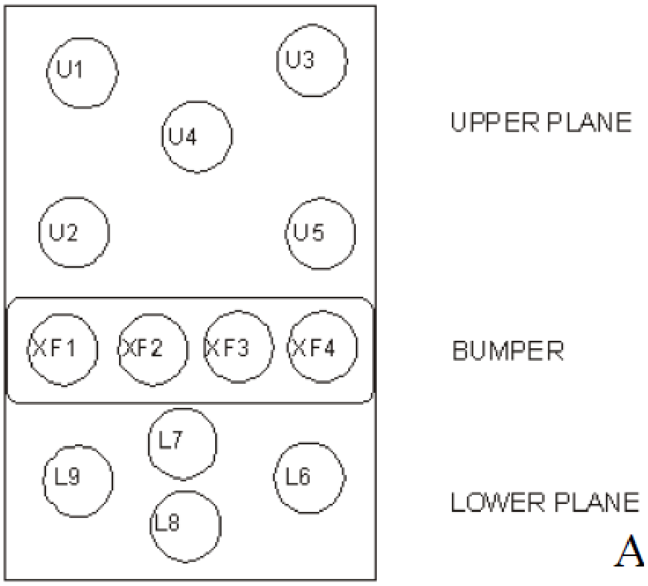
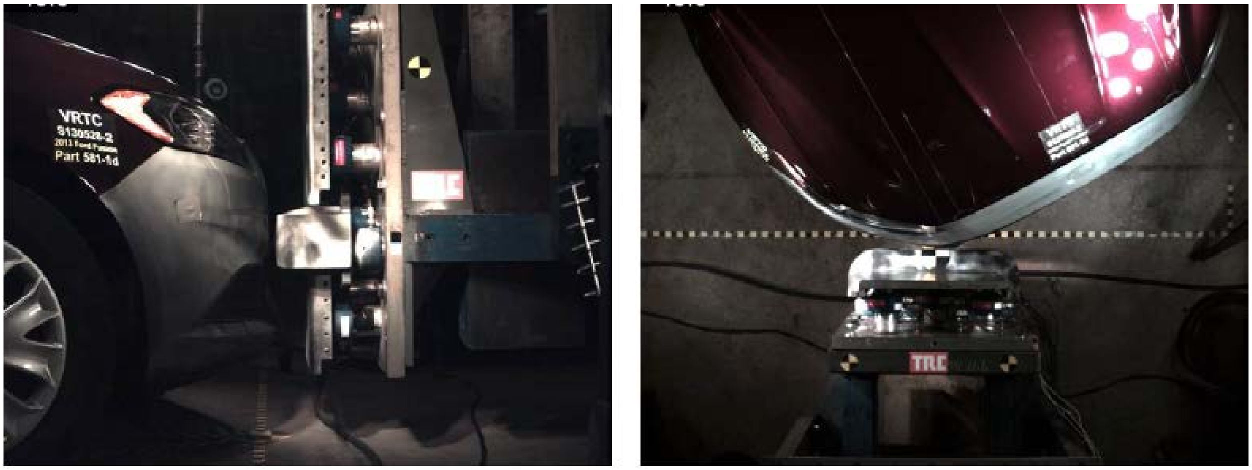


Figure 131. Pendulum load cell configuration.

Test setups for each vehicle are shown in Figures 132 - 134:

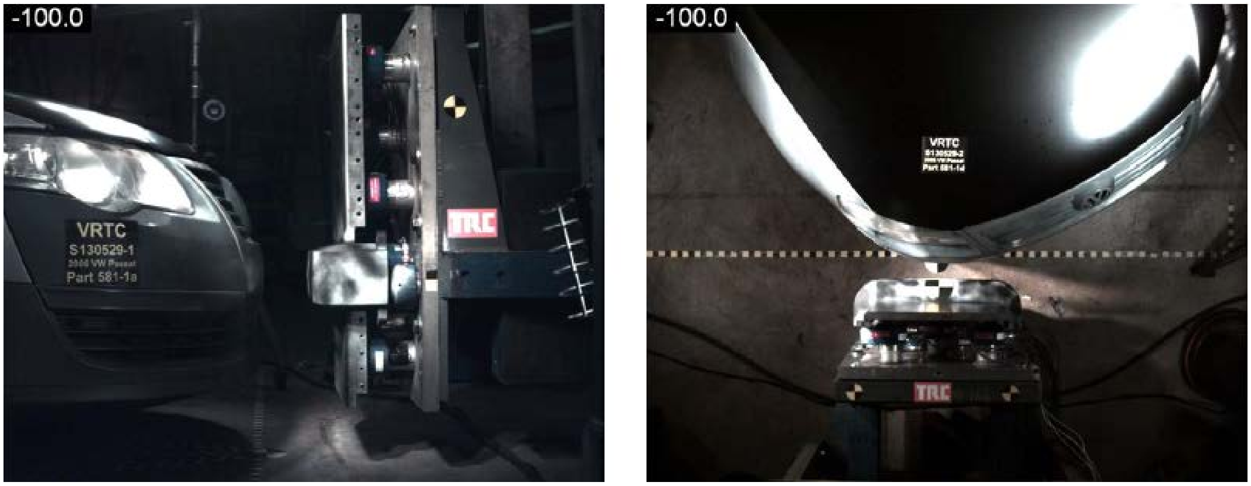


Fusion (2.5 mph longitudinal)
Fusion (1.5 mph corner)

Figure 132. Longitudinal and corner test setups for Fusion.

Cruze (2.5 mph longitudinal) Cruze (1.5 mph corner)

Figure 133. Longitudinal and corner test setups for Cruze.



Passat (2.5 mph longitudinal) Passat (1.5 mph corner)

Figure 134. Longitudinal and corner test setups for Passat.

The Part 581 test results (pendulum forces & damage outcome) were then assessed and compared with the respective vehicle Flex-PLI results.

4.4.1. Results: Flex-PLI vs. Part 581 Feasibility

- **Ford Fusion**

The Plane A/Plane B and impact ridge (“mid-plane”) loads for the Fusion are shown in Figure 135. The Plane A/Plane B sum forces for each test were well below the 8896 N load criterion.

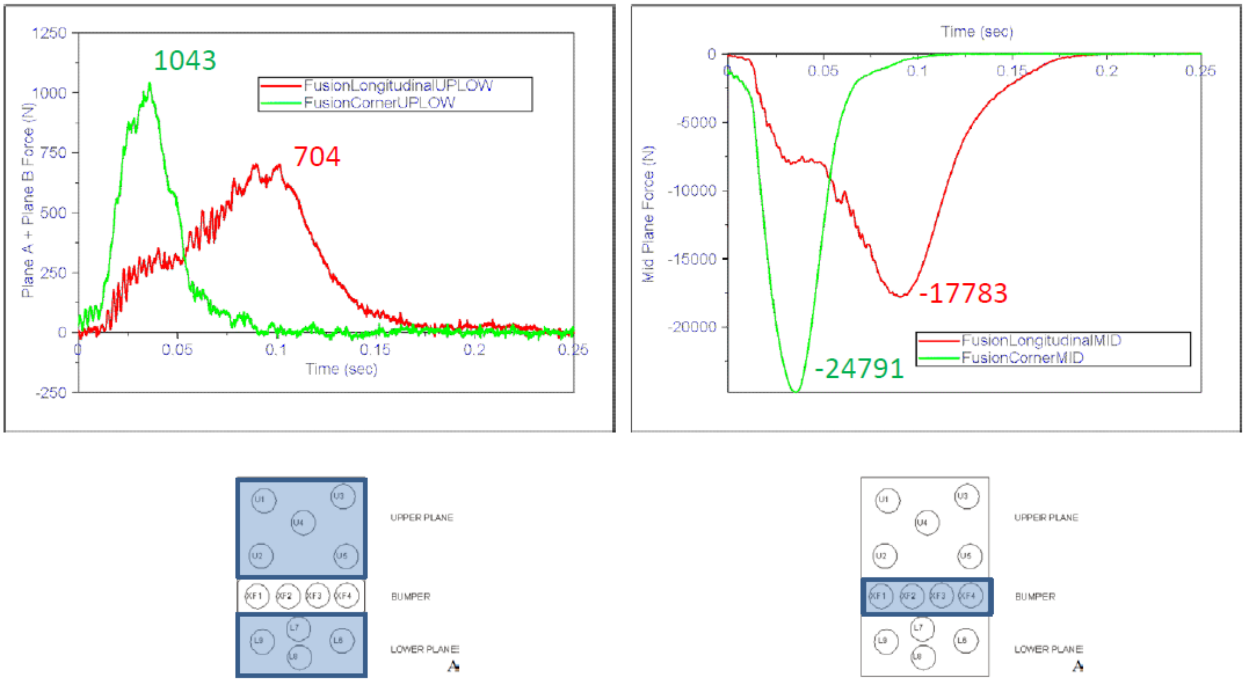


Figure 135. Ford Fusion pendulum loads.

There was no exterior damage to any structures other than the fascia and grille components. Damage to the fascia is shown in Figure 136.

Figure 136. Ford Fusion fascia damage.

- **Chevrolet Cruze**

The Plane A/Plane B and impact ridge ("mid-plane") loads for the Cruze are shown in Figure 137. The Plane A/Plane B sum forces for each test were well below the 8896 N load criterion.

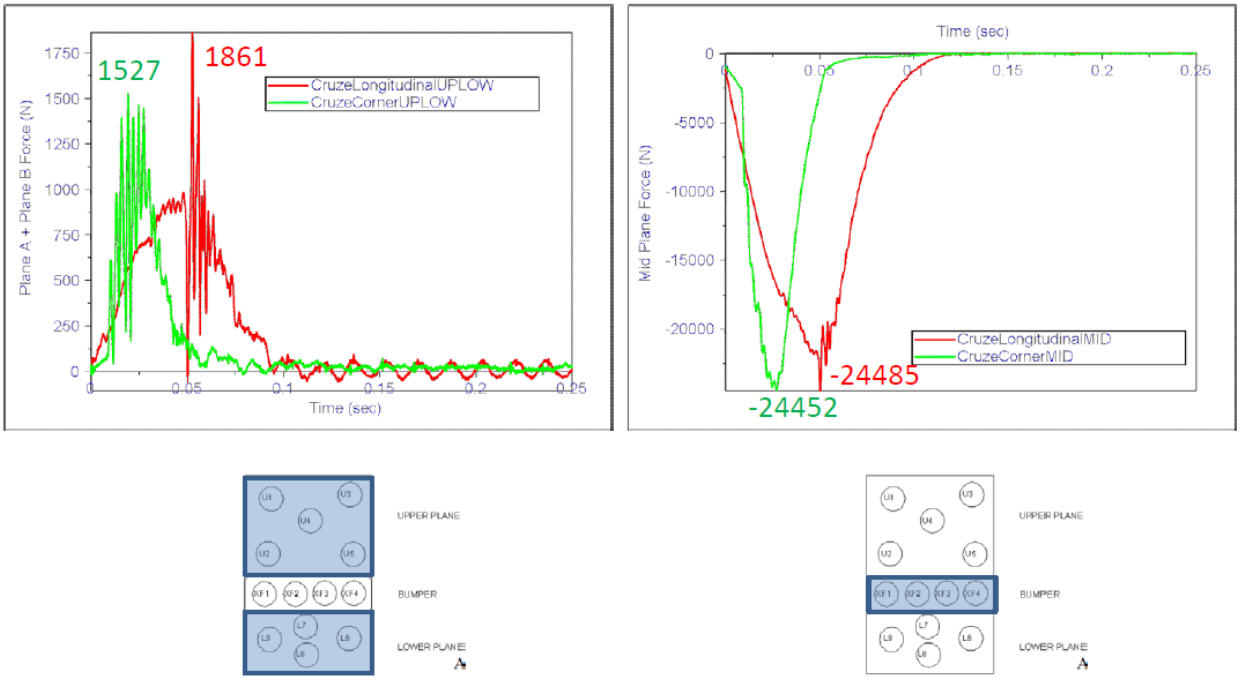


Figure 137. Chevrolet Cruze pendulum loads.

There was no exterior damage to any structures, with only a small smudge on the fascia in the corner impact. Post-test pictures of the vehicle front are shown in Figure 138.

Figure 138. Chevrolet Cruze post-test photos.

- **Volkswagen Passat**

The Plane A/Plane B and impact ridge ("mid-plane") loads for the Passat are shown in Figure 139. The Plane A/Plane B sum forces for each test were well below the 8896 N load criterion.

