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16. Abstract

This report documents NHTSA pedestrian head impact tests to provide updated U.S. fleet baseline performance with respect to GTR no. 9. In addition to obtaining information on recent model vehicles with respect to that standard, three objectives were met. The first objective was to evaluate the GTR language defining the head impact point. The current language could be interpreted in more than one way, and a proposed amendment to the GTR supported by the European industry consortium OICA has been introduced to revise the GTR language to reflect one interpretation. Testing was conducted using several interpretations of the impact point ("targeting protocols") to determine differences in test area coverage and HIC outcome. Across six vehicles, an average 5.7% decrease in launch area was found when using the aiming point (AP) protocol versus the 3D point of first contact (3D POFC) protocol. While all tests using either methodology met the GTR HIC 1700 requirement for the relaxation zone, several of the tests would not be within the compliance margin (80% or HIC 1360) typically used by industry. The effect of vehicle design characteristics on both the test area coverage and HIC was analyzed.

The other objectives of this testing were to gauge response reproducibility of different headforms or instrumentation schemes (damped vs. undamped accelerometers). Headforms from FTSS (now Humanetics) and Cellbond displayed very good reproducibility in both certification and vehicle tests. Use of damped accelerometers resulted in lower HIC outcomes in most cases from tests at the same location using undamped accelerometers.

In summary, this report provides NHTSA with (1) a more recent fleet baseline information, (2) a better understanding of the feasibility and performance repercussions of specifying a particular headform targeting protocol, and (3) technical rationale for headform dimensions and instrumentation in developing a Part 572 technical data package (TDP).

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Executive Summary

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In summary, this report provides NHTSA with (1) a more recent fleet baseline for assessment, (2) a better understanding of the feasibility and performance repercussions of specifying a particular headform targeting protocol, and (3) technical rationale for headform dimensions and instrumentation in developing a Part 572 technical data package (TDP).

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1. Introduction

1.1. Background

Over the past several decades, NHTSA has conducted many pedestrian headform-to-hood impacts to investigate protection provided through vehicle front end design. These investigations have examined various aspects of pedestrian head protection through experimental testing [Pritz 1983, Monk et al 1985, McLaughlin & Kessler 1990, Stammen et al 2001, Mallory et al 2007]. Fleet evaluations have provided snapshots in time for performance of evolving technologies to mitigate pedestrian head injuries. NHTSA participated in the International Harmonization Research Activity (IHRA), where this experimental data as well as other information related to pedestrian injuries in the U.S. was contributed as technical background for the development of a global technical regulation (GTR) for pedestrian safety [UNECE, 2009]. In November 2008, the U.S. voted yes to adopt GTR no. 9 as a harmonized test for evaluating the potential for pedestrian head and leg injuries.

GTR no. 9 specifies a valid headform-to-hood impact as follows:

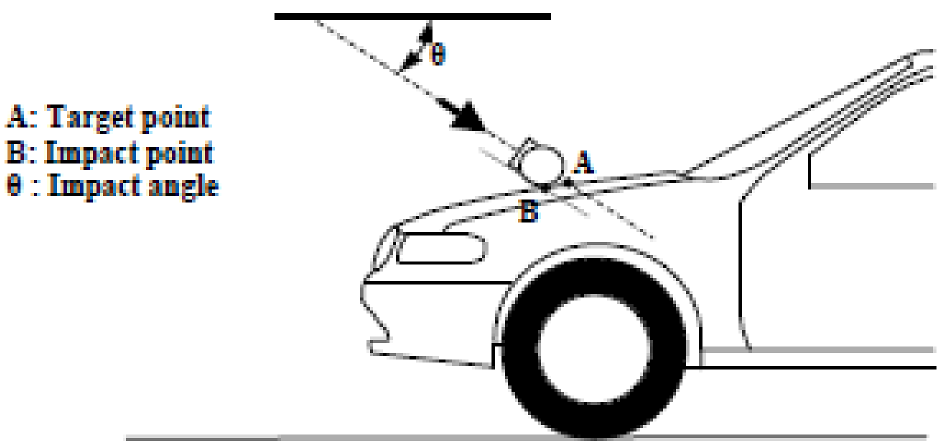


Figure 6: Impact and target point (see paragraphs 3.19. and 3.25.)

The procedure states that "selected **impact points** on the bonnet for the headform impactor shall be, **at the time of first contact",** a minimum of 82.5 inside the defined front/side/rear reference lines within the applicable child or adult WAD zones, with the following definitions for "impact point" and "target point":

- "Impact point" means the point on the vehicle where initial contact by the test impactor occurs. The proximity of this point to the target point is dependent upon both the angle of travel by the test impactor and the contour of the vehicle surface (see point B in Figure 6).

- "Target point" means the intersection of the projection of the headform longitudinal axis with the front surface of the vehicle (see point A in Figure 6.).

The GTR language specifies that the selected “impact point” (not necessarily the “target point”) must be within the test zone. The “impact point” is the point on the vehicle where initial contact by the test impactor occurs. The GTR language does not specify explicitly that this initial contact of the impactor be in the same longitudinal plane as the “target point.” It only states that the “target point” is the intersection of the headform’s longitudinal axis with the vehicle. There is no language to specify that the “selected impact point” is the target point or that the target point has to be inside the 82.5 mm offset boundary lines. It could be interpreted that the 82.5 mm offset accounts for the difference between the target point and impact point locations (the target point can thus be within the 82.5 mm margin). It is evident from the language that the proximity of the impact point to the target point is dependent on the “contour of the vehicle surface”, which can theoretically be in any plane.

Late in 2011, the Netherlands, with support of OICA, proposed an amendment to specify that the GTR language intends that the “target point” be within the test zone and that the “selected impact point” is the same as the “target point” (renamed “2D measuring point”). The amendment attempts to provide more detailed test procedure language to describe a valid test point, in an effort to reduce the possibility of different interpretations of the original language. The amendment contains a revision to specify a “two-dimensional” definition of the impact they refer to as the “2D measuring point,” where the intersection of the longitudinal centerline of the pedestrian headform with the vehicle must be within the prescribed, vehicle-specific test zone boundaries. In contrast, NHTSA has interpreted the language of the original GTR to mean that as long as *any point of* the headform touches inside the 82.5 mm bounded test zone as specified in the GTR, it would be considered a valid test point as long as the target point (headform centerline projection) is within the initially drawn front/side/rear boundaries of the test zone. This method engages more structural members along the extreme periphery of the prescribed zone and therefore could provide more benefit to pedestrians in harder vehicle areas.

Different interpretations of the head impact point could affect HIC outcome in a test, depending on the geometry/contour and underhood structures in the vehicle. Two other aspects of the test that could influence HIC are headform reproducibility and the use of damped or undamped accelerometers. To complete the Part 572 headform technical data package (TDP), which would be incorporated by reference in a Federal Motor Vehicle Safety Standard (FMVSS), these two aspects were also investigated in this study. Previous NHTSA hood impact testing had been done with child and adult-sized headforms from one manufacturer (FTSS), only instrumented with undamped accelerometers. Therefore, to investigate headform response reproducibility and instrumentation specifications, two new child/adult headforms (JASTI/Cellbond) were used in this study along with 7264G damped accelerometers (Meggitt/Endevco).

1.2. Objectives

This study had three main objectives. The first objective was to investigate how the front, side, and rear borders of the GTR "launch area" would change if various targeting protocols are used. The launch area is defined as the area above the hood in which the headform is positioned and launched. The launch area is measured within a horizontal (x-y) plane (i.e., it is flat). The launch area changes depending on the targeting protocol used (NHTSA, Netherlands/OICA, EuroNCAP) even if the test zone boundaries marked on the hood do not change. The test zone boundaries encompass all points of interest on the hood surface, regardless of which targeting protocol is used. The first objective includes testing and analysis to:

- Evaluate how much narrower the launch area would be (from side to side) if the Netherlands "2D measuring point" targeting protocol was adopted.

- Assess the feasibility of conforming to the HIC requirements along the side boundary of the test area for the current targeting protocol vs. the Netherlands targeting protocol.

- Along the front and rear borders, evaluate how much the launch area would change if the EuroNCAP aim point protocol for targeting a test point was implemented.

- Assess the feasibility of conforming to the HIC requirements along the front and rear borders if the EuroNCAP aim point protocol was adopted.

- Along the sides, assess the equivalency of the width of the launch area produced using the Netherlands-proposed and EuroNCAP mark-off protocols.

These effects were investigated for the purpose of developing an objective, repeatable compliance test procedure for evaluating vehicles that reflects the GTR without compromising the safety benefit for pedestrians.

The second goal was to evaluate the response reproducibility of headforms supplied by multiple manufacturers (FTSS/Humanetics and JASTI/Cellbond). This evaluation was important to assure that headform specifications as defined in the regulatory drawing package and procedures for assembly, disassembly, and inspection (PADI) conform to existing headforms on the market. In addition, consistency in HIC outcomes using both headforms is important for compliance testing.

The third objective of this work was to evaluate the effect of using undamped or damped accelerometers in head testing. The GTR preamble contains a recommendation to use damped accelerometers. This need spawned from windshield testing, which was originally part of the testable zone but later removed because it was not deemed feasible to mitigate head impacts in that area of the vehicle. Undamped accelerometers are established sensors and have widespread use in anthropomorphic test device (ATD) testing. Given there is no longer a windshield requirement and use of damped accelerometers may add a cost burden to test laboratories, it is important to understand the repercussions of using damped or undamped sensors for pedestrian headform-to-hood testing.

2. Methods

The study was divided into three phases to provide additional technical data to help the agency (a) decide whether the Netherlands proposal provides improved objectivity to the GTR procedure while maintaining the safety benefit of the GTR, (b) assure that headform responses from different manufacturers are consistent in the same vehicle impact location, and (c) determine whether or not it is necessary to specify damped accelerometers in hood tests. All testing was conducted at the NHTSA Vehicle Research & Test Center (VRTC).

2.1. Vehicle Selection

The following vehicles were tested in this study:

- 2010 Kia Forte
- 2010 Buick LaCrosse
- 2011 Honda Odyssey
- 2010 Hyundai Tucson
- 2010 Acura MDX
- 2011 Jeep Grand Cherokee

The vehicles were selected to represent a range of 2010-2011 vehicle types and sizes that are characteristic of the U.S. fleet in terms of hood designs. A small sedan (Kia Forte), mid-size sedan (Buick LaCrosse), mini-van (Honda Odyssey), small SUV (Hyundai Tucson), mid-sized SUV (Acura MDX), and large SUV (Jeep Grand Cherokee) were tested. These vehicles had hoods ranging from flat traditional geometry to the more clamshell-like geometries. These more undulated hood designs have become more prevalent, increasing the potential for simultaneous first contacts in the same headform test. This trend in hood geometry has led to increased emphasis on making the GTR language more clear to limit the risk of simultaneous first contacts or more severe secondary impacts outside of the prescribed test zone.

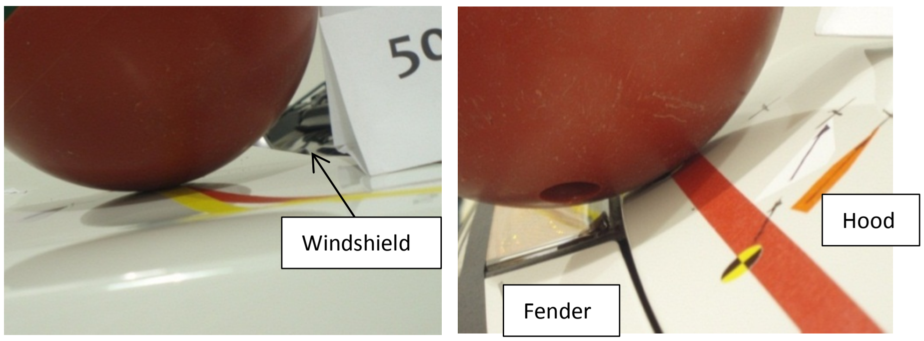
2.2. Phase I: Impact Point Definition

2.2.1. Impact Point Definitions

The GTR definition of the "head impact point" can be interpreted in several ways. With the current GTR language, three different impact point definitions have been put to use by different laboratories: (1) the 3D point of first contact (current NHTSA protocol); (2) the aiming point (EuroNCAP protocol); and (3) the point of first contact on the vertical-longitudinal plane containing the center of the headform impactor, which is known as "2D measuring point" (OICA protocol). The different definitions can lead to different headform impactor positions at the time of contact, which can produce different HIC values. In addition, the launch area of the hood can change depending on the definition that is used. Therefore, a clear definition would provide lab-to-lab consistency, ensure that the test zones are not decreased to limit the GTR's benefit, and would provide clear wording for test procedures. The objectives of Phase I are to (1) investigate how the front, side, and rear borders of the GTR launch area would be expected to change if various targeting protocols are used and (2) assess the effect of the impact point interpretation on HIC.