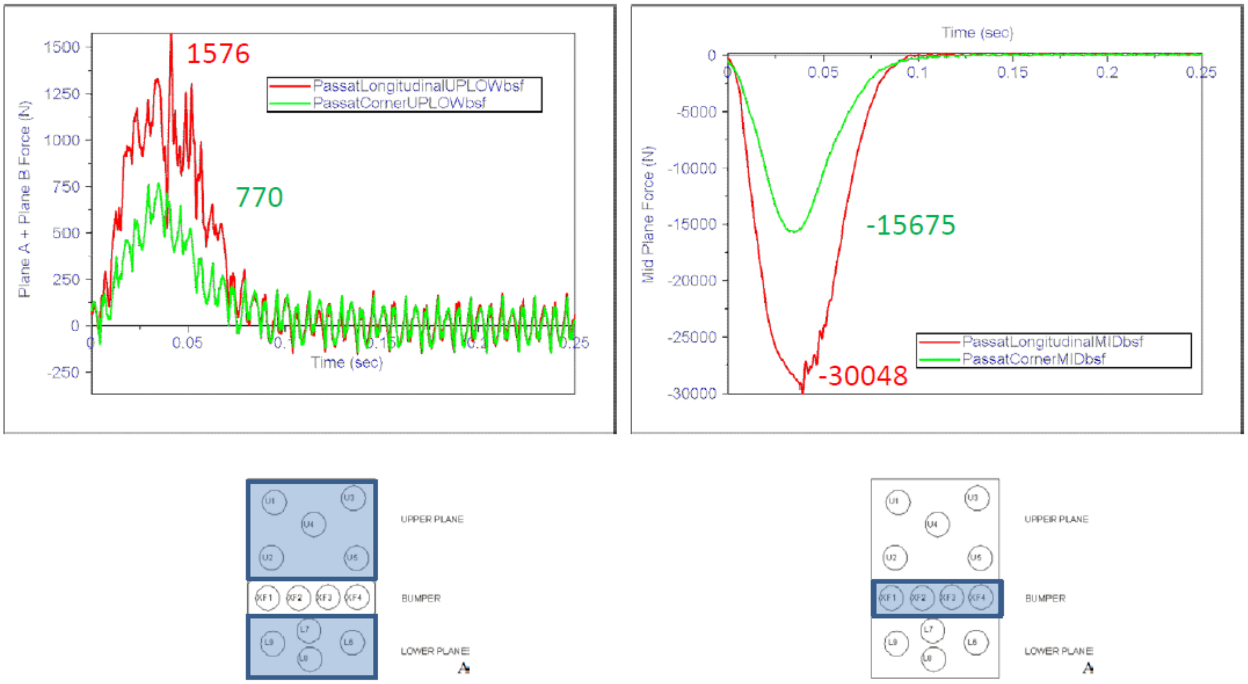


Figure 139. Volkswagen Passat pendulum loads.

No exterior damage was apparent on the Passat following the test (Figure 140).

Figure 140. Volkswagen Passat post-test photos.

4.4.2. Analysis & Discussion: Flex-PLI vs. Part 581 Feasibility

All three vehicles passed the Part 581 requirements for 2.5 mph longitudinal and 1.5 mph corner conditions. The Fusion was tested as purchased, while the Cruze and Passat simply had the EU lower bumper stiffener fastened to the North American bumper system. In the Flex-PLI leg tests, the Fusion passed the GTR9 requirements, the Cruze barely passed, and the Passat (hybrid) barely failed (Table 26). Given that one commercially available vehicle (Fusion) passed both the Part 581 and pedestrian requirements, and two vehicles were on the margin of passing the GTR9 requirements with the simple addition of a lower bumper stiffener, it appears quite possible to pass both standards with a cost-effective, optimized design.

Table 26. Summary of Part 581 vs. Flex-PLI Results

Vehicle	Part 581 (2.5 mph/1.5 mph front pendulum)	Flex-PLI
2013 Ford Fusion	Pass	Passes easily
2011 Chevy Cruze	Pass	Passes barely
2006 VW Passat	Pass	Fails barely

There are a few caveats to consider before definitively concluding it is feasible to pass both requirements. First, only the Fusion passed both requirements by a margin generally used in compliance. However, only 2 of the 9 test conditions were conducted for Part 581. Given that this vehicle is sold in the U.S., it can be surmised that it would pass the entire battery of tests. The other caveat is that neither the Cruze or Passat hybrid systems are assured of meeting all other applicable requirements of each region. Given that the EU systems for both vehicles meet the GTR9 requirements, it would be interesting to see how those systems do in the Part 581 test series.

5. REPEATABILITY & REPRODUCIBILITY

A regulatory test tool must exhibit consistent response so that any variation in the measurements is dictated by the vehicle system itself. *Repeatability* refers to how consistent a single Flex-PLI legform is when tested multiple times in the same conditions. *Reproducibility* quantifies how well multiple Flex-PLI legforms exhibit consistent response in the same condition.

R&R was assessed based on the performance of three different Flex-PLI legforms:

Master SN01 - This legform is owned by Humanetics and was made available to NHTSA for a two-month period in 2013 during round-robin testing among North American participants of the Flex-PLI IWG. It represents Humanetics' latest design (or build level) of the legform.

Master E-Leg – Like SN01, this legform is also owned by Humanetics and was made available to NHTSA for a two-month period in 2013 during round-robin testing among North American participants of the Flex-PLI IWG. It also represents Humanetics' latest design (or build level) of the legform.

VRTC Legform - This legform is owned by NHTSA. It represents a Humanetics build level preceding the Master legforms. It differs from the Master legforms in that it utilizes a shorter rubber skin element.

The masses of each legform are also different but within the tolerance for legform mass (VRTC: 13.096 kg; SN01: 13.260 kg; E-Leg: 13.13 kg)

Although slight revisions were made between the VRTC legform build level and the Master legform build level, the revisions were made to facilitate improved durability and none were expected to affect leg response. Therefore, all three legforms were included in the R&R investigation.

As described in Rhule et al. (2005), NHTSA has categorized the CV scores as shown in Table 27:

Table 27. CV Scores

Repeatability %CV Score	Reproducibility %CV Score	Assessment
$\%CV \leq 5$	$\%CV \leq 6$	Excellent
$5 < \%CV \leq 8$	$6 < \%CV \leq 11$	Good
$8 < \%CV \leq 10$	$11 < \%CV \leq 15$	Marginal
$\%CV > 10$	$\%CV > 15$	Poor

For repeatability, the "marginal" limit is set at a %CV value of 10 percent. For "marginal" reproducibility, a slightly greater %CV of 15 percent is used since multiple legforms produce a wider dispersion of response measurement than in testing a single legform for repeatability. All R&R values in the "poor" category were investigated to assess the cause of the high variance. If needed, corrective measures were made to the legform. As shown in Table 27 to make the interpretation of the results easier, the CV summary tables in this section use the following color code: green - excellent CV, yellow – good to marginal CV, red – poor CV.

We note that %CV is an imperfect metric for assessing repeatability and reproducibility when the target range of a measurement contains zero or when a test measurement is low and affected by signal noise. Considering the formula for the percent coefficient of variation (standard deviation divided by the mean response) it is apparent that the %CV value is generally higher when the magnitude of the mean response is low even if the standard deviation is relatively small.

5.1. Pendulum Qualification Results

Pendulum qualification results are listed in Table 28 and time histories are shown in Figures 141 and 142. Everything passed except that the E-Leg PCL elongation did not meet the qualification requirement.

Table 28. Peak injury measures for the pendulum certification tests. The E-Leg did not meet the PCL qualification requirements (highlighted in red).

Injury Measurement	**Corridor**		**Pendulum Qualification**					
	Lower	**Upper**	**VRTC #1**	**VRTC #2**	**SN01 #1**	**SN01 #2**	**E-Leg #1**	**E-Leg #2**
Tibia 1 (Nm)	235	272	247	248	266	263	259	259
Tibia 2 (Nm)	187	219	205	206	208	204	209	208
Tibia 3 (Nm)	139	166	153	154	157	154	159	159
Tibia 4 (Nm)	90	111	104	105	106	104	107	108
MCL Elongation (mm)	20.5	24	22.8	22.9	23.2	23.3	23.5	23.8
ACL Elongation (mm)	8	10.5	9.36	9.49	9.53	9.49	9.47	9.32
PCL Elongation (mm)	3.5	5	4.58	4.51	4.07	4.22	5.06	5.25
E-Leg PCL elongation did not meet the qualification requirement								

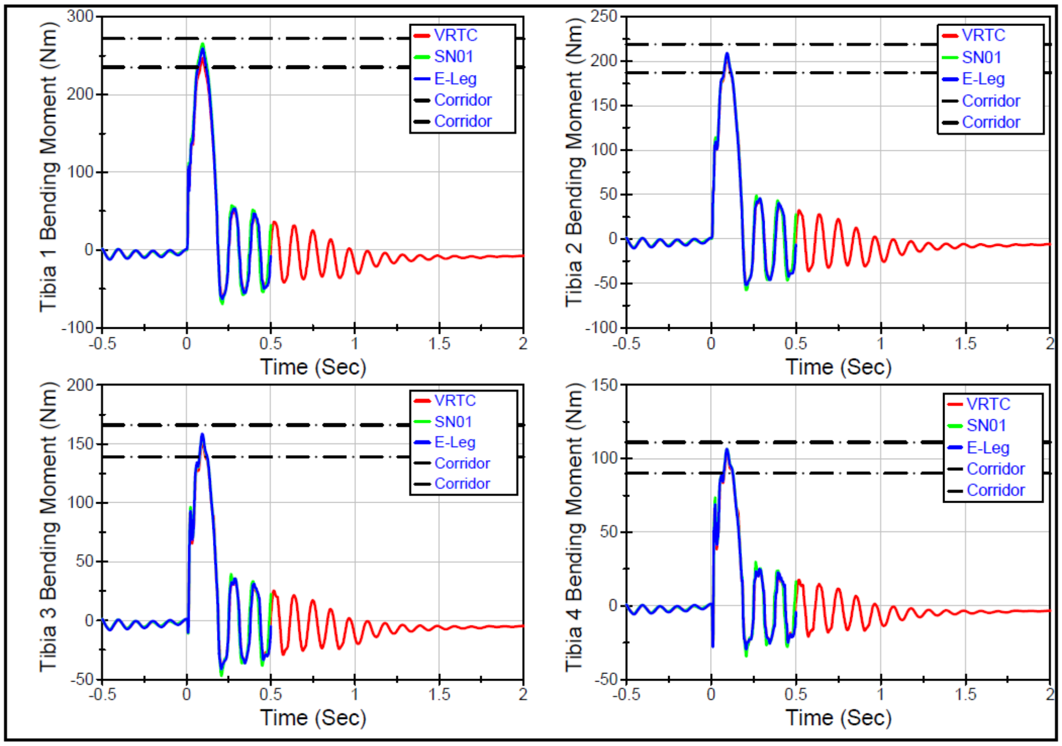


Figure 141. Comparison of Test #1 VRTC, Master SN01, and Master E-Leg tibia moment time histories.

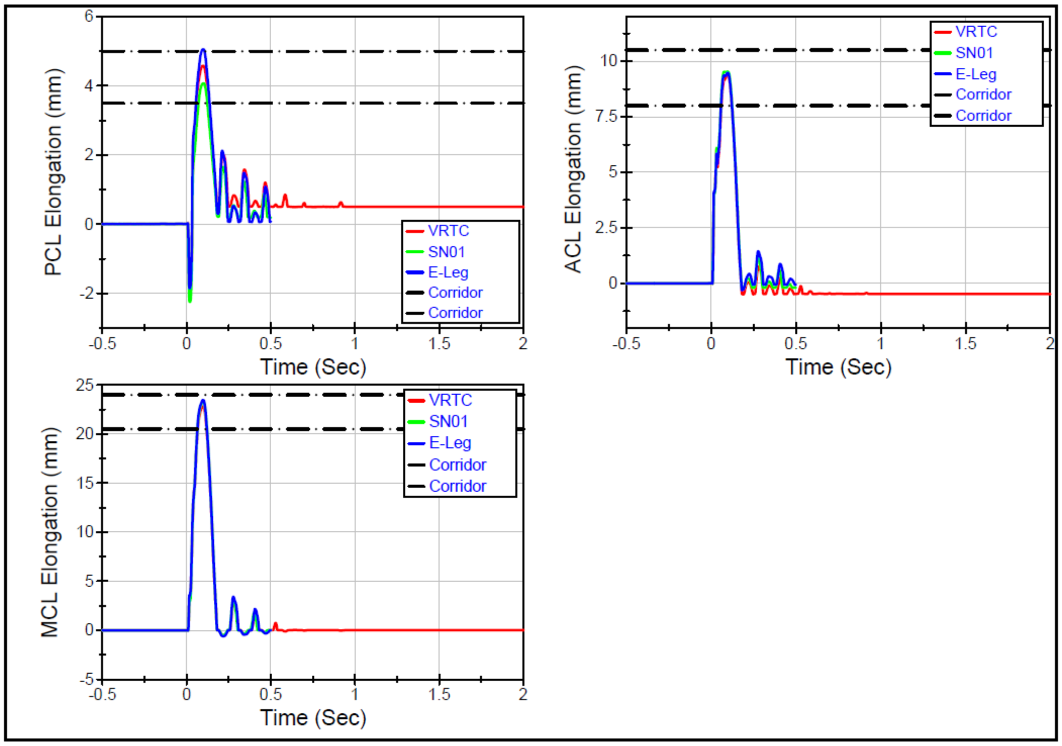


Figure 142. Comparison of Test #1 VRTC, Master SN01, and Master E-Leg ligament elongation time histories.