- **3D Point of First Contact (NHTSA targeting protocol)**

For the 3D point of first contact (3D POFC) targeting protocol, the head's first point of contact is aligned with the point of interest or point that is to be evaluated. In Figure 1a, the point of interest is along the rear test boundary (yellow tape on the hood) and the headform is aligned so that its point of first contact is on the point of interest. In Figure 1b, the point of interest is along the side test boundary (outside or left edge of the red tape) and again, the headform is aligned so that its point of first contact is on the point of interest. If the head's first point of contact, in any axis, contacts within the test zone, then it is considered a valid test. All of the headform impact tests performed by NHTSA during the GTR phase 1 evaluation process were done according to this definition.

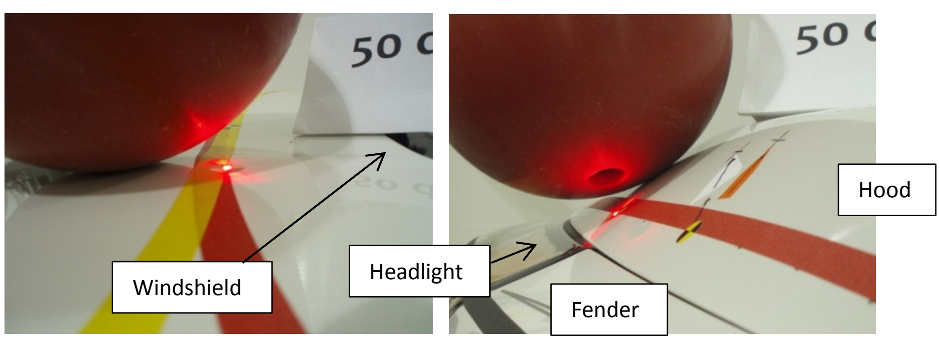


(a) (b)

Figure 1. Headform impactor aligned according to the 3D point of first contact definition along the rear test boundary (a) and along the side test boundary (b).

- **Aiming Point (EuroNCAP targeting protocol)**

For the aiming point (AP) targeting protocol, a line through the center of the headform and along the axis of impact is aligned with the point of interest. In Figure 2a, the point of interest is along the rear test boundary (yellow tape on the hood) and the headform is aligned so that a laser along the centerline of the headform is aimed at the desired point of interest. In Figure 2b, the point of interest is along the side test boundary (outside or left edge of the red tape) and again, the headform is aligned so that a laser along its centerline is aimed at the point of interest. Note that the actual point of first contact of the headform does not coincide with the point of interest.

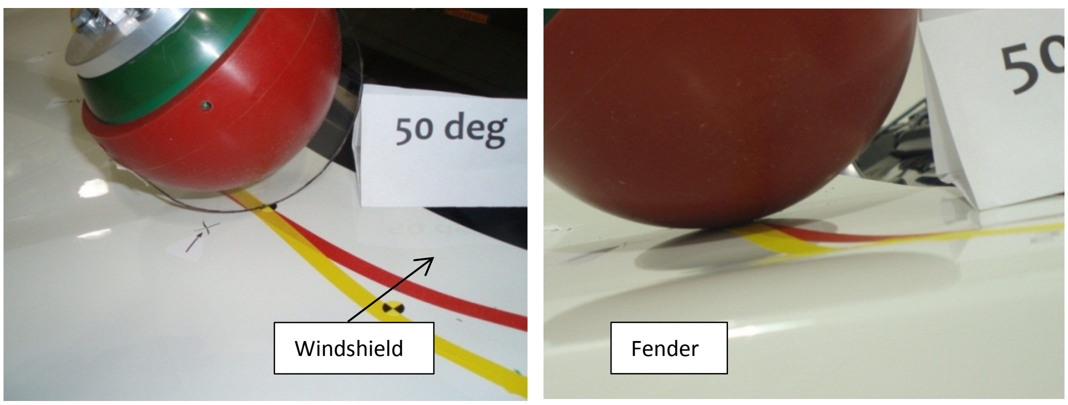


(a) (b)

Figure 2. Headform impactor aligned according to the aiming point definition along the rear test boundary (a) and along the side test boundary (b).

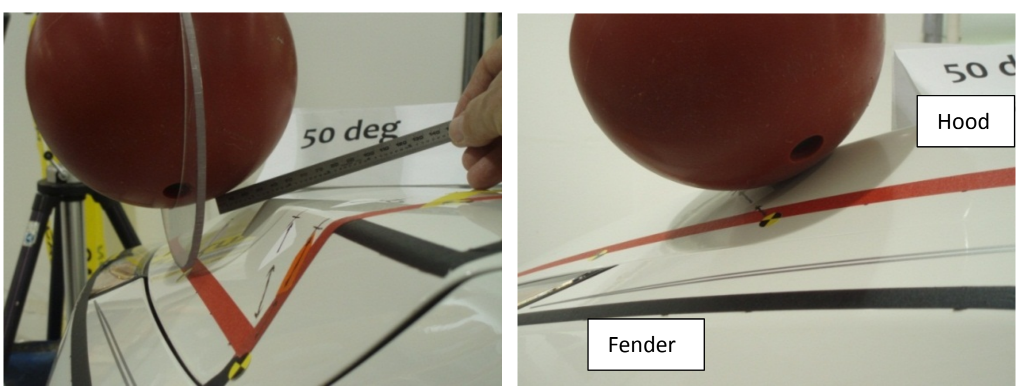
- **2D Measuring Point (Netherlands/OICA targeting protocol)**

For the 2D measuring point (2DMP) targeting protocol, the headform is aligned such that the point of first contact of the vertical-longitudinal plane containing the center of the headform coincides with the point of interest. In Figure 3a, the point of interest is along the rear test boundary (yellow tape on the hood) and the headform is aligned, using a 2D template, so that the point of first contact of the vertical-longitudinal plane of the headform coincides with the point of interest. In Figure 3b, the 2D template is removed and the headform is lowered along its axis of impact to demonstrate the actual point of first contact using the 2D measuring point method. In Figure 4a, the point of interest is along the side test boundary (red tape) and the headform is aligned, using a 2D template, so that the point of first contact of the vertical-longitudinal plane of the headform coincides with the point of interest. In Figure 4b, the 2D template is removed and the headform is lowered along its axis of impact to demonstrate the actual point of first contact using the 2D measuring point method.



(a) (b)

Figure 3. The point of first contact of the vertical-longitudinal plane of the headform impactor is first aligned with the point of interest along the rear test boundary using a 2D template (a) and the headform is then lowered along its axis of impact to demonstrate the actual point of first contact (b).



(a) (b)

Figure 4. The point of first contact of the vertical-longitudinal plane of the headform impactor is first aligned with the point of interest along the side test boundary using a 2D template (a) and the headform is then lowered along its axis of impact to demonstrate the actual point of first contact (b).

2.2.2. Test Zone Survey

- **Bonnet Top**

In order to evaluate the effect of the three impact point interpretations (3D POFC, AP, 2DMP) on the launch area, the bonnet top must first be defined and laid out on the vehicle. The bonnet top is defined in the GTR as the "area on the hood of a vehicle bounded by the bonnet leading edge reference line, the bonnet rear reference line, and the side reference line". The bonnet leading edge reference line (Figure 5) is the geometric trace of points of contact of the front surface of a vehicle with a 1000 mm long straight edge that is 600 mm above the ground. The straight edge must be held parallel to the vertical-longitudinal plane of the vehicle and inclined rearwards by 50 degrees from the vertical. The bonnet rear reference line (Figure 6) is the geometric trace of the most rearward points of contact between the vehicle's front structure and a 165 mm diameter sphere when the sphere is traversed across the front structure while maintaining contact with the windscreen. The side reference line (Figure 7) is the geometric trace of the highest points of contact between the sides of a vehicle's front structure and a 700 mm long straight edge. The straight edge must be held parallel to the transverse-vertical plane of the vehicle and inclined inwards by 45 degrees. An example of a constructed bonnet top is shown in Figure 8. In general, this is how the bonnet top is defined, but for those vehicles with front ends that conflict with these guidelines, the GTR lists additional steps for constructing the bonnet top.

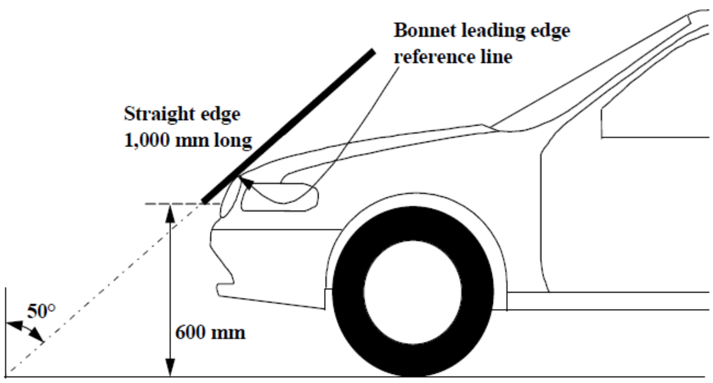


Figure 5. Guidelines for constructing the bonnet leading edge (BLE) reference line

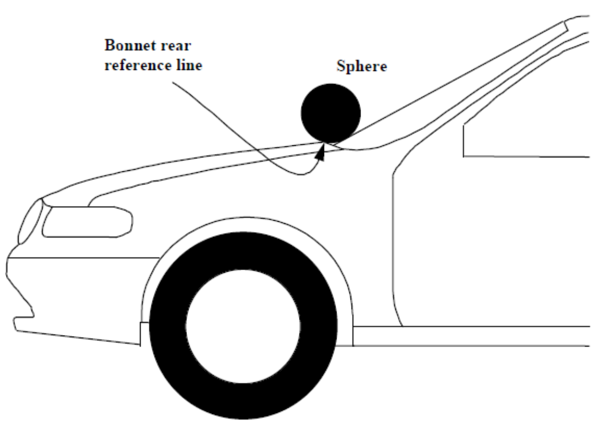


Figure 6. Guidelines for constructing the bonnet rear reference line (BRRL)

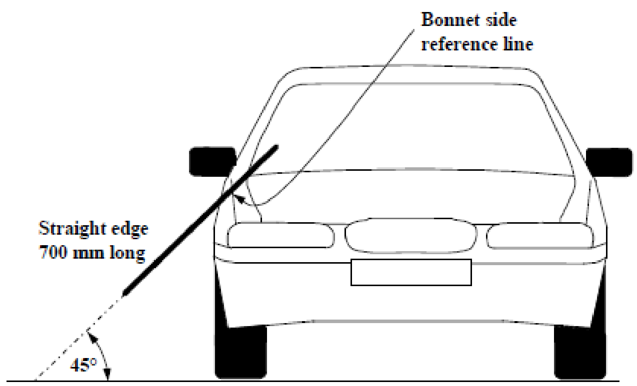


Figure 7. Guidelines for constructing the bonnet side reference line


Figure 8. The bonnet top of a vehicle as defined by the GTR

- **Performance Requirements**

The GTR specifies the following:

"The HIC recorded shall not exceed 1,000 over a minimum of one half of the child headform test area and 1,000 over two thirds of the combined child and adult headform test areas. The HIC for the remaining areas shall not exceed 1,700 for both headforms. In case there is only a child headform test area, the HIC recorded shall not exceed 1,000 over two thirds of the test area. For the remaining area the HIC shall not exceed 1,700."