The reproducibility of the legform by itself can be evaluated using the pendulum certification results. Time histories of pendulum certification tests for each legform are shown to be very similar. In addition, means, standard deviations, and percent coefficient of variations for each injury measure were calculated from the pendulum certification results and are shown in Table 29. With the exception of PCL elongation, the percent coefficients of variation for all other injury measures are below 10%, indicating good reproducibility.

Table 29. Mean, standard deviation, and %CV for the pre pendulum qualification tests.

Injury Measurement	**Pendulum Certification**								
	VRTC		**SN01**		**E-Leg**		**Mean**	**STDEV**	**%CV**
Tibia 1 (N-m)	247	248	266	263	259	259	257	7.82	3.04%
Tibia 2 (N-m)	205	206	208	204	209	208	207	1.97	0.95%
Tibia 3 (N-m)	153	154	157	154	159	159	156	2.68	1.72%
Tibia 4 (N-m)	104	105	106	104	107	108	106	1.63	1.55%
MCL Elongation (mm)	22.8	22.9	23.2	23.3	23.5	23.8	23.3	0.37	1.60%
ACL Elongation (mm)	9.36	9.49	9.53	9.49	9.47	9.32	9.44	0.08	0.88%
PCL Elongation (mm)	4.58	4.51	4.07	4.22	5.06	5.25	4.62	0.46	10.0%

In the certification tests, all of the measurements stayed within the corridor except the PCL in the E-leg. The E-leg exhibited a PCL peak value above the upper limit in the pendulum certification test; however, in vehicle testing, the PCL is typically well below the ACL elongation and is thus not commonly used as the cruciate injury limit.

5.2. Repeatability in Vehicle Testing

The series of tests in this section of the report was intended to evaluate the repeatability of the Flex-PLI legform. In order to evaluate repeatability, multiple impacts were performed on a 2007 Chevrolet Silverado and a 2011 Jeep Grand Cherokee. Testing was performed on the Chevrolet Silverado using the VRTC Flex-PLI while testing was performed on the Jeep Grand Cherokee using the Master SN01 Flex-PLI (Table 30).

For this analysis, we selected the Cherokee from among our test vehicles (described in Section 2) because it represents a newer model built upon a larger vehicle platform that is common in the North American market and generally larger than those tested by the European members of the IWG. In the previous section, the Cherokee was shown to fail the proposed Flex-PLI IARV limits.

We also performed a repeat test of the Silverado that came about due to a polarity issue with the MCL elongation measurement. The repeat test gave us an opportunity to assess Flex-PLI repeatability on a vehicle with a front-end – that of a full-sized pickup truck - that differs markedly from those evaluated by the IWG.

The Silverado tests were carried out with NHTSA's own Flex-PLI legform. As such, the results provide us with a good reference on how repeatability may have been affected by the most recent revisions to the legform as reflected by the results with Master SN01 used in the Cherokee series.

Testing was performed according to the basic procedures described earlier. They are also outlined in Amendment 1 of the Proposal for a Global Technical Regulation (GTR) for the Protection of Pedestrians [GRSP, 2010] at NHTSA's Vehicle Research and Test Center (VRTC). Bumper systems were replaced after each test.

Table 30. Test matrix for evaluating the repeatability of the Flex-PLI.

Vehicle	**Legform**		
	Test #1	**Test #2**	**Test #3**
2007 Chevrolet Silverado	VRTC	VRTC	--
2011 Jeep Grand Cherokee	Master SN01	Master SN01	Master SN01

To evaluate the repeatability of the legform alone, multiple pendulum qualification tests were completed on each of the three legforms (see Section 5.1).

5.2.1. Results: Repeatability in Vehicle Tests

Preliminary acceptance levels for the Flex-PLI lower legform tests have been set by the Flex-PLI Technical Evaluation Group (FLEX-TEG) to be the following limits:

- Maximum dynamic MCL elongation ≤ 22 mm
- Maximum dynamic ACL and PCL elongation ≤ 13 mm
- Maximum dynamic bending moments at the tibia ≤ 340 N-m except for manufacturer defined relaxation zone where maximum dynamic bending moments at the tibia ≤ 380 N-m

Vehicles must meet all of the above requirements to comply with the GTR.

5.2.1.1. 2007 Chevrolet Silverado

Two tests were run with both impacts at the center for the front-end. Figure 143 shows screen captures at time of first contact and at maximum legform bending. Peak values for injury measures for the 2007 Chevrolet Silverado impacts are listed in Table 31 and time histories are shown in Figures 144 - 146. The Chevrolet Silverado passed all proposed injury assessment reference values except for MCL elongation, which it exceeded by only a small amount.

Figure 143. 2007 Chevrolet Silverado impact at times of first contact (left) and maximum deflection (right).

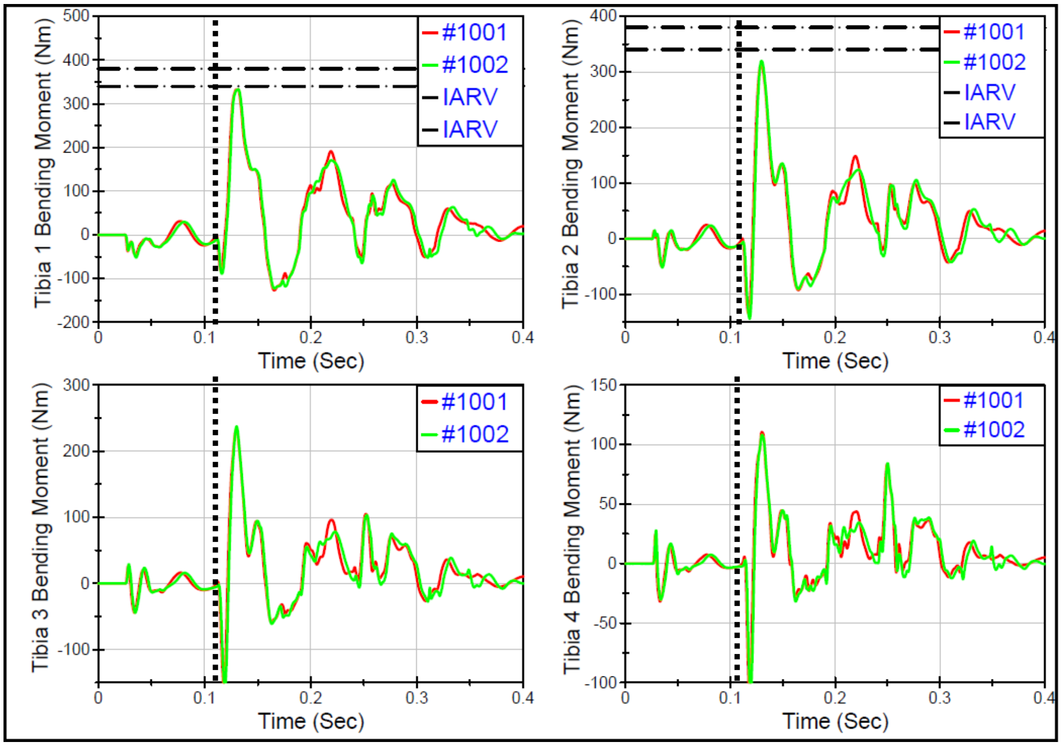


Figure 144. Tibia bending moment time histories for the 2007 Chevrolet Silverado. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

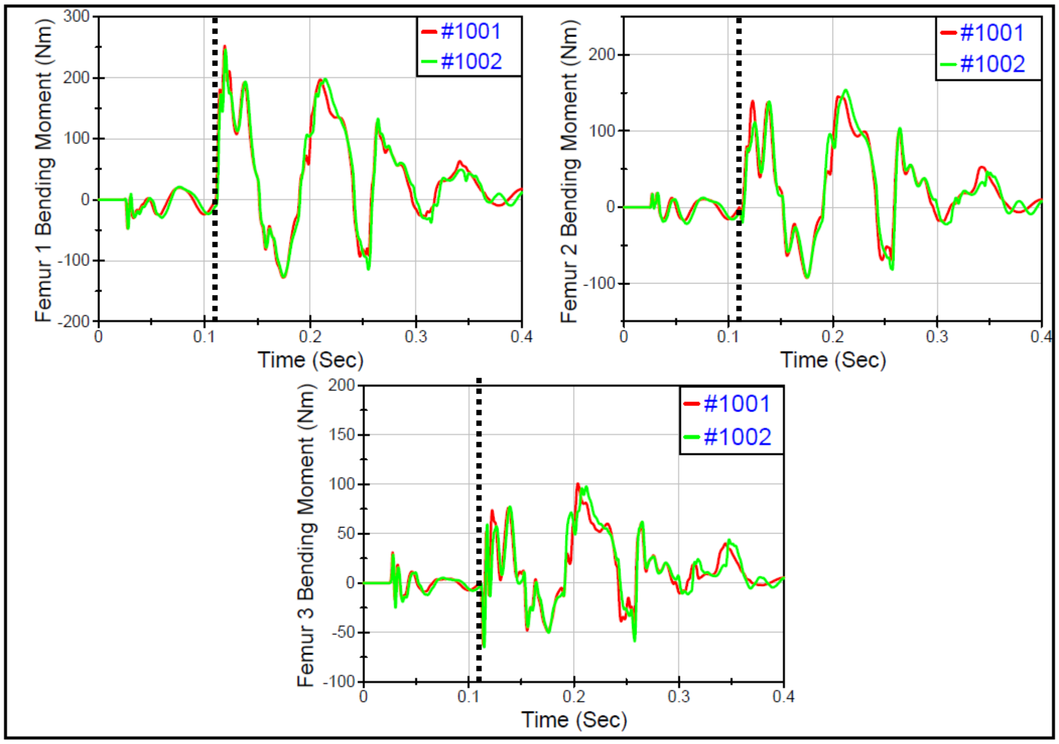


Figure 145. Femur bending moment time histories for the 2007 Chevrolet Silverado. Dotted vertical lines show the time of first contact.

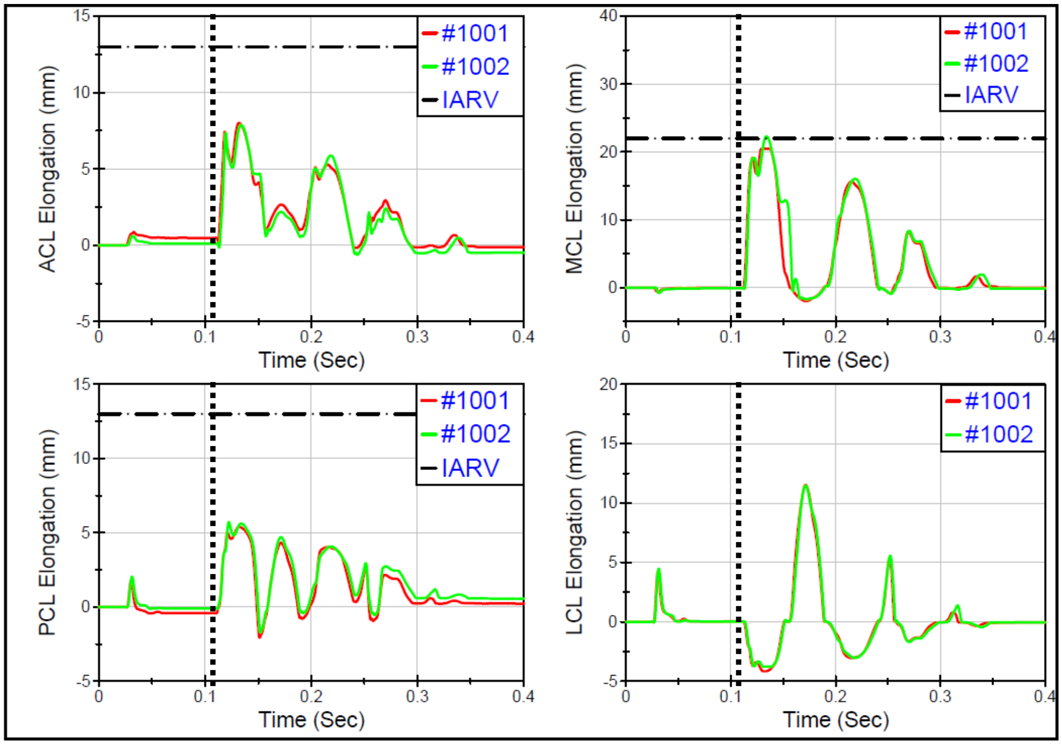


Figure 146. Ligament elongation time histories for the 2007 Chevrolet Silverado. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

5.2.1.2. 2011 Jeep Grand Cherokee

Figure 147 shows screen captures at time of first contact and at maximum legform bending. Peak values for the 2011 Jeep Grand Cherokee center impacts are listed in Table 32 and time histories are shown in Figure 148 - 150. The Jeep Grand Cherokee exceeded the Tibia Moment, MCL, and ACL GTR limits.

Figure 147. 2011 Jeep Grand Cherokee impact at times of first contact (left) and maximum deflection (right).

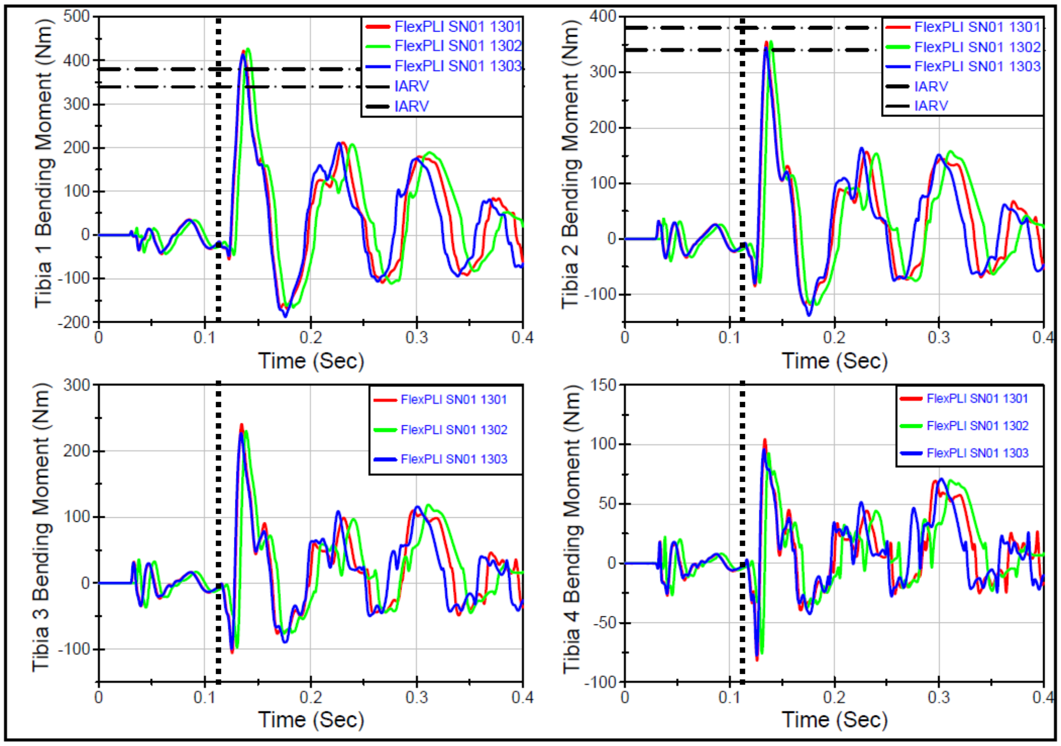


Figure 148. Tibia bending moment time histories for the 2011 Jeep Grand Cherokee. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

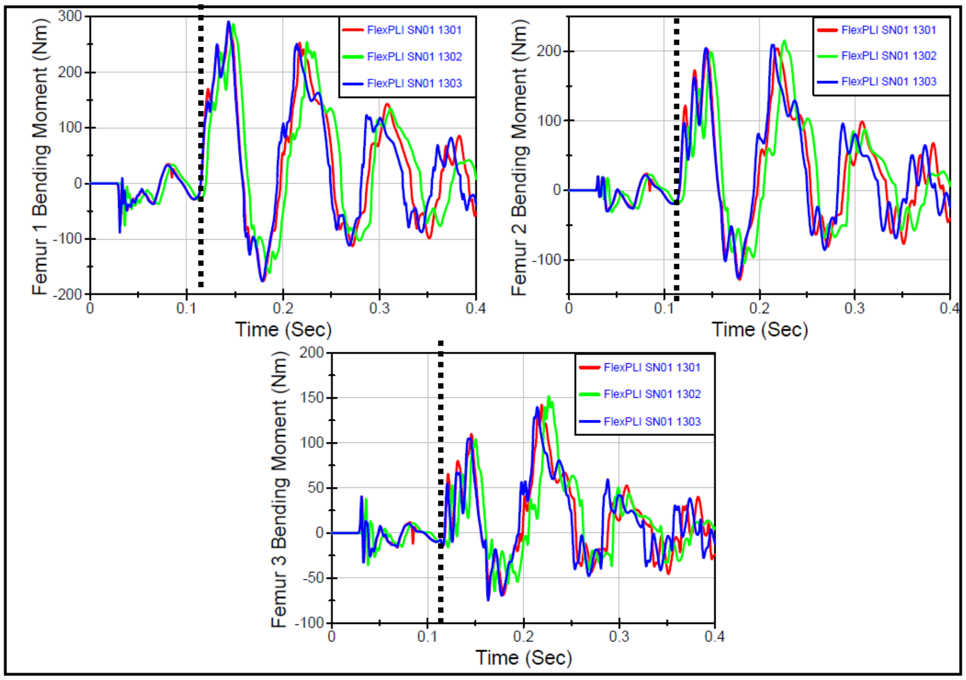


Figure 149. Femur bending moment time histories for the 2011 Jeep Grand Cherokee. Dotted vertical lines show the time of first contact.

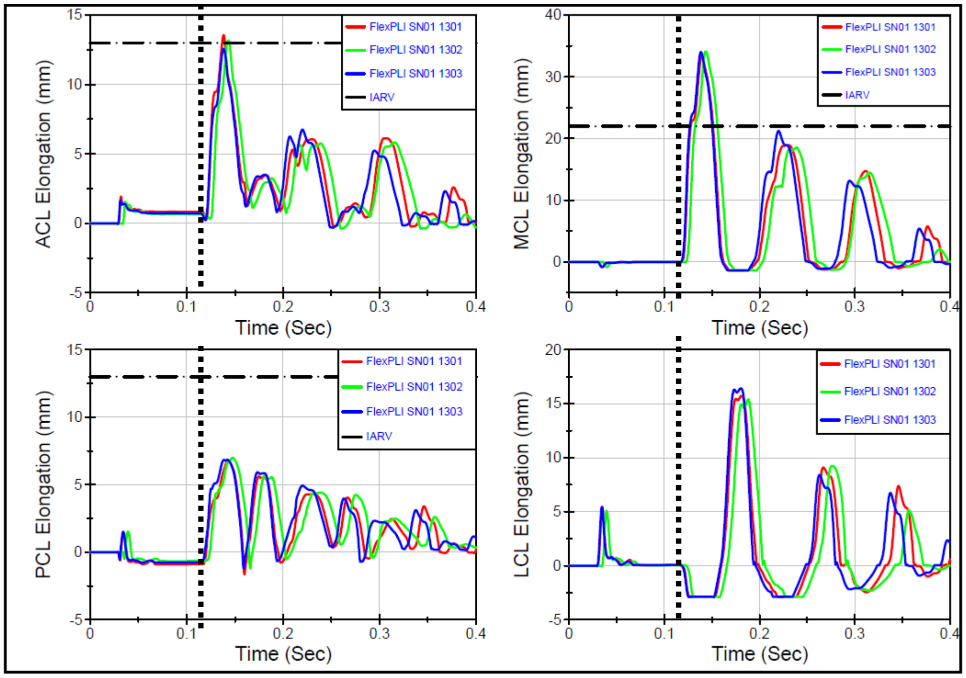


Figure 150. Ligament elongation time histories for the 2011 Jeep Grand Cherokee. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

5.2.2. Analysis & Discussion: Repeatability

The Chevrolet Silverado was tested with the VRTC legform to evaluate repeatability. Two tests were performed using the VRTC legform at the bumper center. Mean, standard deviation, and percent coefficient of variation were calculated for each channel for the repeated tests and are shown in Table 31 below.

Table 31. Mean, standard deviation, and %CV for the 2007 Chevrolet Silverado impacts.

Injury Measurement		IARV	2007 Chevrolet Silverado				
			Center Impact				
			VRTC Legform				
			Test #1001	Test #1002	Mean	STDEV	%CV
Femur Moment (N-m)	**Femur 3 (Upper)**	--	73.7	77.3	**76**	**2.5**	**3.4%**
	Femur 2 (Middle)		139	139	**139**	**0.0**	**0.0%**
	Femur 1 (Lower)		252	246	**249**	**4.2**	**1.7%**
Tibia Moment (N-m)	**Tibia 1 (Upper)**	**340 N-m (380 N-m)**	333	333	**333**	**0.0**	**0.0%**
	Tibia 2 (Mid Upper)		311	320	**316**	**6.4**	**2.0%**
	Tibia 3 (Mid Lower)		234	237	**236**	**2.1**	**0.9%**
	Tibia 4 (Lower)		111	108	**110**	**2.1**	**1.9%**
MCL Elongation (mm)		**22 mm**	--	22.3	**--**	**--**	**--**
ACL Elongation (mm)		**13 mm**	8	7.87	**7.9**	**0.1**	**1.2%**
PCL Elongation (mm)		**13 mm**	5.41	5.61	**5.5**	**0.1**	**2.6%**
LCL Elongation (mm)		**--**	-4.16	-3.76	**-4.0**	**0.3**	**-7.1%**
Tibia Acceleration (g)		--	52.0	50.3	**51.2**	**1.2**	**2.4%**
Impact Velocity (m/s)		**11.1 ± 0.2 m/s**	11.055	11.137	**11.10**	**0.1**	**0.5%**

The Jeep Grand Cherokee was tested with the Master SN01 legform to evaluate repeatability. Three tests were performed using the Master SN01 legform at the bumper center. Mean, standard deviation, and percent coefficient of variation were calculated for each channel for the repeated tests and are shown in Table 32 below.

Table 32. Mean, standard deviation, and %CV for the 2011 Jeep Grand Cherokee impacts.

Injury Measurement		**IARV**	**2011 Jeep Grand Cherokee**					
			Center Impact					
			Legform SN01					
			Test #1301	**Test #1302**	**Test #1303**	**Mean**	**STDEV**	**%CV**
Femur Moment (N-m)	**Femur 3 (Upper)**	--	142	152	140	**145**	**6.4**	**4.4%**
	Femur 2 (Middle)		204	215	209	**209**	**5.5**	**2.6%**
	Femur 1 (Lower)		287	287	290	**288**	**1.7**	**0.6%**
Tibia Moment (N-m)	**Tibia 1 (Upper)**	**340 N-m (380 N-m)**	422	427	413	**421**	**7.1**	**1.7%**
	Tibia 2 (Mid Upper)		355	356	344	**352**	**6.7**	**1.9%**
	Tibia 3 (Mid Lower)		241	230	227	**233**	**7.4**	**3.2%**
	Tibia 4 (Lower)		104	93	96	**98**	**5.7**	**5.8%**
MCL Elongation (mm)		**22 mm**	33.4	34.1	34.0	**33.8**	**0.4**	**1.1%**
ACL Elongation (mm)		**13 mm**	13.6	13.2	12.6	**13.1**	**0.5**	**3.8%**
PCL Elongation (mm)		**13 mm**	6.9	7.0	6.8	**6.9**	**0.1**	**1.4%**
LCL Elongation (mm)		--	15.7	15.4	16.4	**15.8**	**0.5**	**3.2%**
Tibia Acceleration (g)		--	202	204	195	**200**	**4.7**	**2.4%**
Impact Velocity (m/s)		11.1 ± 0.2 m/s	11.181	11.190	11.225	**11.20**	**0.023**	**0.2%**

All %CV results shown in Tables 31-32 are within the acceptable range with a majority of the results in the good range.

5.3. Reproducibility in Vehicle Testing

The series of tests in this section of the report was intended to evaluate the reproducibility of the Flex-PLI legform. In order to evaluate reproducibility, vehicles were impacted with multiple legforms. Three different legforms were used: the VRTC legform, the Master SN01 legform, and the Master E-Leg legform. A 2006 Volkswagen Passat and a 2011 Hyundai Tucson were tested with each of the three legforms (Table 33).

Testing was performed according to the basic procedures outlined herein and in Amendment 1 of the Proposal for a Global Technical Regulation (GTR) for the Protection of Pedestrians [GRSP, 2010] at NHTSA's Vehicle Research and Test Center (VRTC). Bumper systems were replaced after each test.

Table 33. Test matrix for evaluating the reproducibility of the Flex-PLI.

Vehicle	**Legform**		
	Test #1	**Test #2**	**Test #3**
2006 Volkswagen Passat	VRTC	Master SN01	Master E-Leg
2011 Hyundai Tucson	VRTC	Master SN01	Master E-Leg

To evaluate the reproducibility of the legforms alone, multiple pendulum qualification tests were completed on each of the three legforms.

5.3.1. Results: Reproducibility in Vehicle Tests

5.3.1.1. 2006 Volkswagen Passat

Figure 151 shows screen captures at time of first contact and at maximum legform bending. Peak values for the 2006 Volkswagen Passat impacts are listed in Table 34 and time histories are shown in Figures 152 - 154. The Volkswagen Passat exceeded the Tibia Moment and MCL GTR limits.

Figure 151. 2006 Volkswagen Passat impact at times of first contact (left) and maximum deflection (right).