The 2/3-HIC 1000 area is computed relative to the effective hood area. The effective hood area is created by projecting the marked-off hood borders used to define the bonnet top (side ref lines, BRRL, and BLE/WAD1000 line) onto a horizontal (x-y) plane. Thus, the launch area lies inside the effective hood area and is slightly smaller. Under NHTSA's interpretation of the GTR, the amount of launch area needing to meet HIC 1000 must be at least 2/3 times the effective hood area.

- **Headform Test Zones**

After the bonnet top is laid out on the vehicle, the headform test zones (Figure 9) can then be constructed using the guidelines stated in the GTR.

The child headform test zone is defined as follows:

(a) a minimum of 82.5 mm inside the defined side reference lines, and;
(b) forward of the WAD1700 line, or a minimum of 82.5 mm forward of the bonnet rear reference line - whichever is most forward at the point of measurement, and;
(c) be rearward of the WAD1000 line, or a minimum of 82.5 mm rearwards of the bonnet leading edge reference line - whichever is most rearward at the point of measurement

The adult headform test zone is defined as follows:

(a) a minimum of 82.5 mm inside the defined side reference lines, and;
(b) forward of the WAD2100 line, or a minimum of 82.5 mm forward of the bonnet rear reference line - whichever is most forward at the point of measurement, and;
(c) rearward of the WAD1700 line

Figure 9. Child & adult test zones shaded in gray as defined by the GTR on vehicle's bonnet top.

After the test zones are laid out on the vehicle, the three different headform targeting protocols (3D POFC, AP, 2DMP) can be evaluated for their effect on launch area using the child and adult headforms. In this study, points of interest were chosen along the front, rear, and side test zone boundaries. The headform impactor was then aligned at each point of interest and positioned at the proper GTR angle (depending on which test zone the point lies within: 50 degrees for child and 65 degrees for adult) using the three protocols. At each point of interest and for each protocol, the actual point of first contact of the headform was marked. Once all points of interest were evaluated, a new launch area consisting of the points of first contact for each targeting protocol was constructed, thereby defining the actual launch area of the hood using that protocol (Figure 10). The actual launch areas of the three targeting protocols could then be compared.

Figure 10. Evaluation of impact point definition on a vehicle. The outer white boundary represents the bonnet top. The inner white boundary represents the test zone as well as the 3D first contact launch area. The orange boundary represents the driver side half of the aiming point launch area. The launch area using the 2D measuring point is not pictured (to be discussed later).

2.2.3. Impact Tests

Using the results of the launch area survey, child and adult headform impacts were then performed. Points of interest were chosen on the hood where the greatest launch area boundary variances in the targeting protocols were found. A measuring tape, laser, and plumb-bob were used to find the distance of the point of interest from the center of the vehicle and the wrap around distance so that the same point of interest can be reproduced for future impacts (Figures 11 and 12). Depending on the size of the vehicle, three to five points of interest were chosen per vehicle and marked on each hood.

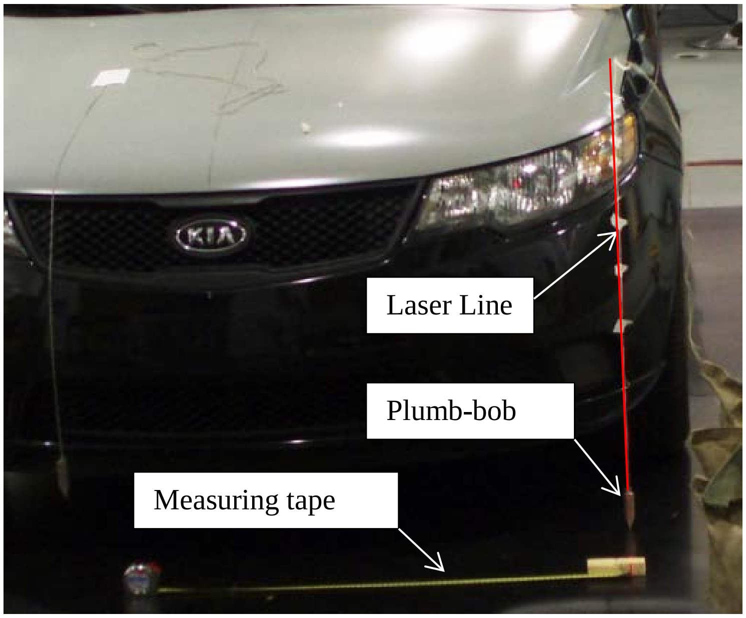


Figure 11. Procedure for measuring the location of the point of interest on a vehicle's hood.

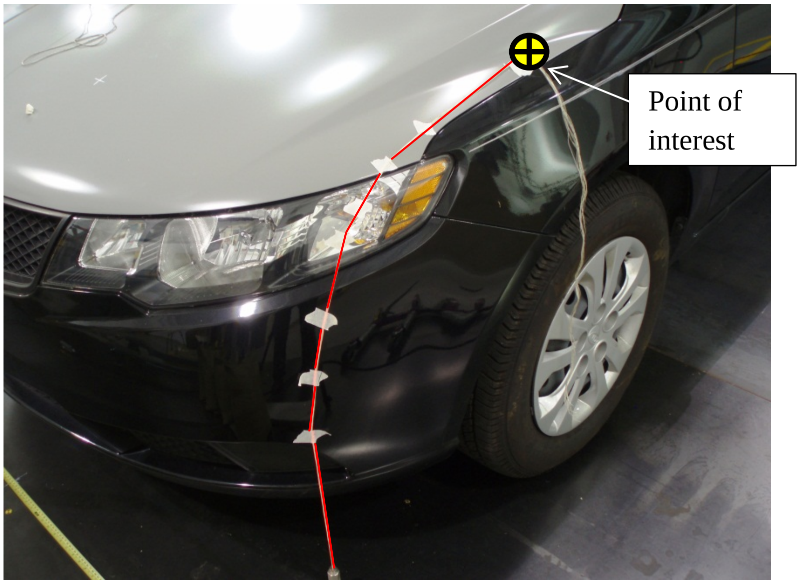


Figure 12. Procedure for measuring the wrap around distance.

After the hood was marked with the desired points of interest, the points of first contact using the 3D point of first contact protocol were marked for each point of interest on one hood, which always coincided with the desired point of interest. The point of first contact using the aiming point protocol on the same set of desired points of interest was marked on a second hood (Figures 13 and 14), with the headform centerline coincident with the point of interest. The 2D measuring point protocol was not evaluated due to similarities to the other targeting protocols depending on the region of the test zone, which is explained later in the discussion.

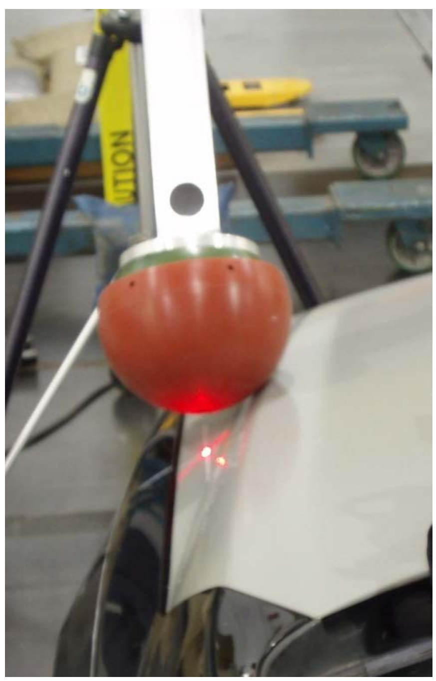


Figure 13. Determining the point of first contact using the aiming point (AP) targeting protocol.

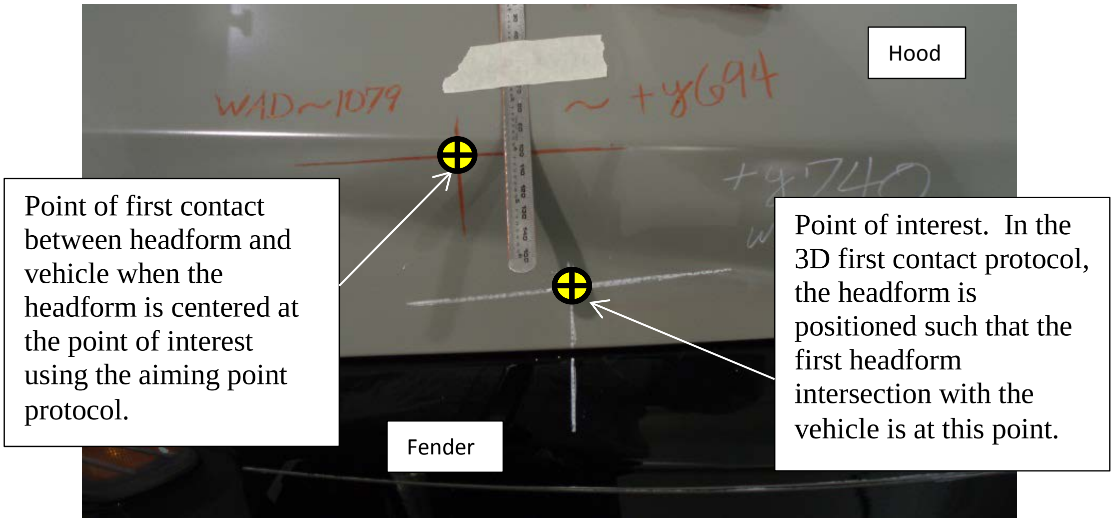


Figure 14. The point of interest coincides with the center of the headform using the aiming point protocol or the first intersection of headform and vehicle using the 3D POFC protocol.

The headform (child or adult, depending on the location of the point of interest) was then attached to the launch mechanism via an impactor guide (Figure 15), which places the headform a certain distance away from its initial launch position at which it achieves a constant velocity during free flight before impacting the vehicle. The impactor and vehicle were then positioned so that the direction of impact is downward and rearward with respect to the vehicle at the specified child (50 +/- 2 degrees) or adult (65 +/- 2 degrees) test angle in the vertical-longitudinal plane of the vehicle, and the point of first contact of the headform is within +/- 10 mm to the marked impact point (Figure 16).