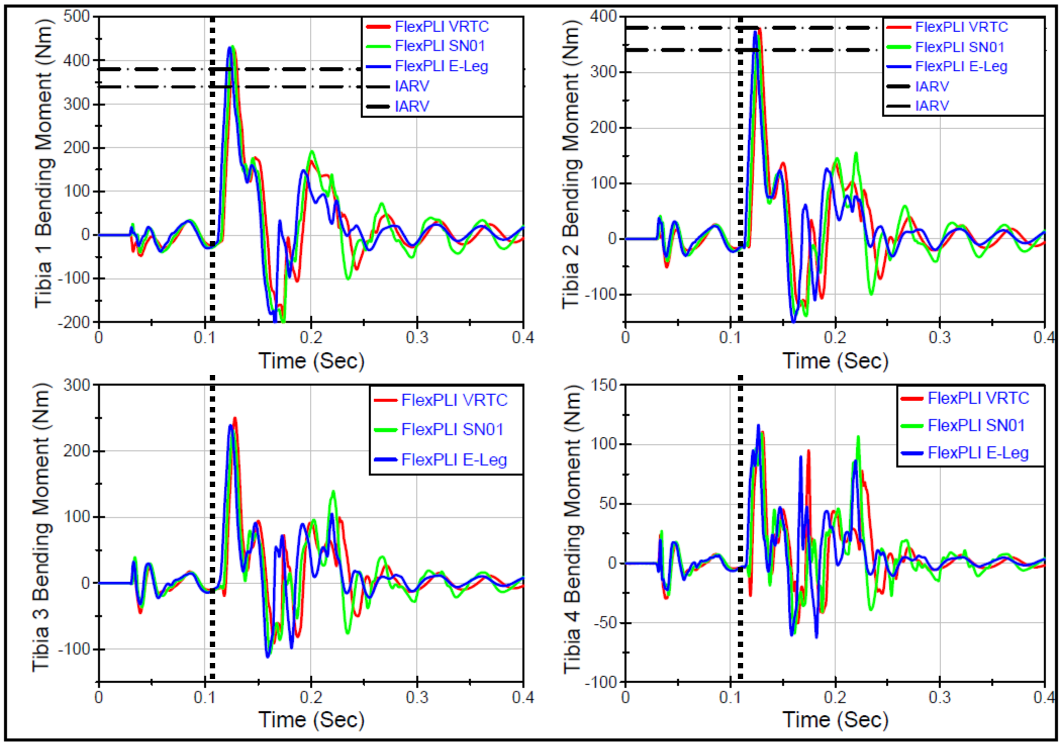


Figure 152. Tibia bending moment time histories for the 2006 Volkswagen Passat. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

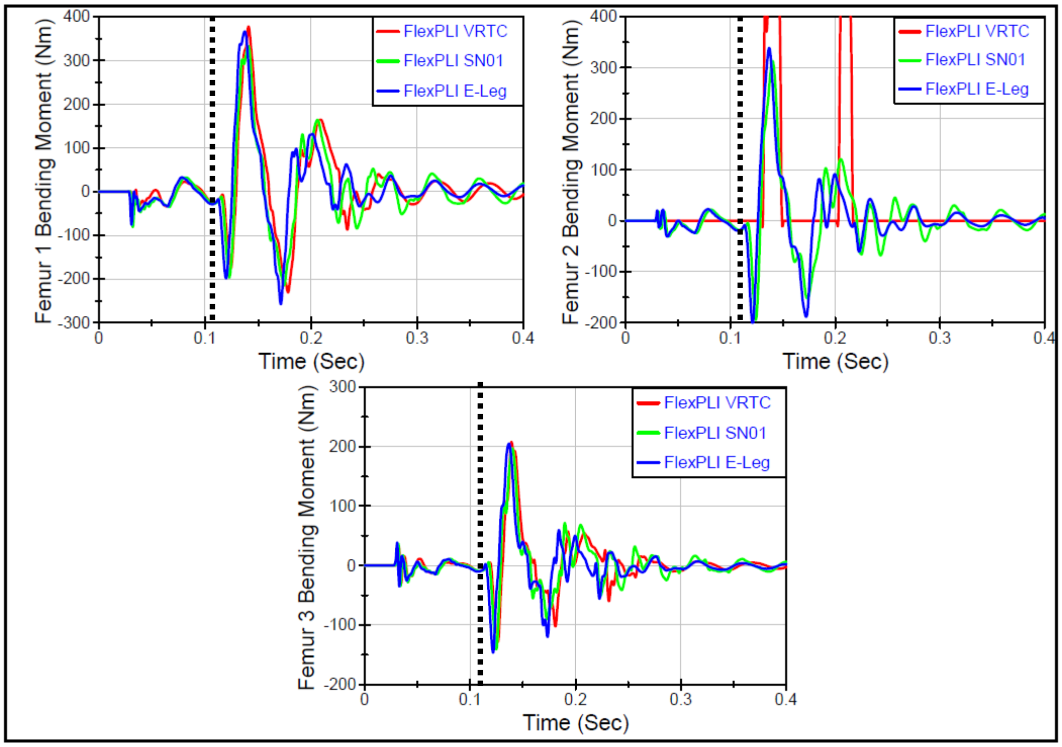


Figure 153. Femur bending moment time histories for the 2006 Volkswagen Passat. Dotted vertical lines show the time of first contact.

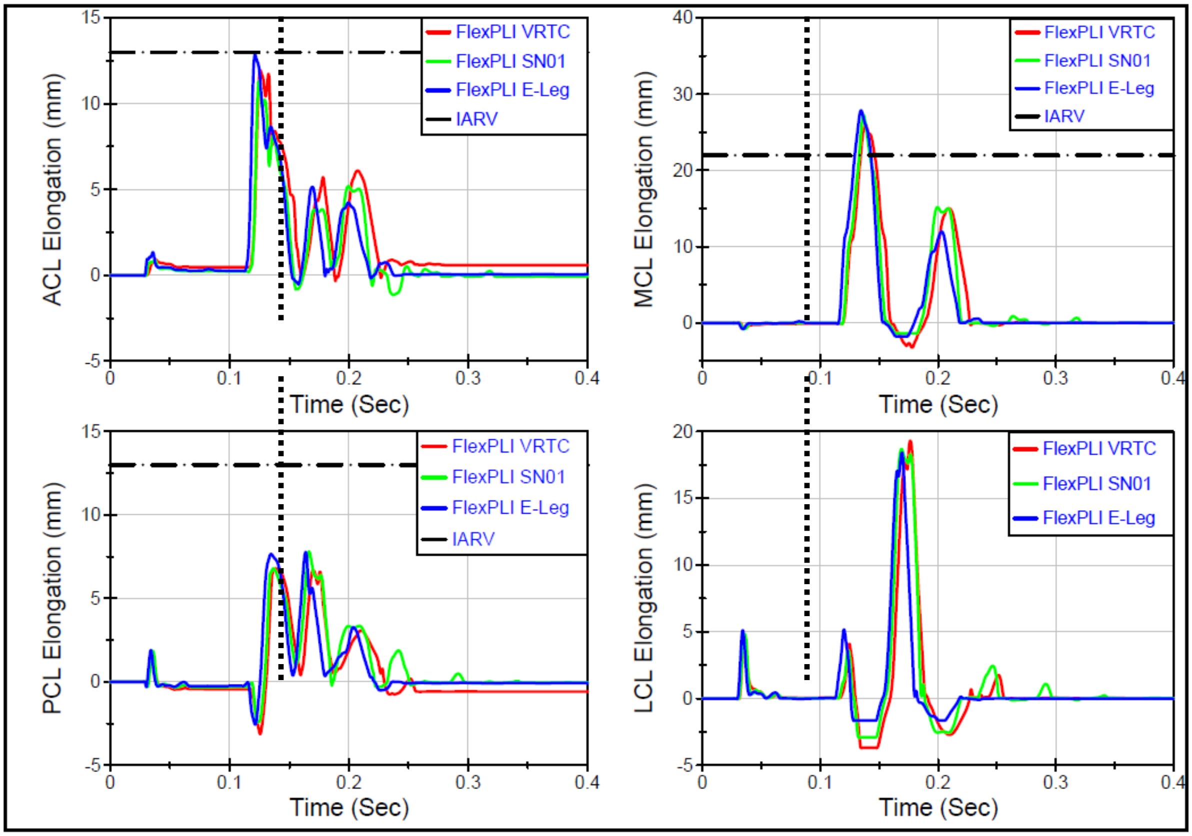


Figure 154. Ligament elongation time histories for the 2006 Volkswagen Passat. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

5.3.1.2. 2011 Hyundai Tucson

Figure 155 shows screen captures at time of first contact and at maximum legform bending. Peak values for the 2011 Hyundai Tucson impacts are listed in Table 35 and time histories are shown in Figures 156 - 158. The Hyundai Tucson exceeded the Tibia Moment, ACL, and MCL GTR limits.

Figure 155. 2011 Hyundai Tucson impact at times of first contact (left) and maximum deflection (right).

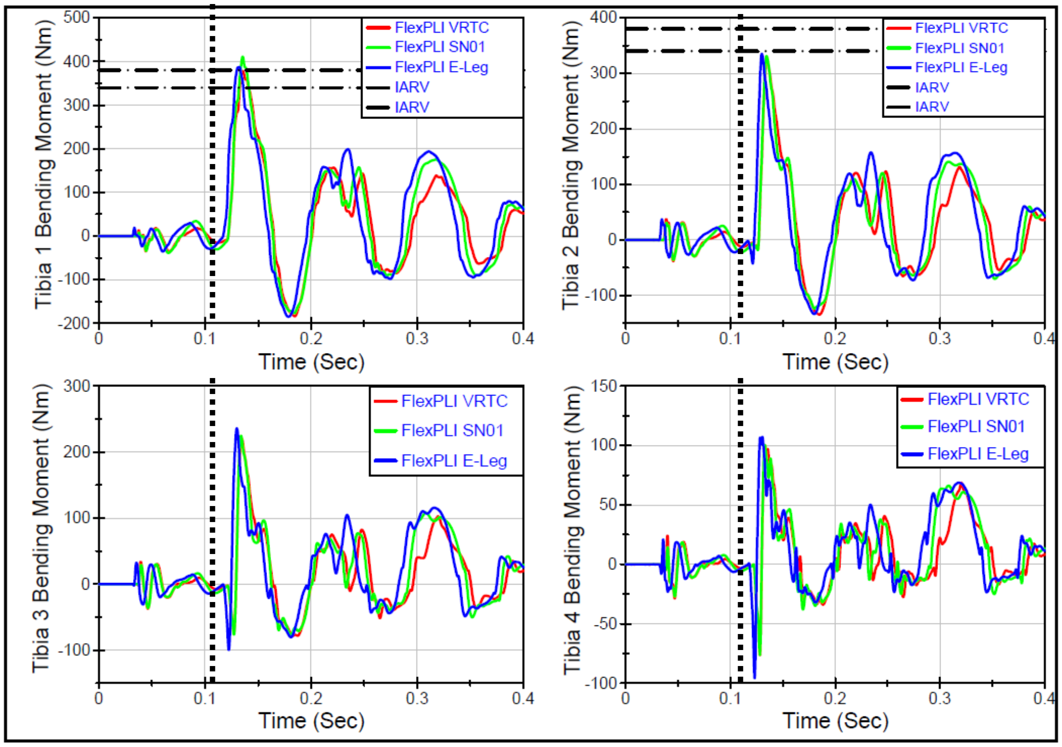


Figure 156. Tibia bending moment time histories for the 2011 Hyundai Tucson. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

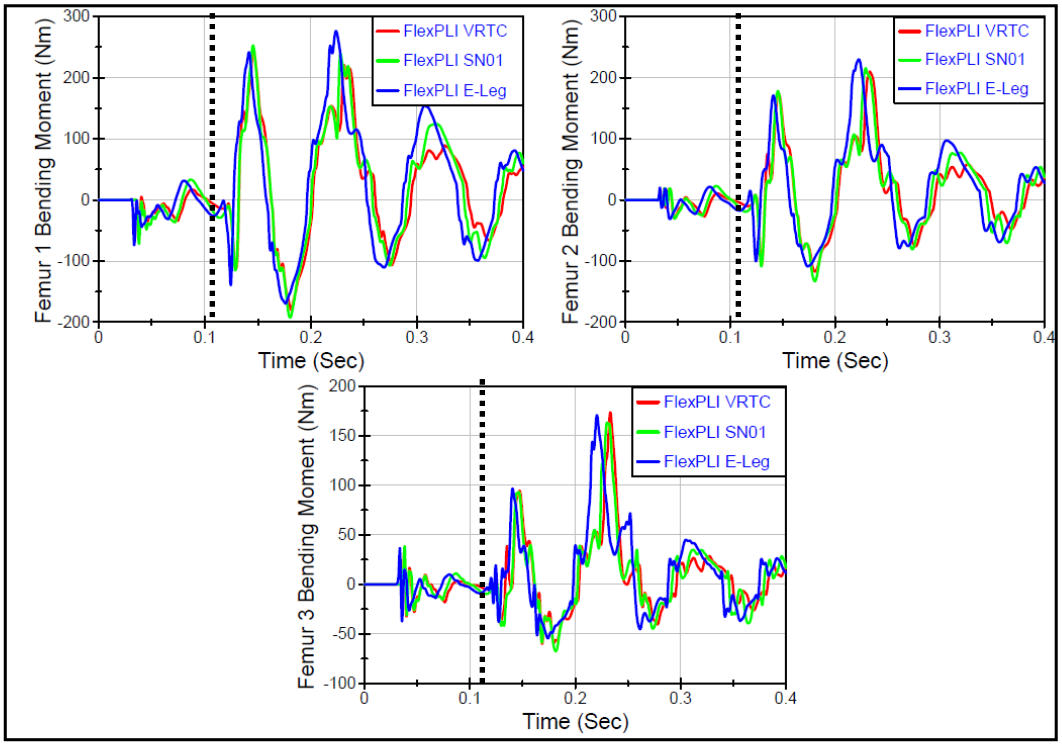


Figure 157. Femur bending moment time histories for the 2011 Hyundai Tucson. Dotted vertical lines show the time of first contact.