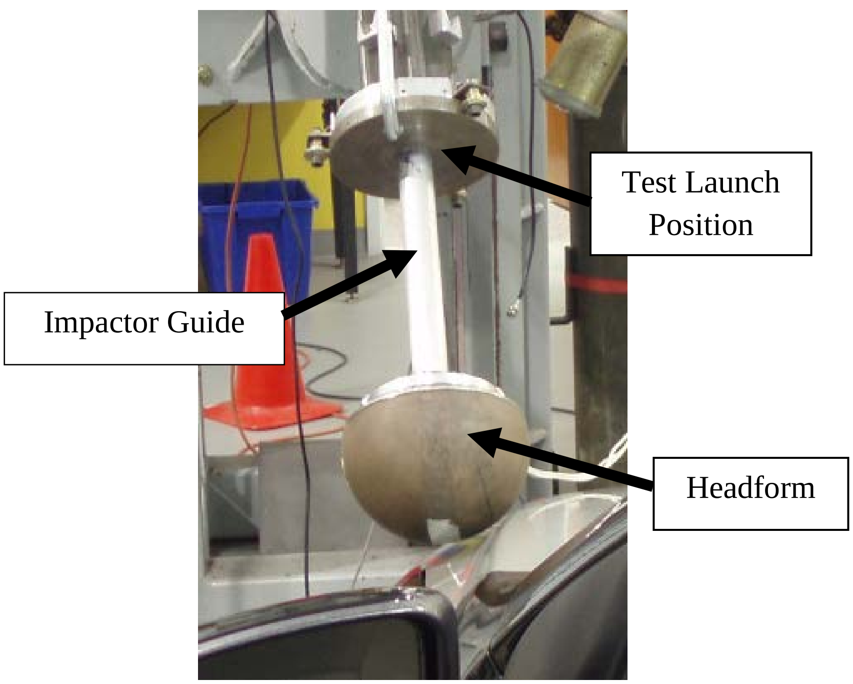
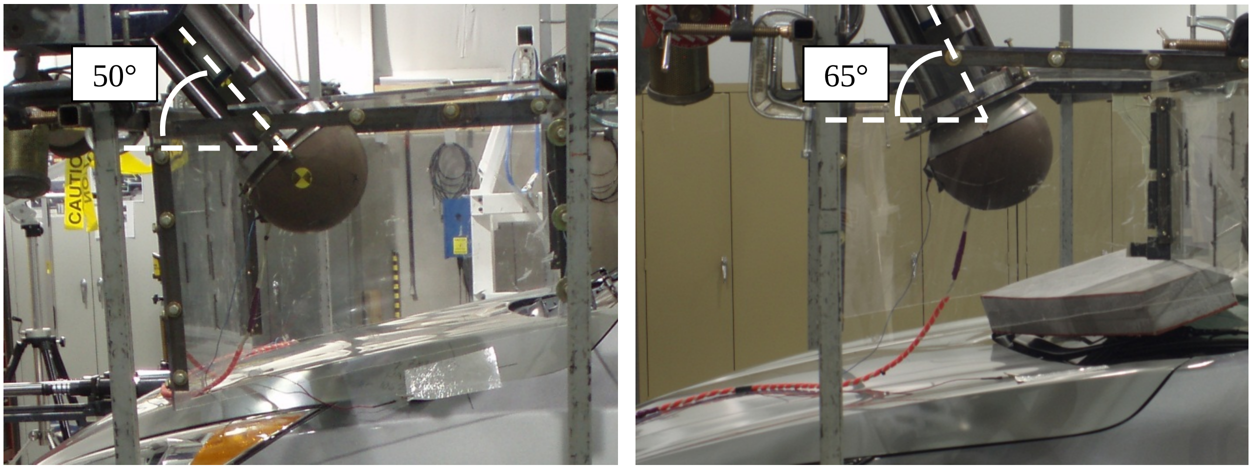


Figure 15. The impactor guide places the headform a certain distance away from its initial launch position so it achieves a constant, desired velocity at impact.



(a) (b)

Figure 16. Child headform positioned at an impact angle of 50 degrees from horizontal (a) and adult headform positioned at an impact angle of 65 degrees from horizontal (b).

Impacts were performed according to the GTR such that the velocity at the time of impact for both headforms was 9.7 +/- 0.2 m/s. The marked impact points using the 3D POFC protocol were tested on one hood while the marked impact points using the AP protocol were tested on a second hood.

Child and adult headforms manufactured by FTSS (now Humanetics) were used in Phase I of this study. Both headforms were instrumented with three undamped, uniaxial accelerometers (Endevco 7264C) located at the center of gravity of each headform. The Head Injury Criterion (HIC) was calculated for each impact over a 15 ms interval (i.e., HIC15) using the resultant headform acceleration, as specified by the GTR.

2.3. Phase II: Headform Reproducibility

The objective of the second phase of this study was to evaluate the reproducibility of the headform impactor test device. Child and adult headforms manufactured by both FTSS and Cellbond were evaluated. Both headforms met the GTR specifications for mass, diameter, and seismic mass location with respect to the center of gravity. The mass of all four headforms met the GTR requirement (FTSS Child = 3.6 kg, FTSS Adult = 4.5 kg, Cellbond Child = 3.6 kg, Cellbond Adult = 4.6 kg), and all headforms were 165 mm in diameter. There were however some notable differences between them. Figures 17 and 18 show that the headforms possess the same diameter but different heights (height is not specified by the GTR). Figure 19 shows a difference in back plate construction for the child headforms. The FTSS child back plate has a diameter of 133 mm and a depth of 13 mm. The Cellbond child back plate has a diameter of 139.5 mm and a depth of 22 mm. The FTSS adult back plate has a diameter of 109 mm and a depth of 40 mm. The Cellbond adult back plate has a diameter of 125.5 mm and a depth of 31.8 mm. Figure 20 shows differences in the internal construction to meet the mass and inertial requirements in the GTR, with the accelerometer placement relative to the center of gravity staying the same in both headforms.

Figure 17. Cellbond (left) and FTSS (right) child headforms.

Figure 18. Cellbond (left) and FTSS (right) adult headforms.

Figure 19. Backplates of the FTSS child (left) and Cellbond child (right) headforms.

Figure 20. FTSS child (left) and Cellbond child (right) headforms with backplates removed.

As in Phase I, impacts were performed according to the GTR procedures such that the child headform was tested at an angle of 50 +/- 2 degrees below horizontal, the adult headform was tested at an angle of 65 +/- 2 degrees below horizontal, and the velocity at the time of impact for both headforms was 9.7 +/- 0.2 m/s. Unlike Phase I, all headforms in this phase of the study were instrumented with three damped, uniaxial accelerometers located at the center of gravity of each headform. Care was taken to ensure that each accelerometer was mounted in the same axis for all the headforms.

Three vehicles that were tested in Phase I of the study were also tested in this phase: Kia Forte, Buick LaCrosse, and Acura MDX. The same points of interest that were evaluated in Phase I for the three vehicles were also evaluated in this phase. However, points of interest were evaluated using only the 3D point of first contact method and with headforms from two different manufacturers. The Cellbond headform was tested first at each point of interest on one hood. After testing was complete, the corresponding FTSS headform was tested on the same points of interest on a second hood. Impacts on each hood were performed in the same order to reduce the effect of impacting a hood with previous impacts at other locations.

Due to the geometric differences, the Cellbond headforms had to be centered differently than the FTSS headforms on the launch mechanism. The FTSS child headform was centered on the magnetic launch plate using centering bolts and washers as shown in Figure 21. The FTSS adult headform, on the other hand, was not held up using a magnet but with a centering plate and nylon screws as shown in Figure 22, which also centered the headform on the launch mechanism. Like the FTSS child headform, the Cellbond child and adult headforms were centered on the magnetic launch plate using centering bolts and washers as shown in Figure 23. However, due to the differences in headform geometry, a different set of centering bolts and washers had to be utilized.

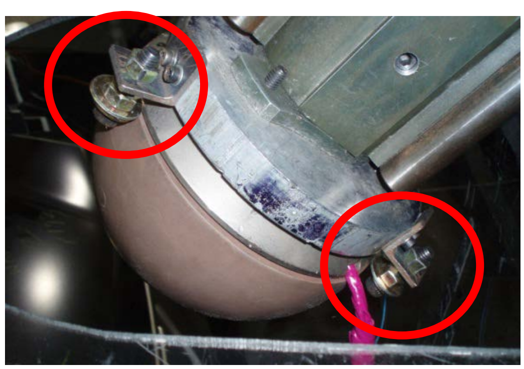
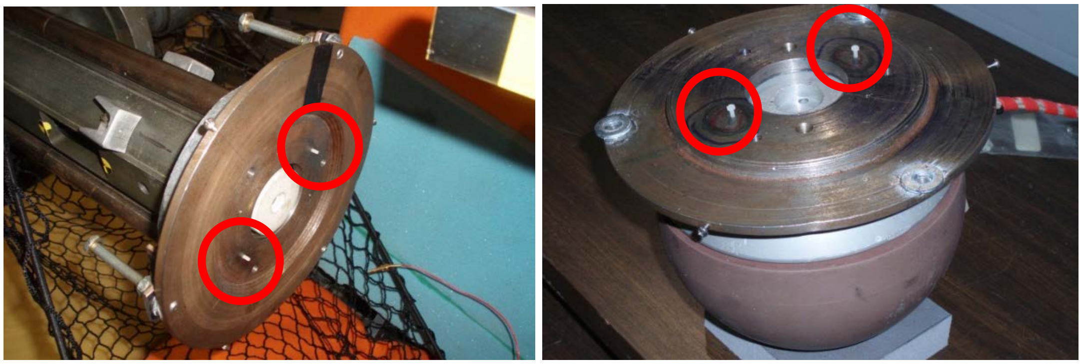
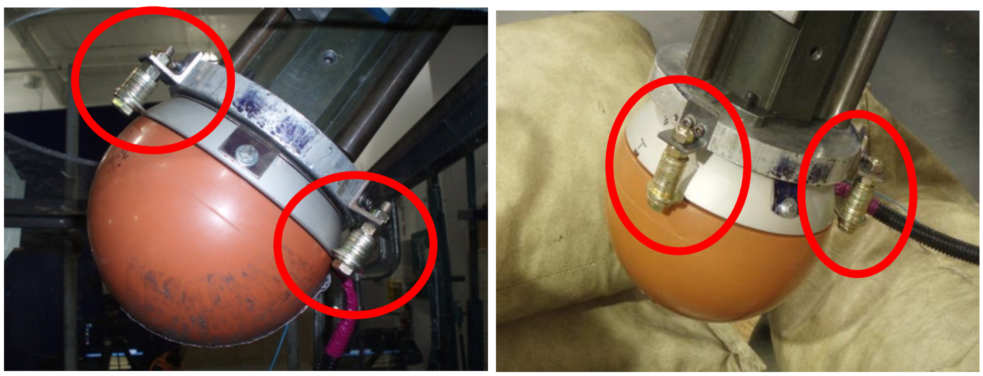


Figure 21. FTSS child headform centered on launch plate using centering bolts and washers.



(a) (b)

Figure 22. Plate used to position and center the FTSS adult headform on the launch plate (a). FTSS adult headform attached to the centering plate using nylon screws (b). Nylon screws circled.



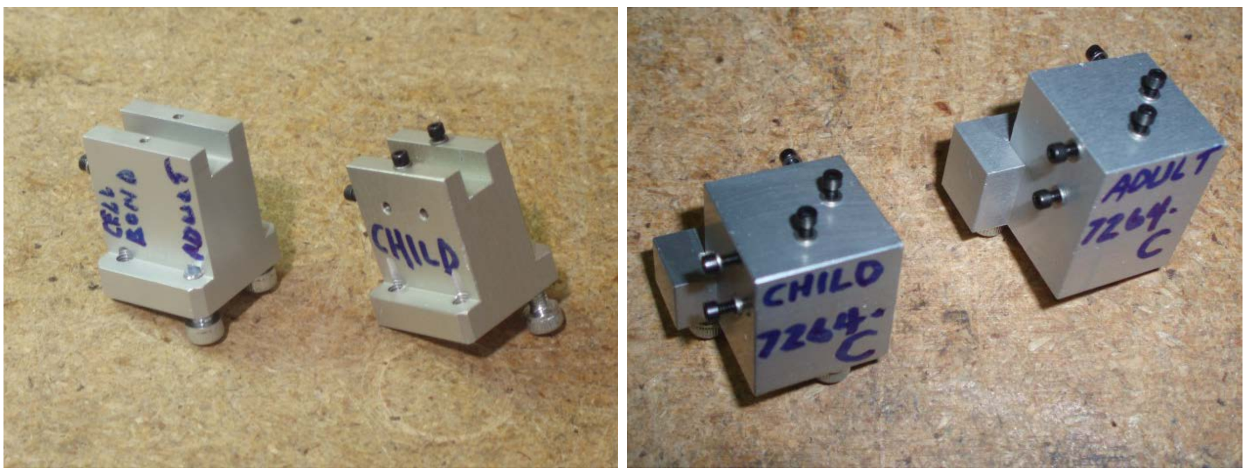
(a) (b)

Figure 23. Cellbond child (a) and adult (b) headforms centered on the launch plate using centering bolts and washers.

It was also important to ensure that the proper accelerometer mount was installed on the Cellbond headform. For the FTSS headforms, accelerometers were mounted on a simple triaxial block inside the head (Figure 24a). For the Cellbond headforms, triaxial blocks were provided that are specific to the different accelerometer models (Figure 24b). For example, a different triaxial block was designed for Kyowa ASE or Endevco 7264B (Figure 25a) and Endevco 7264C/7264G (Figure 25b) accelerometers. The proper block must be used so that the seismic masses of the accelerometers are located at the headforms' center of gravity.

(a) (b)

Figure 24. FTSS (a) and Cellbond (b) headforms with mounted accelerometers



(a) (b)

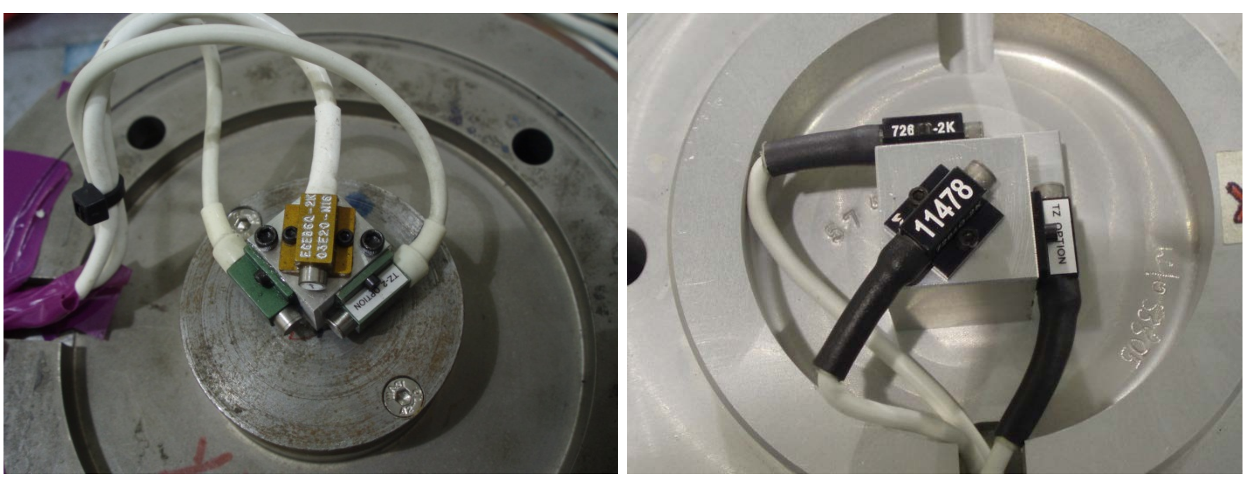
Figure 25. Accelerometer mount for uni-axial Kyowa ASE or Endevco 7264B accelerometers (a) and for Endevco 7264C/7264G accelerometers (b).

In addition, a thin metal plate with a small enough mass (child = 0.104 kg, adult = 0.081 kg, including bolts and washers) to maintain conformance with GTR specifications was attached to the back plate of the Cellbond headforms in order to produce a stronger connection with the launch plate magnet prior to the test (Figure 26). Without the additional thin plate, the magnet was not strong enough to hold the Cellbond headforms up in position prior to a test, given the lack of steel in the headform.

Figure 26. Cellbond headform with additional thin metal back plate used to produce a stronger connection with the launch plate magnet.

2.4. Phase III: Accelerometer Scheme

In Phase I, impacts were performed with both child and adult FTSS headforms on the Kia Forte, Buick LaCrosse, and Acura MDX using the 3D point of first contact targeting protocol. Undamped accelerometers were used in these impacts. In Phase II, the same impacts were performed on the same vehicles, at the same points of interest, and with both Cellbond and FTSS headforms. However, in Phase II, damped accelerometers were used instead of undamped accelerometers. In order to determine whether or not damped accelerometers are needed for GTR headform testing, Phase III of the study compares the undamped accelerometer impact results from Phase I and the damped accelerometer impact results from Phase II for impacts conducted with the same headform and at the same hood location. For the undamped impacts, Endevco 7264C accelerometers were used (Figure 27a). For the damped impacts, Endevco 7264G accelerometers were used (Figure 27b).



(a) (b)

Figure 27. Undamped Endevco 7264C (a) and damped Endevco 7264G (b) accelerometers.

2.5. Child vs. Adult at WAD 1700

The GTR specifies that the child headform should be used forward of the WAD 1700 and the adult headform should be used rearward of the WAD 1700. At exactly a wrap-around distance (WAD) of 1700 mm, the GTR does not specifically state which headform should be used. Vehicle countermeasures designed for the adult headform may not be the same as for the child headform given the difference in mass and impact angle. To investigate this issue, two tests were compared. The FTSS child headform instrumented with undamped accelerometers was tested at WAD 1700 of the Acura MDX in Phase I of the study. In Phase II, the FTSS adult headform configured the same way was tested at the same point of interest. Both tests used the 3D POFC targeting protocol so they were in the same impact location. Therefore, the child and adult headform responses could be compared for the same point of interest.

2.6. Headform Certification

The FTSS and Cellbond headforms were certified according to GTR procedures, and their responses were compared to further investigate reproducibility without variability due to the vehicle or vehicle test setup. Drop tests were conducted according to Figure 28. The headforms were suspended at a height of 376 mm and a drop angle of 50 degrees and 65 degrees with respect to the vertical for the child and adult headforms, respectively. Drop tests were performed three times with each headform rotated 120 degrees around its symmetrical axis for each subsequent test. The FTSS headforms were instrumented with Endevco 7264C undamped accelerometers. The Cellbond headforms were instrumented with Endevco 7264G damped accelerometers. Acceleration results were filtered at 1000 Hz.

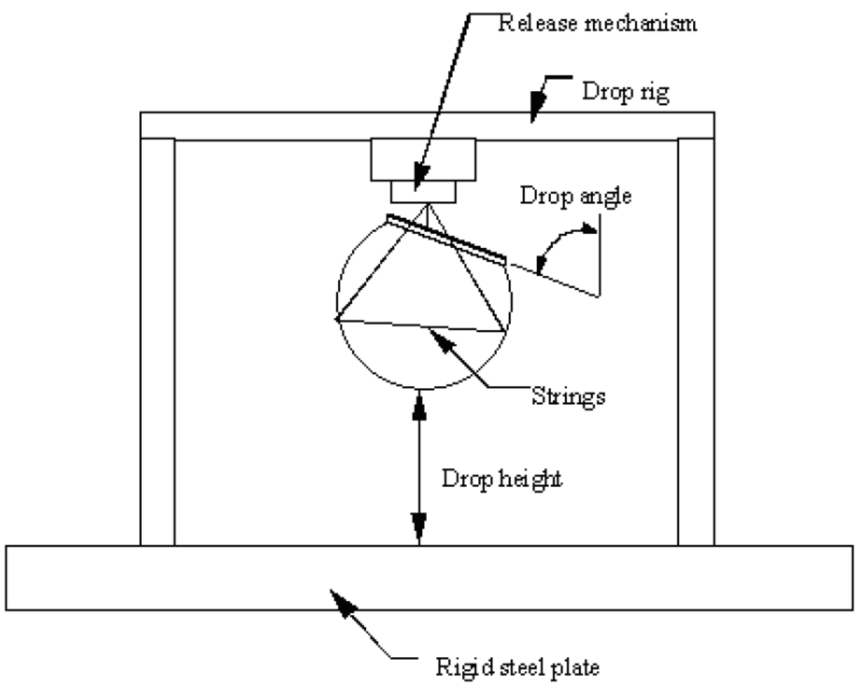


Figure 28. Test set-up for headform certification testing (GTR no. 9)

3. Results

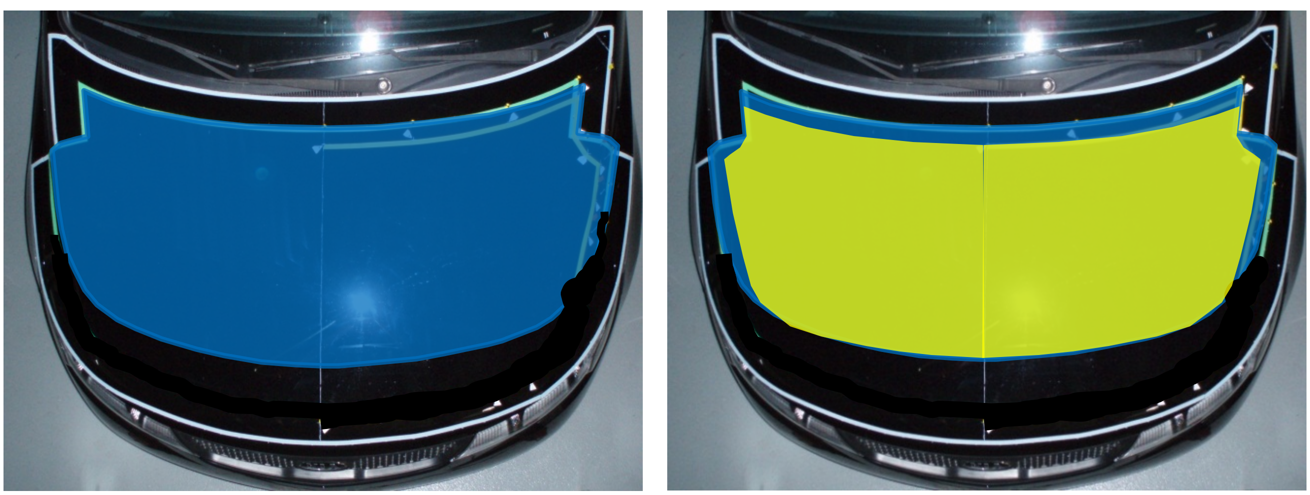
3.1. Phase I Results – Impact Point Definition

3.1.1. Launch Area Assessment

Results of the launch area surveys using the different targeting protocols are shown in Figures 29 through 34 below. The bonnet top, child and adult test zones, and the boundaries for the launch areas using the 3D POFC and AP protocols are shown in each of the figures. The boundaries for the launch areas using the 2DMP protocol are not directly shown in the figures below. It was observed that the point of first contact using the 2DMP protocol was a hybrid of the 3D point of first contact and aiming point protocols. The contact points at the front and rear test zone boundaries using 2DMP were the same as 3D POFC. The contact points at the side test zone boundary were similar to AP. Therefore, the launch area boundaries using 2DMP is a mix of the launch area boundaries when using 3D POFC in the front and rear and AP at the sides.

- **2010 Kia Forte**

The results of the Kia Forte launch area survey are shown in Figure 29 below. Due to the small size of the Kia Forte, an adult test zone did not exist (WAD 1700 line coincident with rear boundary). The launch area using 3D POFC is the same as the test zone and is shown by the blue area in Figure 29a. When aligning the headform using AP along the test zone boundary, the actual point of first contact of the headform was forward of the front and rear boundaries and inward of the side boundary. The launch area using AP is therefore smaller as shown by the yellow area in Figure 29b.

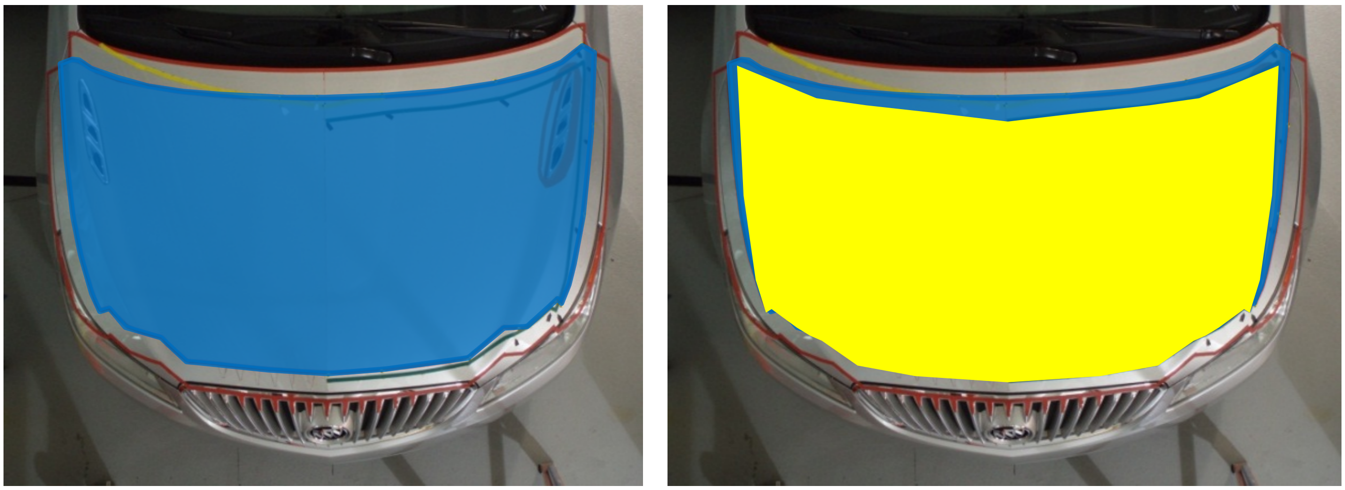


(a) (b)

Figure 29. For the Kia Forte, the launch area using 3D POFC is shown in blue (a). The launch area using AP is smaller and shown in yellow (b).