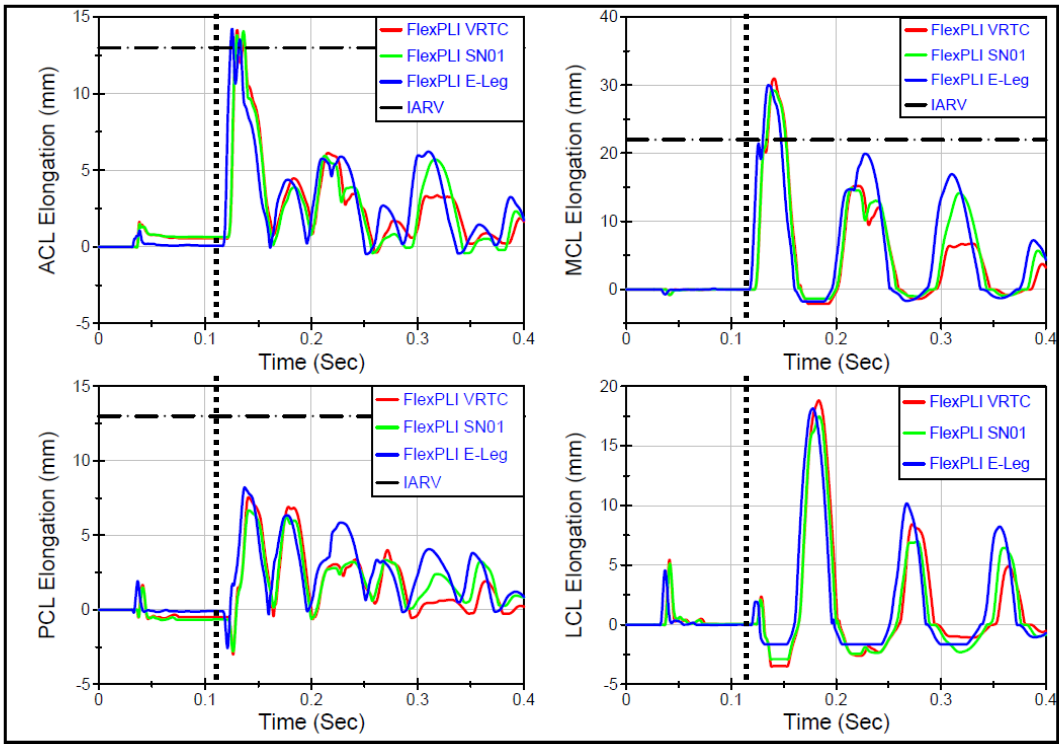


Figure 158. Ligament elongation time histories for the 2011 Hyundai Tucson. Horizontal dashed lines indicate the GTR limits. Dotted vertical lines show the time of first contact.

5.3.2. Analysis & Discussion: Reproducibility

The Volkswagen Passat and the Hyundai Tucson were tested with all three legforms (VRTC, Master SN01, and Master E-Leg) to evaluate reproducibility. All tests were performed at the bumper center. Mean, standard deviation, and percent coefficient of variation were calculated for each channel for the repeated tests and are shown in Tables 34 and 35 below.

Table 34. Mean, standard deviation, and %CV for the 2006 Volkswagen Passat impacts.

Injury Measurement		**IARV**	**2006 Volkwagen Passat**					
			Center Impact					
			VRTC*	**SN01**	**E-Leg**	**Mean**	**STDEV**	**%CV**
Femur Moment (N-m)	**Femur 3 (Upper)**	--	207	197	205	**203**	**5.3**	**2.6%**
	Femur 2 (Middle)		484**	313	339	**326**	**18.4**	**5.6%**
	Femur 1 (Lower)		333	333	366	**344**	**19.1**	**5.5%**
Tibia Moment (N-m)	**Tibia 1 (Upper)**	**340 N-m (380 N-m)**	426	433	430	**430**	**3.5**	**0.8%**
	Tibia 2 (Mid Upper)		379	366	374	**373**	**6.6**	**1.8%**
	Tibia 3 (Mid Lower)		251	231	239	**240**	**10.1**	**4.2%**
	Tibia 4 (Lower)		111	109	116	**112**	**3.6**	**3.2%**
MCL Elongation (mm)		**22 mm**	26.1	27.3	27.9	**27.1**	**0.9**	**3.4%**
ACL Elongation (mm)		**13 mm**	11.9	11.3	12.8	**12.0**	**0.8**	**6.3%**
PCL Elongation (mm)		**13 mm**	6.8	7.8	7.8	**7.5**	**0.6**	**7.7%**
LCL Elongation (mm)		--	19.3	18.7	18.4	**18.8**	**0.5**	**2.4%**
Test Velocity (m/s)		11.1 ± 0.2 m/s	11.019	11.188	11.247	**11.15**	**0.118**	**1.1%**

***VRTC Legform data was presented at the 2012 SAE Government Industry (*NHTSA Evaluation of the Flex-GTR on US Vehicles*)**

****The Femur 2 strain gauge of the VRTC legform was damaged during the test and was repaired**

Table 35. Mean, standard deviation, and %CV for the 2011 Hyundai Tucson impacts.

Injury Measurement		**IARV**	**2011 Hyundai Tucson**					
			Center Impact					
			VRTC	**SN01**	**E-Leg**	**Mean**	**STDEV**	**%CV**
Femur Moment (N-m)	**Femur 3 (Upper)**	--	174	163	171	**169**	**5.7**	**3.4%**
	Femur 2 (Middle)		210	215	230	**218**	**10.4**	**4.8%**
	Femur 1 (Lower)		245	253	276	**258**	**16.1**	**6.2%**
Tibia Moment (N-m)	**Tibia 1 (Upper)**	**340 N-m (380 N-m)**	378	411	387	**392**	**17.1**	**4.4%**
	Tibia 2 (Mid Upper)		329	331	335	**332**	**3.1**	**0.9%**
	Tibia 3 (Mid Lower)		220	225	236	**227**	**8.2**	**3.6%**
	Tibia 4 (Lower)		100	100	107	**102**	**4.0**	**3.9%**
MCL Elongation (mm)		**22 mm**	31.0	29.3	30.0	**30.1**	**0.9**	**2.8%**
ACL Elongation (mm)		**13 mm**	14.1	14.1	14.2	**14.1**	**0.1**	**0.4%**
PCL Elongation (mm)		**13 mm**	7.6	6.7	8.2	**7.5**	**0.8**	**10.1%**
LCL Elongation (mm)		--	18.8	17.5	18.1	**18.1**	**0.7**	**3.6%**
Impact Velocity (m/s)		**11.1 ± 0.2 m/s**	10.968	11.146	11.162	**11.09**	**0.1**	**1.0%**

Almost all of the results are within a 5% coefficient of variation, indicating good reproducibility. However, the ACL and PCL results were found to be outside of the acceptable range with coefficient of variations of 6% and 8%, respectively in the Passat impacts and a PCL variance of 10% in the Tucson impacts.

6. DURABILITY

Table 36 shows the vehicle testing regimen by legform. These vehicles represent a cross-section of those covered by the proposed GTR requirements, including small and midsized sedans, minivans, small and large SUVs, and full sized pickup trucks. For the most part, all of the vehicles tested were North American versions with front-ends that were not designed for PEDPRO conformity. And as observed earlier, most of these tests produced elevated Flex-PLI measurements (above the proposed injury threshold in most cases). As such, the testing regimen exposed the legforms to a fairly harsh test environment in which the durability of the Flex-PLI can be assessed.

Table 36. Summary of tests for durability assessment.

	VRTC Legform	**Master SN01**	**Master E-leg**
2011 Chevrolet Cruze	3		
2009 Chevrolet Equinox	1		
2007 Chevrolet Silverado	2		
2012 Ford Focus	2		
2013 Ford Fusion	3		
2002 Honda Civic	3		
2011 Honda Odyssey	2		
2003 Honda Pilot	1		
2011 Hyundai Tucson	1	1	1
2011 Jeep Grand Cherokee	4	3	
2002 Mazda Miata	3		
2010 Toyota Yaris	3		
2006 Volkswagen Passat	5	1	1
Total impacts	**33**	**5**	**2**

6.1. Analysis & Discussion: Durability

By far, the VRTC legform was used the most (Table 36). The only major damage observed with VRTC's Flex-PLI was a damaged middle femur strain gage. It is not known how the middle femur strain gage was damaged. However, testing continued since the femur data is not used as an injury criterion and because the middle femur strain typically falls between the lower and upper femur strains. No major damage was observed on either of the Humanetics Master legforms, SN01 and the E-leg.

In addition to the damaged femur strain gage, all three versions of the Flex-PLI legform showed a misalignment of the femur and tibia knee blocks after each impact, which was easily realigned (Figure 159). This is normal, and the legform was designed to undergo this type of misalignment and to be re-aligned by the test operator without sustaining permanent damage.

In rebound impacts with the floor, minor damage was sustained to all three versions of the Flex-PLI legform. Figure 160 shows a small tear in the neoprene skin as a result of floor contact after impact and cosmetic damage to the femur knee block just underneath the neoprene tear.

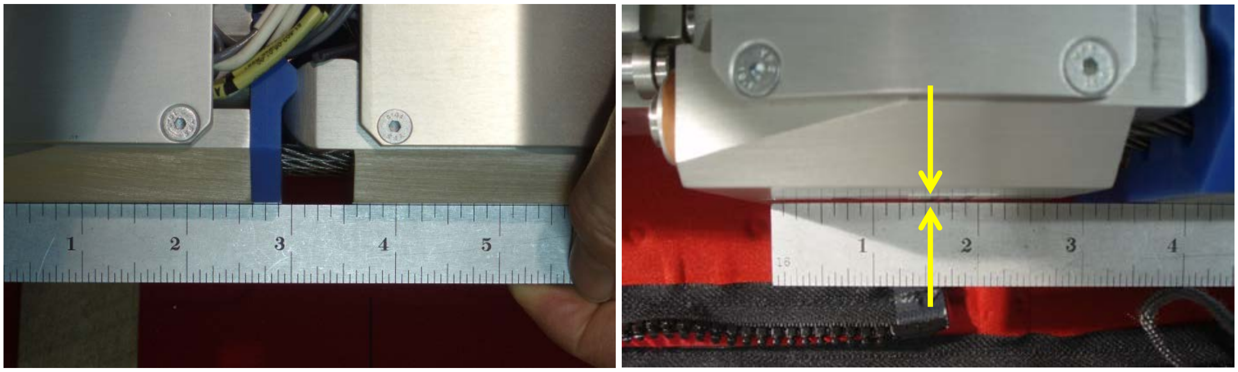


Figure 159. Misalignment of the tibia and femur knee blocks. The tibia and femur knee blocks should be flush with each other as shown in the left photo. The gap between the measuring scale and the knee block in the right photo shows a misalignment between the tibia and femur knee blocks.

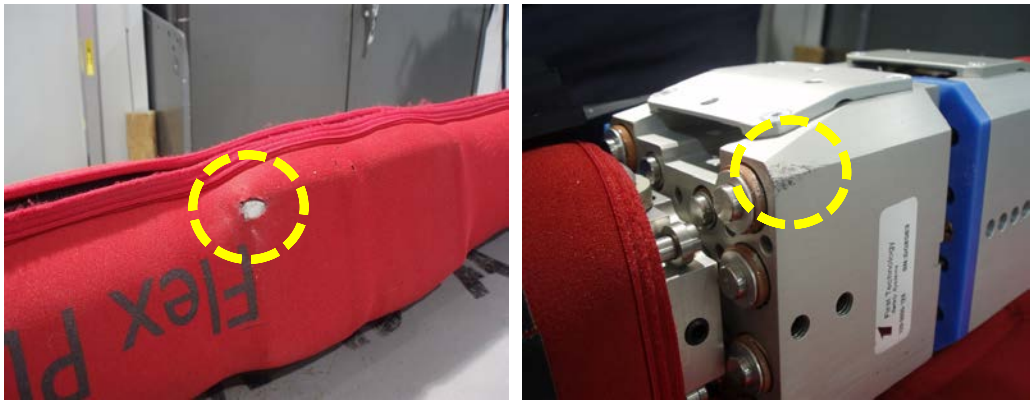


Figure 160. Cosmetic damage to the neoprene skin (left) and femur knee block (right).