- **2010 Buick LaCrosse**

The results of the Buick LaCrosse launch area survey are shown in Figure 30 below. Again, due to the small size of the Buick LaCrosse, an adult test zone did not exist. The launch area using the aiming point decreased from the 3D point of first contact (Figure 30a), with the differences along the sides and shifted forward from the rear boundary of the test zone (Figure 30b).

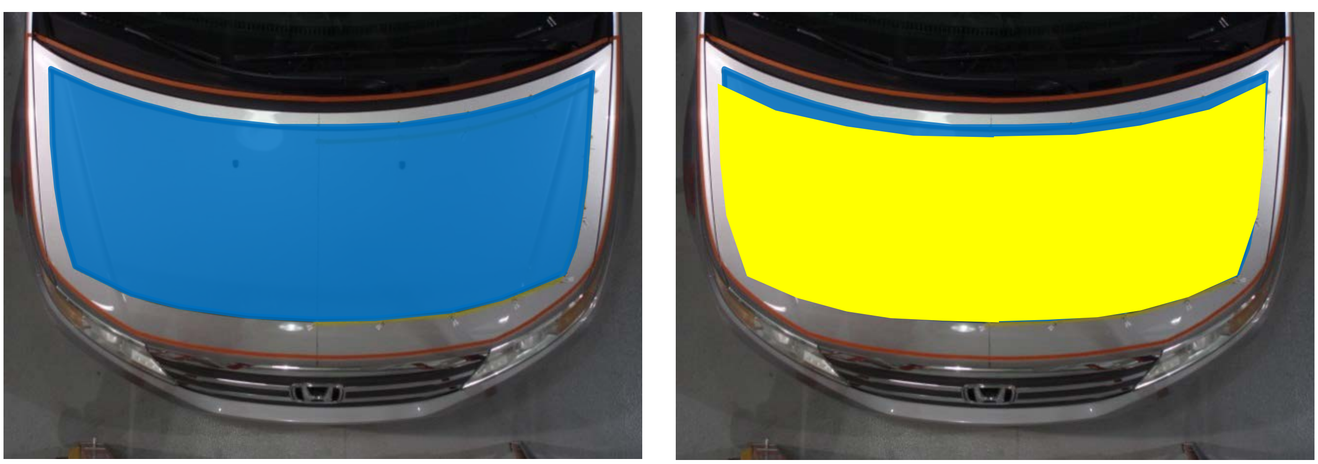


(a) (b)

Figure 30. For the Buick LaCrosse, the launch area using 3D POFC is shown in blue (a). The launch area using AP is smaller and shown in yellow (b).

- **2011 Honda Odyssey**

The results of the Honda Odyssey launch area survey are shown in Figure 31 below. Due to the short and steep hood of the Honda Odyssey, an adult test zone did not exist. The launch area using the aiming point was smaller and is shown by the yellow area in Figure 31b.

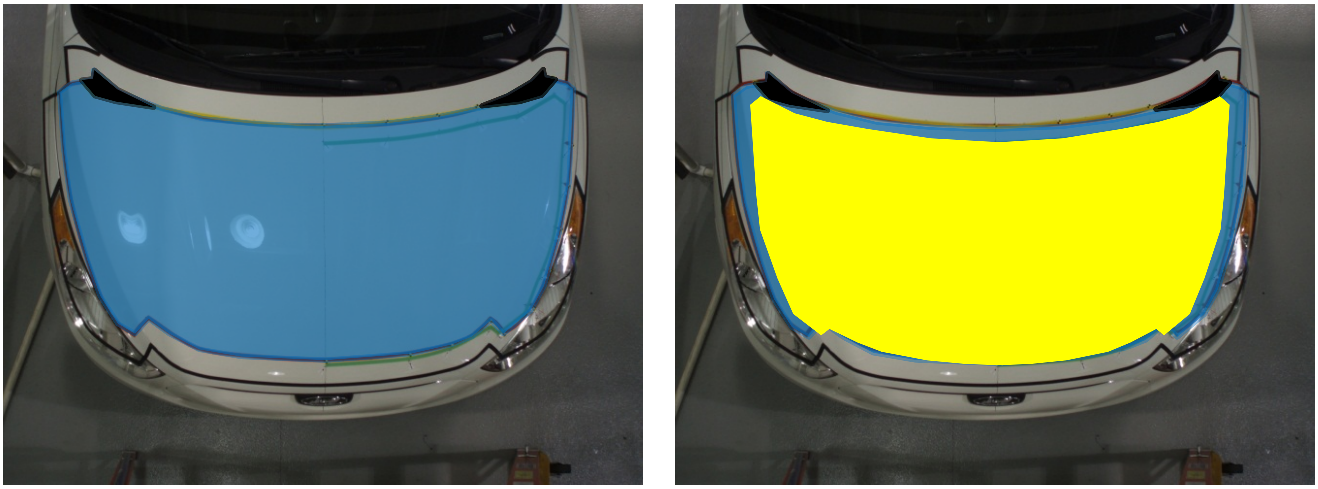


(a) (b)

Figure 31. For the Honda Odyssey, the launch area using 3D POFC is shown in blue (a). The launch area using AP is shown in yellow (b).

- **2011 Hyundai Tucson**

The results of the Hyundai Tucson test zone survey are shown in Figure 32 below. The launch area using 3D POFC is the same as the test zone and is shown by the blue and black areas for the child and adult headforms, respectively in Figure 32a. The launch area using AP decreased at the sides and shifted forward of the rear test zone boundary and is shown by the yellow area in Figure 32b.

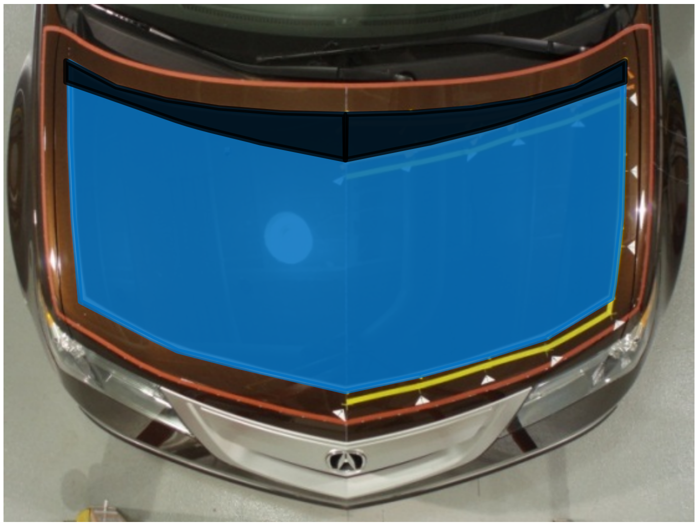
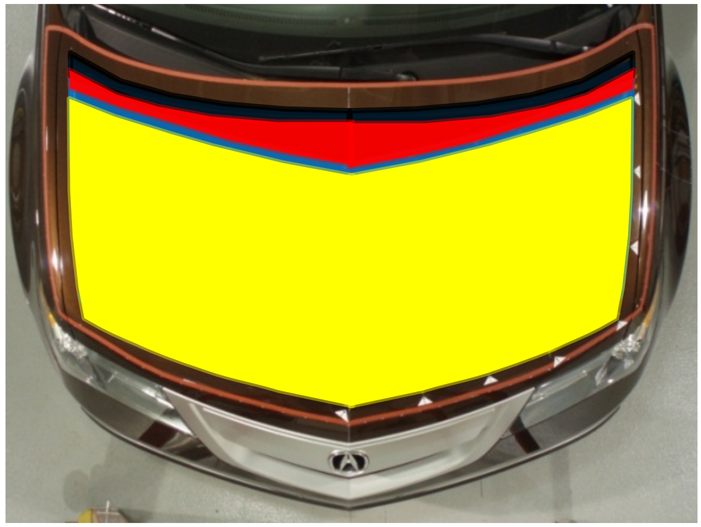


(a) (b)

Figure 32. For the Hyundai Tucson, the launch area using 3D POFC is shown in blue and black for the child and adult, respectively (a). The launch area using AP is shown in yellow (b).

- **2010 Acura MDX**

The results of the Acura MDX launch area survey are shown in Figure 33 below. The launch area using 3D POFC is the same as the test zone boundary and is shown in Figure 33a by the blue and black areas for the child and adult, respectively. The launch area using the aiming point was shifted forward and is shown in Figure 33b by the yellow and red areas for the child and adult, respectively. In addition, when using AP, a non-impact region of the hood was created between the actual child and adult launch areas due to the different impact angles of the child and adult headforms.

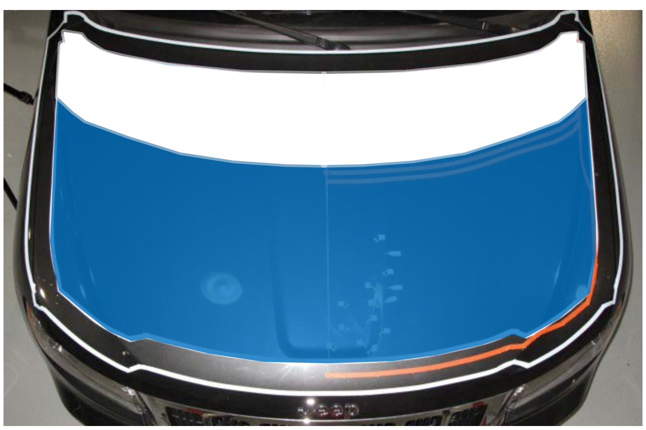



(a) (b)

Figure 33. For the Acura MDX, the actual launch area using 3D POFC is shown in blue and black for the child and adult, respectively (a). The actual launch area using AP is shown in yellow and red for the child and adult, respectively (b).

- **2011 Jeep Grand Cherokee**

The results of the Jeep Grand Cherokee launch area survey are shown in Figure 34 below. The launch area using 3D POFC is the same as the test zone boundary and is shown by the blue and white areas for the child and adult, respectively, in Figure 34a. For both child and adult, the launch area using AP decreased at the sides and shifted forward and is shown by the yellow and red areas in Figure 34b. In addition, when using AP, a non-impact region of the hood was created between the actual child and adult launch areas due to the different impact angles of the child and adult headforms.




(a) (b)

Figure 34. For the Jeep Grand Cherokee, the launch area using 3D POFC is shown in blue and white for the child and adult, respectively (a). The launch area using AP is shown in yellow and red for the child and adult, respectively (b).

For all vehicles, the launch area when using 3D POFC was the same as the test zone laid out by the GTR procedures. The launch area using AP was smaller than the defined test zone due to a combination of shifting forward of the rear edge of the test zone and inward of the points of interest along the sides of the test zone. ImageJ software was used to estimate the launch areas of the 3D POFC and AP protocols, and the differences in the areas were quantified. Since the 3D first contact launch areas coincided with the GTR test zones and since the 3D POFC protocol was NHTSA's interpretation of the procedure for previous impacts, the 3D first contact area was used as the baseline for the percent change. The differences in the launch area between the two protocols are tabulated in Table 1. Only areas within the GTR defined test zone were included in the calculations (for example, the forward shift in front of the WAD 1000 line was not included in the % change in impacted area).