Legform durability was also indirectly evaluated as a result of the pre and post pendulum qualification tests. For the VRTC legform, qualification testing was carried out before, during, and after the test series. For the Master legforms, qualification tests were carried out directly before and after their respective vehicle testing regimen. In all cases, the legforms were within the qualification corridors.

Bar charts were created for the tibia bending moment and ligament injury measures in Figures 161 and 162 below. In the figures, solid bars indicate pre-testing qualification results and the hashed bars indicate post-testing results. The results show that the pre and post-testing qualification results do not change much, indicating good legform durability since the responses were not significantly affected by the vehicle testing regimen.

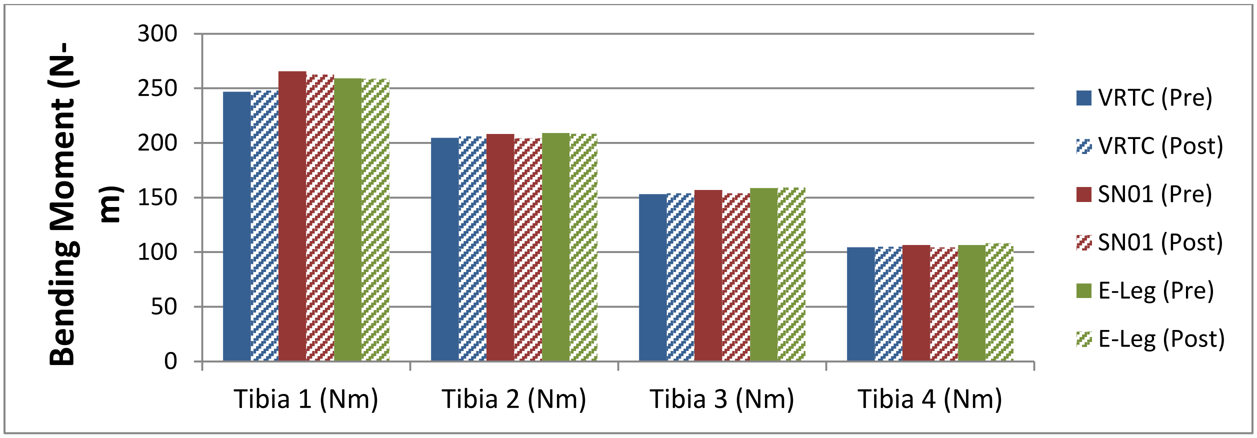


Figure 161. Tibia bending moment (pre and post vehicle testing qualification).

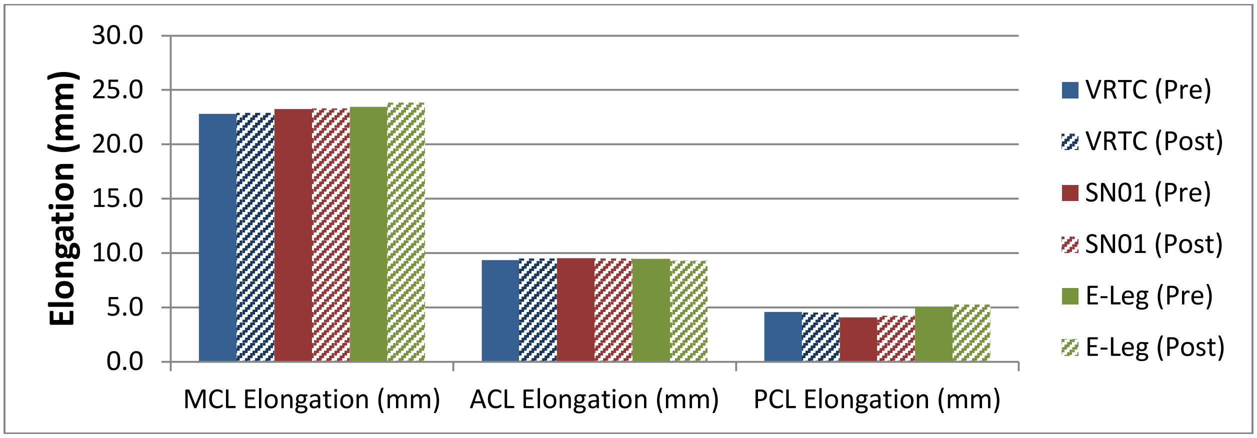


Figure 162. Knee ligament elongation (pre and post vehicle testing qualification).

The Flex-PLI survived the aggressive outboard passenger car impacts as well as the aggressive larger vehicle impacts and the response of the legform was consistent before and after the test series. The Flex-PLI was concluded to be a durable test device.

7. SUMMARY OF FLEX-PLI VEHICLE TEST RESULTS

Table 37 summarizes the Flex-PLI results for the different vehicles and bumper configurations tested in the evaluation. Regarding fleet performance with respect to Flex-PLI IARV values, there is definite room for benefits from the GTR. With the exception of the Fusion, none of the NA version vehicles passed all three Flex-PLI requirements. It should be noted that several of the vehicles tested were model years prior to adoption of the GTR, and several more would be in the design cycle prior to adoption. In the case of the MCL injury, all of the elongations were above the proposed 22mm limit with the exception of the Fusion (18 mm in center/15 mm in outboard impacts) and Cruze (14 mm in center impact). In the case of tibia fracture risk, the Fusion (250 Nm) and Silverado (333 Nm) were the only two vehicles that passed the proposed GTR requirement of 340 N-m. The rest of the NA vehicles had tibia bending moments above the proposed limit, and ranged from 361 Nm to 475 Nm. Six of the 13 NA-version vehicles passed the ACL elongation requirement of 13 mm, including the Silverado (7.9 mm). Interestingly, the Silverado was the largest (highest bumper) vehicle tested, and it passed two of the three GTR injury limits. This demonstrates that vehicle size is not necessarily predictive of pedestrian leg protection.

Table 37. Summary of Results.

Vehicle	Bumper System	Bumper Location	Tibia Bending Moment (IARV=340 Nm)	MCL Elongation (IARV=22 mm)	ACL Elongation (IARV=13 mm)
2009 Chevrolet Equinox	NA	Center	378	34.4	11.9
2002 Mazda Miata	NA	Center	460	24.1	14.3
2007 Chevrolet Silverado	NA	Center	333	22.3	7.9
2003 Honda Pilot	NA	Center	402	32.1	15.5
2001 Honda Civic	NA	Center	475	27.0	14.8
2011 Hyundai Tucson	NA (3 legforms)	Center	392 +/- 17.1	30.1 +/- 0.9	14.1 +/- 0.1
2006 Volkswagen Passat	NA (3 legforms)	Center	430 +/- 3.5	27.1 +/- 0.9	12.0 +/- 0.8
	EU	Center	232	16.8	8.9
	NA w/EU LBS	Center	354	21.3	13.1
2011 Chevrolet Cruze	NA	Center	361	13.9	6
	EU	Center	200	10.3	3.8
	NA w/EU LBS	Center	335	14.9	8.1
2013 Ford Fusion	NA	Center	250	18	7.2
	NA	Outboard (2nd hit)	177	14.6	6.7
	NA	Outboard (1st hit)	184	15.1	7.4
2012 Ford Focus	NA	Center	372	28.6	10.7
	EU	Center	182	10	4.7
2010 Toyota Yaris	NA	Center	407	32.9	14
	EU	Center	258	18.6	7.8
	NA w/EU LBS	Center	348	25.5	12.9
2011 Jeep Grand Cherokee	NA (3 repeats)	Center	421 +/- 7.1	33.8 +/- 0.4	13.1 +/- 0.1
	NA w/EU LBS	Center	387	32.3	14.3
2011 Honda Odyssey	NA	Center	385	31.2	14.5
	NA w/adapted LBS	Center	390	31	15.7

7.1. New, “Global” North American Models vs Older Models.

In this section, we examine whether newer, global models have become more pedestrian compliant in their front-end designs by comparing the performance of newer, global models against older models. Only the results of North American versions are compared (not E.U. or Hybrid versions). The vehicles are grouped into two categories:

> ***Category 1 - New, “Global” Models***: These are new vehicles that are known to be built on global platforms such that U.S. and E.U. models have the same underpinnings. The E.U. versions are compliant with the GTR. These include:
>
> - 2013 Ford Fusion
> - 2011 Chevy Cruse
> - 2011 Hyundai Tucson
> - 2011 Toyota Yaris
> - 2011 Jeep Grand Cherokee
>
> ***Category 2 - Older Models***: These are older vehicles with a unique North American design or with a more distinct North American vs. E.U. design. These include:
>
> - 2001 Honda Civic
> - 2002 Masda Miata
> - 2003 Honda Pilot
> - 2006 VW Passat
> - 2009 Chevy Equinox

The 2007 Chevy Silverado is excluded from this comparison because it is a pickup truck unique to the North American market, built upon a large-vehicle platform. In other words, there is no global version of this vehicle for comparison that may be more pedestrian compliant.

Comparing the results in Figure 163, we see that for all the injury measures, the newer, “global”, models tend to perform better than the older models.

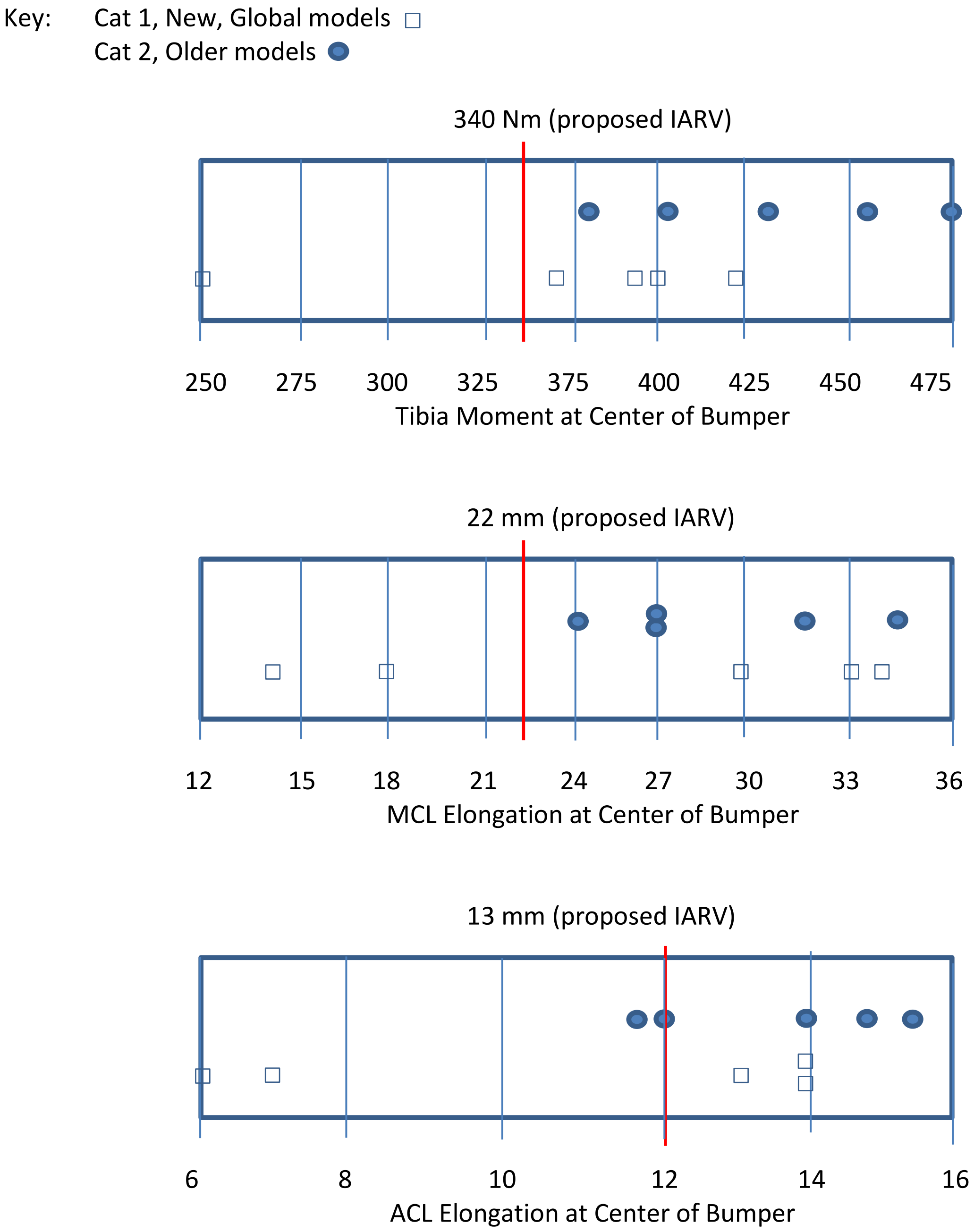


Figure 163. Analysis of injury measurements for older vs. newer model year vehicles

8. CONCLUSIONS

The primary findings from this evaluation were that the Flex-PLI legform is:

- **Durable**, as it didn't sustain any significant structural damage in 30+ vehicle bumper impacts at 40 km/h. Many of these vehicles were far from complying with the GTR injury limits.