Table 1. Difference between actual launch area for 3D point of first contact (3D POFC) and aiming point (AP) protocols

Vehicle	% Change in Impacted Area
Buick LaCrosse, 2010	-8.2
Kia Forte, 2010	-6.6
Acura MDX, 2010	-1.7
Hyundai Tucson, 2010	-9.2
Honda Odyssey, 2011	-5.2
Jeep Grand Cherokee, 2011	-3.2
Average	**-5.7**

Summarizing the launch area survey, the 3D first contact launch area was found to be the same as the GTR defined test zone. Using AP, the launch area boundaries generally shifted forward at the front and rear and inboard at the sides. Overall, a 5.7% decrease in launch area was observed between the 3D POFC and AP protocols. The 2DMP protocol was observed to be a hybrid of the 3D POFC and AP protocols. Using the 2DMP protocol, the boundaries of the front and rear launch areas were similar to 3D POFC and the side boundaries were similar to AP. Therefore, it can be surmised that the overall decrease in launch area when using the 2DMP protocol would be between 0% and 5.7%.

3.1.2. Impact Tests

Using the results of the survey, child and adult headform impacts were performed. Points of interest were chosen on the hood where the greatest variances in the targeting protocols were found, typically appearing along the test zone boundaries. Three to five points of interest were chosen for each vehicle depending on vehicle size. Point of interest locations and HIC results for both 3D point of first contact and aiming point protocols are tabulated in Table 2.

Table 2. Point of interest locations and HIC results for the Phase I impact tests. Adult head impacts are shaded in yellow.

Description	Point of interest Location		3D First Contact (3D POFC)	Aiming Point (AP)
	From Vehicle Centerline (mm)	WAD (mm)	HIC 15 ms	HIC 15 ms
2010 Kia Forte				
Rear, Passenger Side	-370	1586	597	498
Front, Driver Side	220	1000	626	703
Side, Passenger Side	-740	1130	1587	927
2010 Buick LaCrosse				
Rear, Passenger Side	-369	1690	686	640
Front, Driver Side	220	1000	1026	1041
Side, Driver Side	769	1289	1602	888
2011 Honda Odyssey				
Rear, Driver Side, Inboard	413	1555	1358	1103
Front, Driver Side, Outboard	709	1000	1302	1379
Front, Passenger Side, Inboard	-186	1000	1129	1280
Side, Passenger Side, Inboard	-675	1276	731	623
2010 Hyundai Tucson				
Rear, Driver Side, Inboard	126	1700	461	460
Rear, Passenger Side, Outboard	-660	1704	1036	1173
Front, Driver Side, Inboard	120	1000	638	670
Side, Driver Side	783	1482	1484	1171
2010 Acura MDX				
Rear, Driver Side, Outboard	607	1700	1100	875
Rear, Driver Side, Inboard	174	1700	550	487
Rear, Passenger Side, Outboard	-740	1755	1696	1472
Front, Driver Side, Inboard	183	1120	1283	1326
Front, Passenger Side, Outboard	-670	1151	785	812
2011 Jeep Grand Cherokee				
Rear, Driver Side, Inboard	400	1700	491	443
Rear, Passenger Side, Outboard	-500	2000	877	1430
Front, Driver Side, Inboard	50	1190	651	874
Side, Driver Side	795	1655	979	898

All recorded HIC 15 ms values were below the GTR relaxation zone HIC requirement of 1700. In general, the HIC values observed using the AP protocol were lower at the rear and side test zone boundaries than the 3D POFC protocol. The HIC values were generally higher using the AP protocol at the front test zone boundaries.

3.2. Phase II Results – Headform Reproducibility

HIC results for the repeated impacts using Cellbond and FTSS headforms are presented for the Kia Forte, Buick LaCrosse, and Acura MDX in Tables 3, 4, and 5, respectively. Only child headforms from Cellbond and FTSS were tested with the Kia Forte and Buick LaCrosse. Child and adult headforms from Cellbond and FTSS were tested on the Acura MDX.

3.2.1. 2010 Kia Forte

Resultant acceleration time histories for Cellbond and FTSS child headform impacts with damped accelerometers are shown in Figure 35. Head Injury Criterion (HIC) results are tabulated in Table 3.

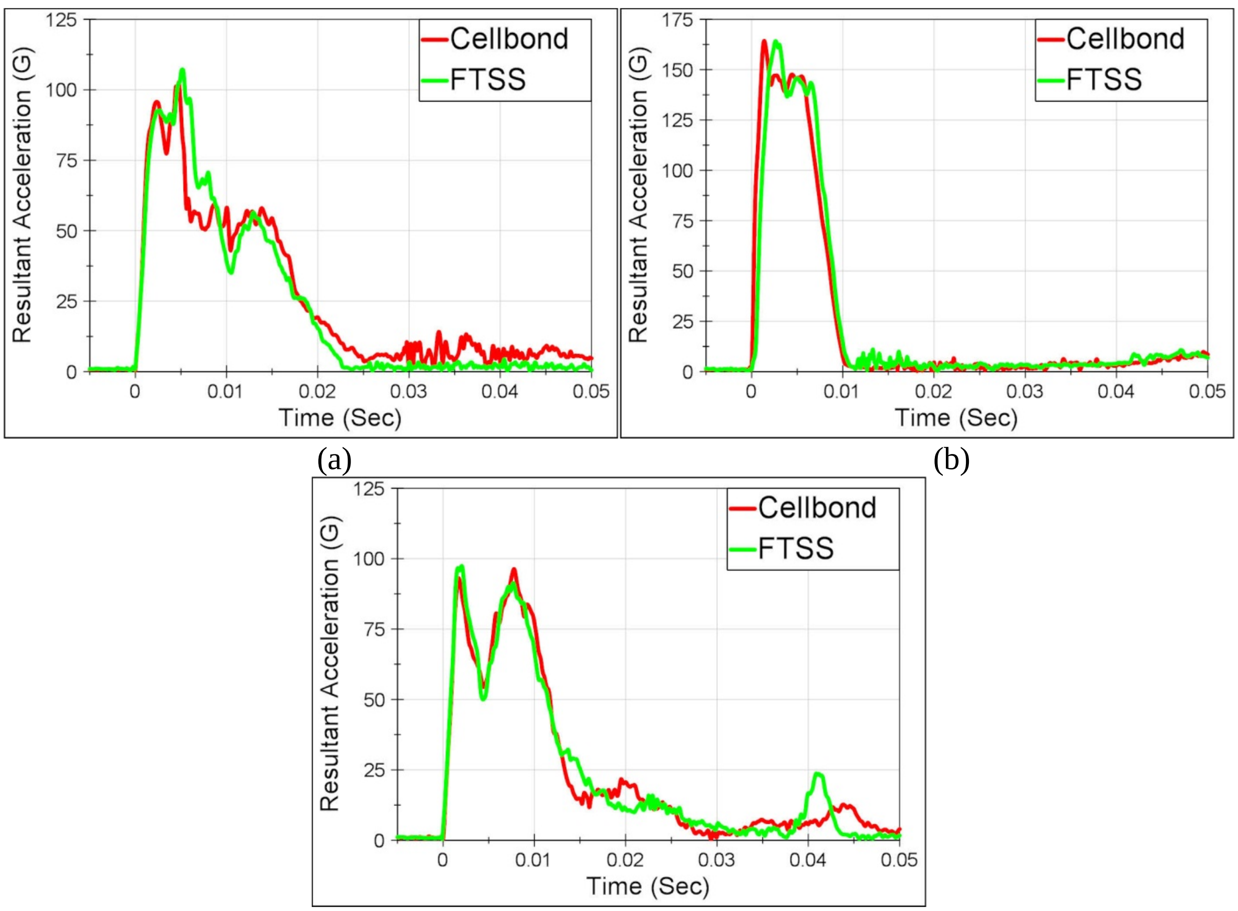


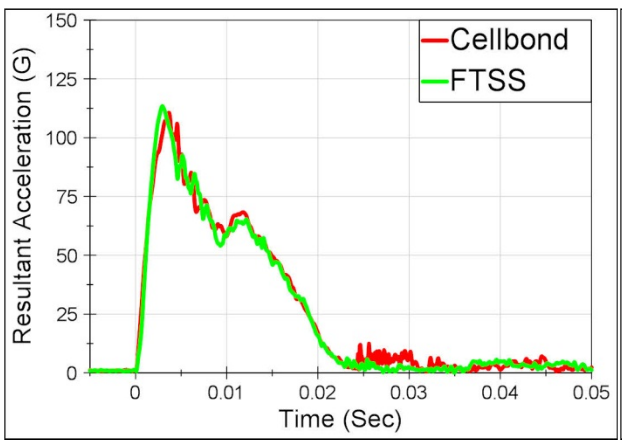
Figure 35. Kia Forte resultant acceleration time histories for the Cellbond (red) and FTSS (green) child headform impacts with damped accelerometers. Cowl (a), fender (b), and leading edge (c) results are shown.

Table 3. Phase II repeated impact results for the Kia Forte.

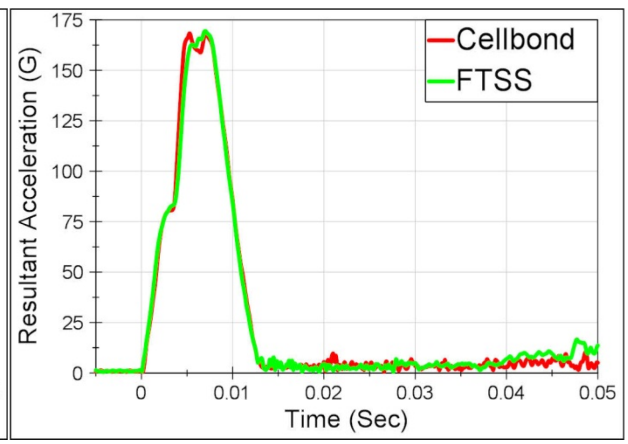
2010 Kia Forte			
Impact Location	HIC		Pct Diff (FTSS Baseline)
	Cellbond Child - Damped	FTSS Child - Damped	
Cowl	486	516	-5.8%
Fender	1537	1540	-0.2%
Leading Edge	524	506	+3.6%

3.2.2. 2010 Buick LaCrosse

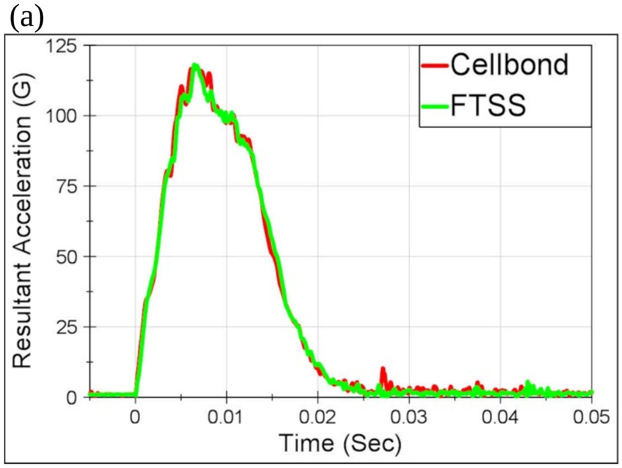
Resultant acceleration time histories for Cellbond and FTSS child headform impacts with damped accelerometers are shown in Figure 36. Head Injury Criterion (HIC) results are tabulated in Table 4.



(a)



(b)



(c)

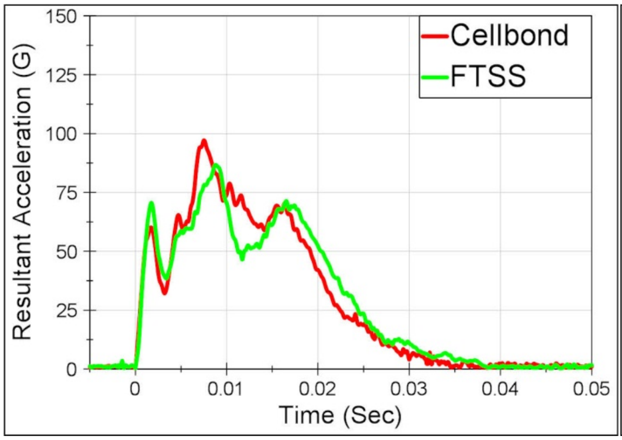
Figure 36. Buick LaCrosse resultant acceleration time histories for the Cellbond (red) and FTSS (green) child headform impacts with damped accelerometers. Cowl (a), fender (b), and leading edge (c) results are shown.