- **Biofidelic**, as the legform maintained conformance with qualification corridors derived from biomechanical data

- **Repeatable**, with percent coefficients of variation (%CV) below 5% for all channels and below 2% for all injury channels (MCL and tibia 1 bending moment) in vehicle bumper tests

- **Reproducible**, with %CV of 10% or below for three different legforms in vehicle bumper tests and below 4% in pendulum qualification tests without vehicle or test setup-related variance

- **Sensitive to vehicle design**, as demonstrated through testing a large range of compliant and non-compliant bumper systems. The Flex-PLI discriminated between systems containing pedestrian countermeasures, such as the lower bumper stiffener and modular energy absorber, and older model year, non-GTR compliant systems present in the U.S. fleet

In summary, this assessment demonstrated that the Flex-PLI is an appropriate test tool for evaluating pedestrian lower extremity protection in vehicle bumper impacts.

In addition to these positive aspects of the Flex-PLI, testing with the legform led to a better understanding of (a) the feasibility of producing a bumper system that can comply with both GTR and bumper damageability requirements, (b) the differences expected from using the Flex-PLI instead of the EEVC leg, and (c) the current performance of the U.S. fleet with respect to the GTR.

- Compared to older N.A. models, newer "global" N.A. models generally perform better when assessed with the Flex-PLI.

- One system currently sold in the U.S. market appears capable of meeting both GTR and Part 581 requirements, and the addition of a lower bumper stiffener to another vehicle resulted in passing Flex-PLI measurements and passing Part 581 requirements. However, the full Part 581 series of tests was not conducted and therefore it cannot be stated with certainty that it is completely feasible to pass both requirements.

- In comparing vehicle performance versus their respective injury limits, the Flex-PLI and EEVC display differences which are likely a function of their different structures and measurements.

- One of the thirteen North American (NA) version vehicles passed all three GTR injury requirements with the Flex-PLI. Six of the 13 passed ACL elongation, two of 13 passed the tibia bending moment, and two of the 13 passed MCL elongation.

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10. APPENDIX

EEVC Legform Static Qualification

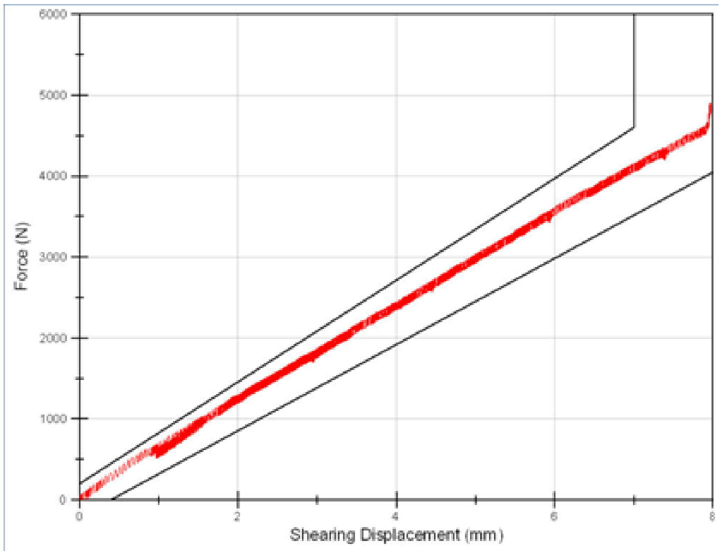
Vehicle Research & Test Center – PO Box 37 East Liberty, OH 43319

Procedure: GTR, ECE/TRANS/WP.29/GRSP/2007/94, 23 July 2007, Part 8.1.1
Performed by: D. Hyder, B.Suntay
Report: B.Suntay

Summary: Both shear and bending tests were within the performance requirements in the GTR. Note however, that ***temperature was not recorded*** during these tests.

Shear Qualification Test

Date: 03/29/2011
Temperature: Not measured
Result: **PASS**



TRL Static Shear Certification (Shear TRL 1103) 03/29/2011
Certification Shear Loading

Figure 2: Applied force versus knee shear displacement, overlaid onto GTR qualification corridor

Shear Requirements: The applied force/shearing displacement response shall be within the limits shown in the figure.

Bending Qualification Test

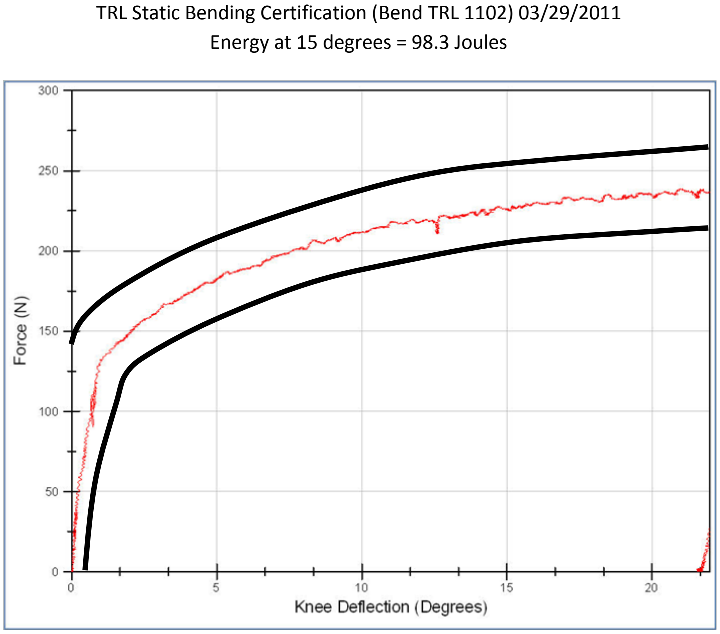
Date: 03/29/2011

Temperature:

Not measured

Energy at 15º = 98.3 J

Result: **PASS**



TRL Static Bending Certification (Bend TRL 1102) 03/29/2011
Energy at 15 degrees = 98.3 Joules

Figure 3: Applied force versus knee bending angle, overlaid onto GTR qualification corridor.

Requirements: The applied force/bending angle response shall be within the limits shown in figure 3 and the energy at 15.0 degrees of bending shall be 100 +/- 7 J.

EEVC Legform Dynamic Qualification

Vehicle Research & Test Center – PO Box 37 East Liberty, OH 43319

Procedure: GTR, ECE/TRANS/WP.29/GRSP/2006/2 3 March 2006, Part 8.1.1
Performed by: D. Hyder, B. Suntay
Report: B. Suntay

Dynamic Qualification Results

Date	Test No.	Impact Velocity (m/s)	Peak Accel (g)	Peak Bend Angle (degrees)	Peak Shear Disp. (mm)	Result
Qualification Corridor		7.4-7.6	120-250	6.2-8.2	3.5-6.0	
3/31/11	DYN CERT TRL 1101	7.56	213	7.9	4.6	**PASS**

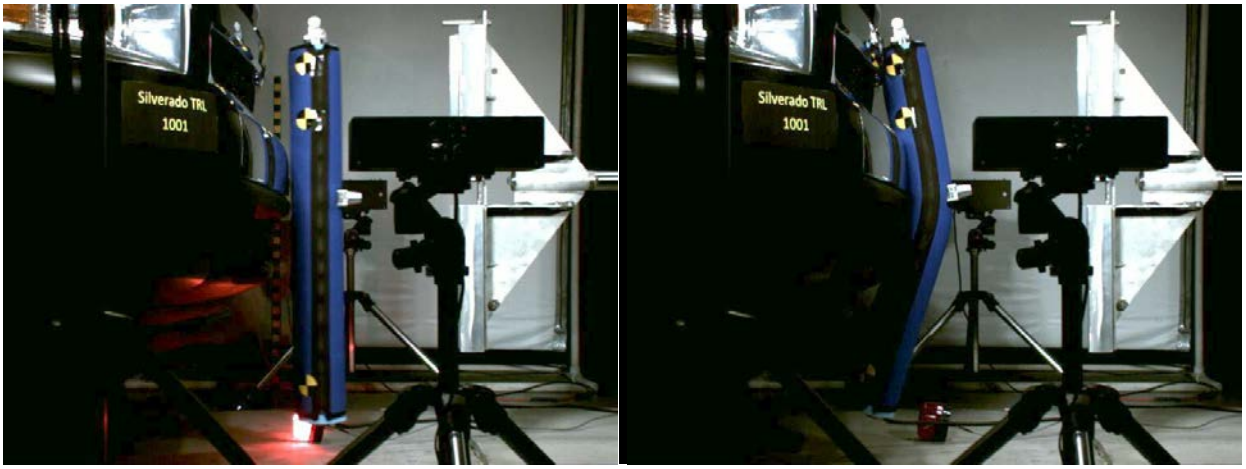
Passed Dynamic Qualification Tests

Date: 3/31/2011
Test Area:
Temperature: 21.6 degrees C
Humidity: 22%
Time in test area following 4-hour soak: 39 minutes
Result: Valid test → **PASS**

EEVC Screen Captures (see 4.1.1.1 for Test Information & Data)

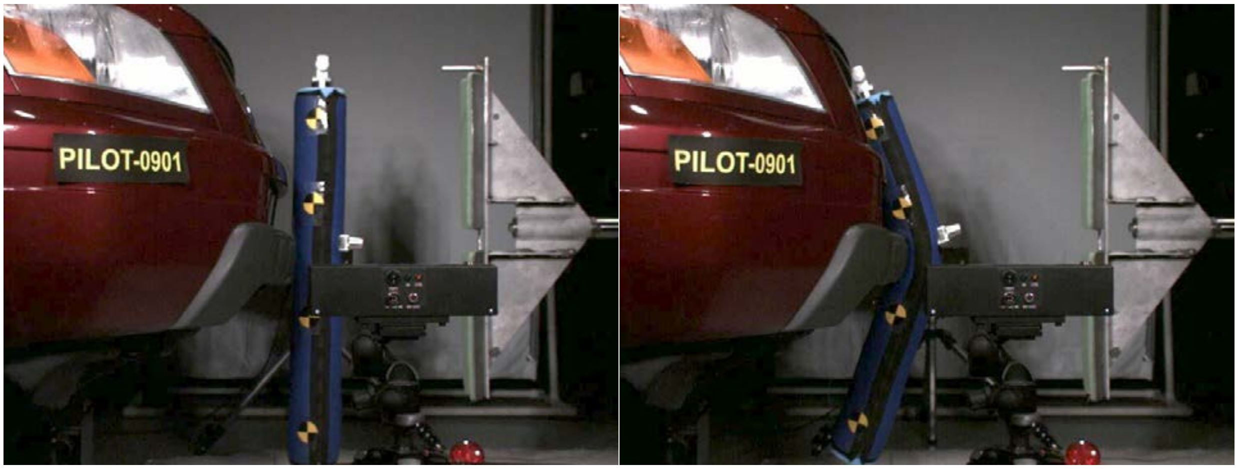
2001 Honda Civic

2009 Chevrolet Equinox

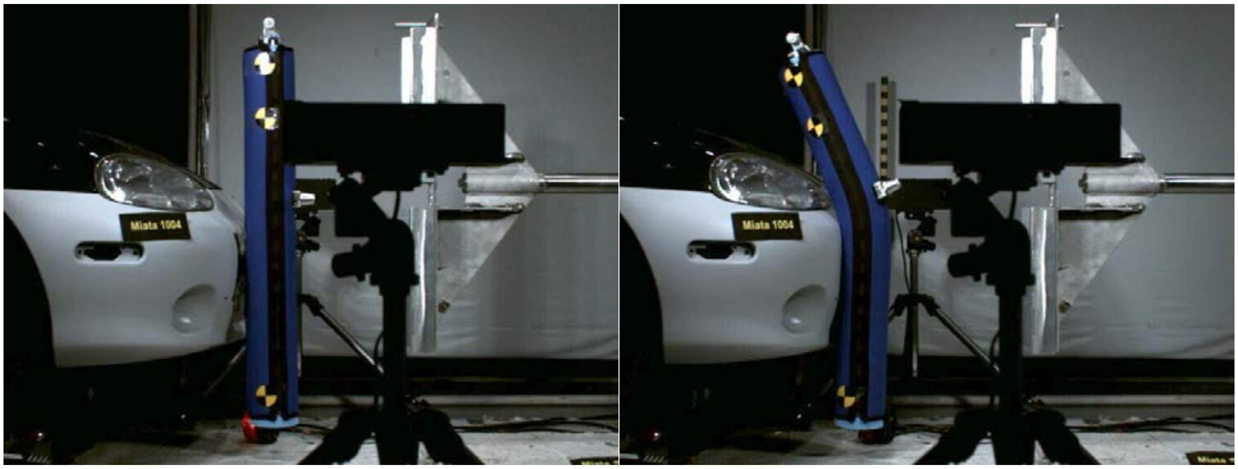


2007 Chevrolet Silverado

2006 Volkswagen Passat



2005 Honda Pilot



2001 Mazda Miata