Table 4. Phase II repeated impact results for the Buick LaCrosse.

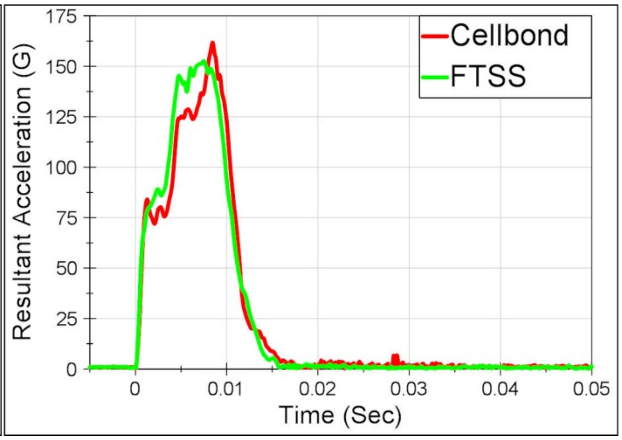
2010 Buick LaCrosse			
Impact Location	HIC		Pct Diff (FTSS Baseline)
	Cellbond Child - Damped	FTSS Child - Damped	
Cowl	650	636	+2.2%
Fender	1578	1482	+6.5%
Leading Edge	1053	1025	+2.7%

3.2.3. 2010 Acura MDX

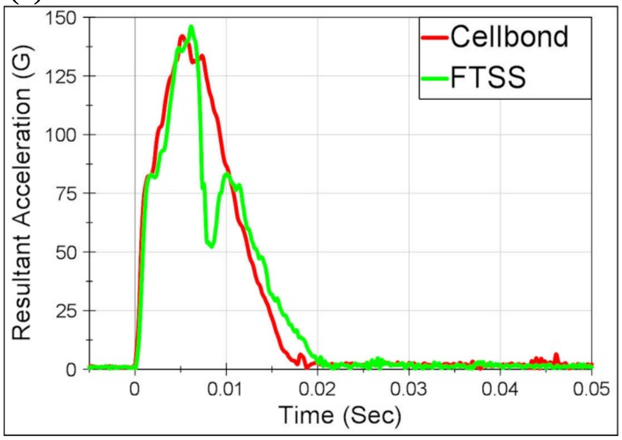
Resultant acceleration time histories for Cellbond and FTSS child headform impacts with damped accelerometers are shown in Figure 37. Head Injury Criterion (HIC) results are tabulated in Table 5. The adult headforms were used at the WAD 1700 and fender locations. The child headforms were used at the leading edge location.



(a)



(b)



(c)

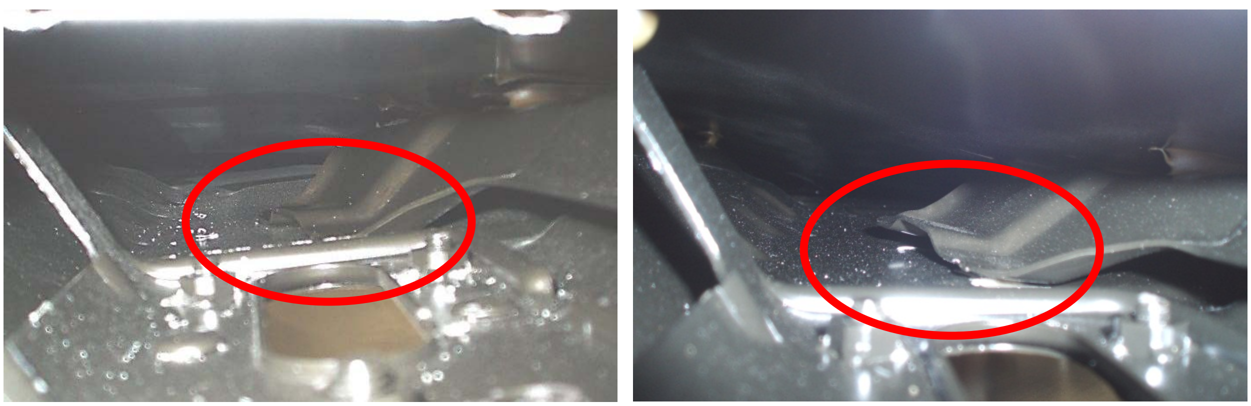
Figure 37. Acura MDX resultant acceleration time histories for the Cellbond (red) and FTSS (green) headform impacts with damped accelerometers. Cowl (a), fender (b), and leading edge (c) results are shown for both adult (a & b) and child (c) headforms.

Table 5. Phase II repeated impact results for the Acura MDX.

2010 Acura MDX			
Impact Location	HIC		Pct Diff (FTSS Baseline)
	Cellbond - Damped	FTSS - Damped	
WAD 1700 (adult)	603	505	+19.4%
Fender (adult)	1366	1519	-10.1%
Leading Edge (child)	1324	969*	+36.6%

*Post-test inspection of the hood structure showed a spot weld separation directly below the impact point.

The large variation in the leading edge test for the MDX appeared to be influenced by a spot weld separation discovered in the hood structure following the FTSS damped test (Figure 38). This damage appeared to cause an abrupt decrease in the acceleration trace (seen in Figure 37c) in the FTSS damped test. The 19.4% variation in the WAD 1700 test is attributed to some slight fender deformation present on the same side as the impact point in the FTSS damped test. The Cellbond damped test had no same-side deformation on the fender.

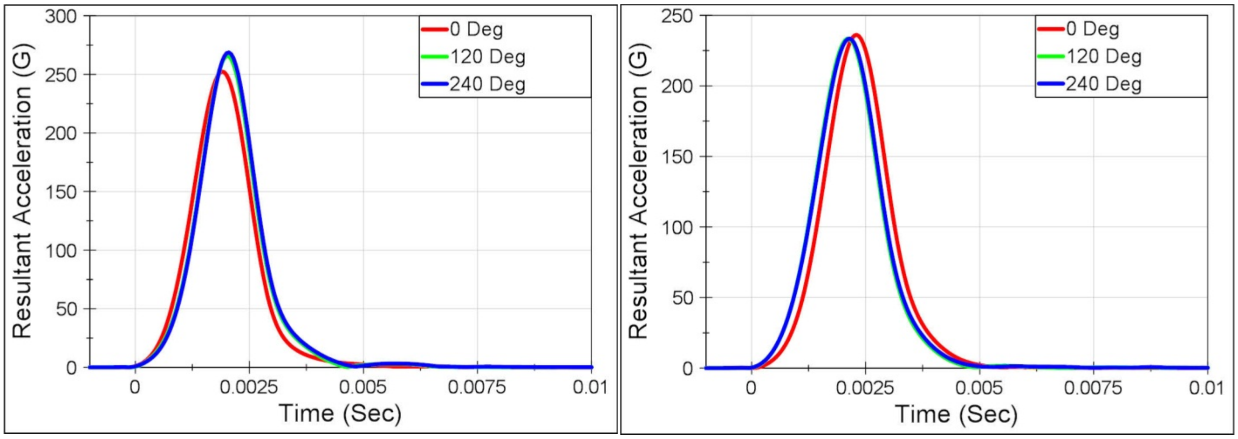


(a) (b)

Figure 38. Spot weld separation in Acura MDX hood structure: undamaged in Cellbond damped (a) and damaged in FTSS damped (b) tests

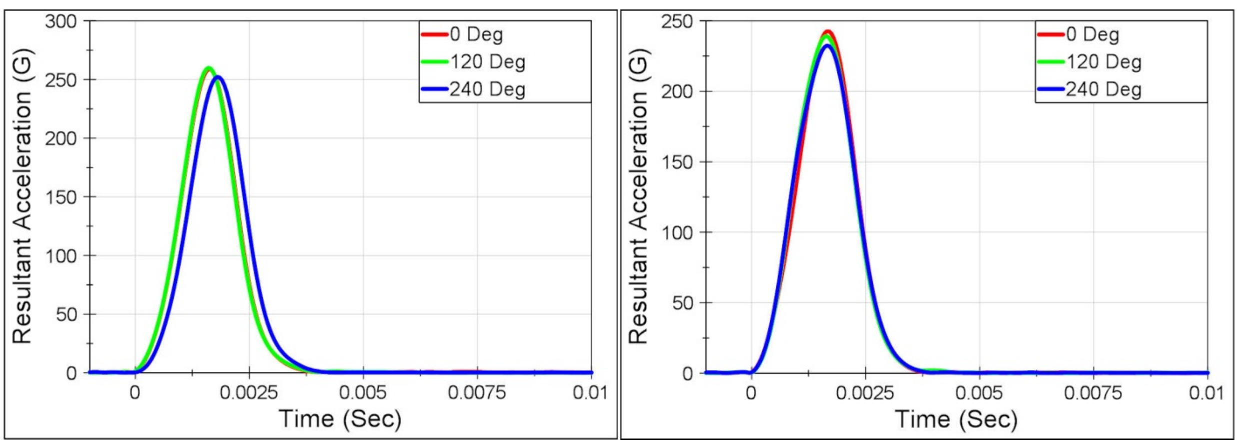
3.3. Headform Certification Tests

For the headform certification tests, peak resultant acceleration for the child headform should be between 245 G and 300 G. Peak resultant acceleration for the adult headforms should be between 225 G and 275 G. As shown in Figures 39 and 40, both FTSS and Cellbond headforms passed the certification requirements.



(a) (b)

Figure 39. Resultant acceleration results from the headform certification tests for the FTSS child (a) and adult (b) headforms. Both headforms were instrumented with undamped accelerometers.



(a) (b)

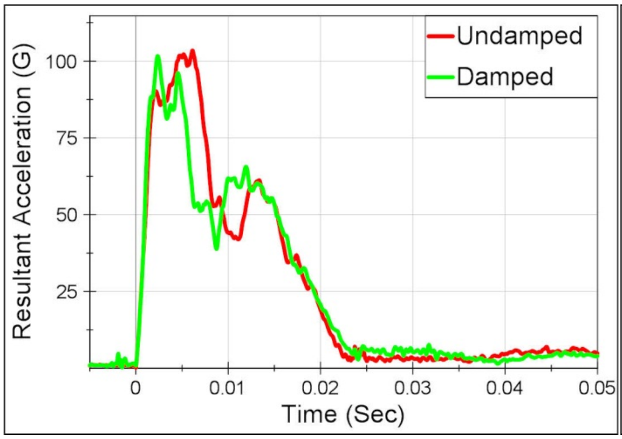
Figure 40. Resultant acceleration results from the headform certification tests for the Cellbond child (a) and adult (b) headforms. Cellbond headforms were instrumented with damped accelerometers.

3.4. Phase III Results – Accelerometer Scheme

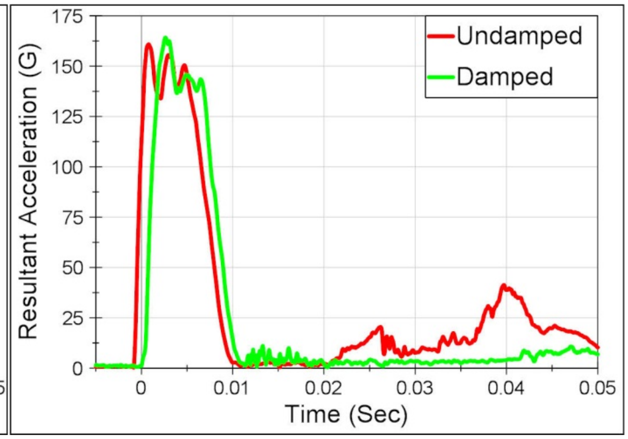
Acceleration time histories for the repeated impacts with FTSS headforms using undamped and damped accelerometers are presented for the Kia Forte, Buick LaCrosse, and Acura MDX in Figures 41, 42, and 43, respectively. Corresponding HIC values are presented in Tables 6, 7, and 8. Only child headforms were tested with the Kia Forte and Buick LaCrosse. Child (leading edge location) and adult (front boundary and fender locations) headforms were tested on the Acura MDX.

3.4.1. 2010 Kia Forte

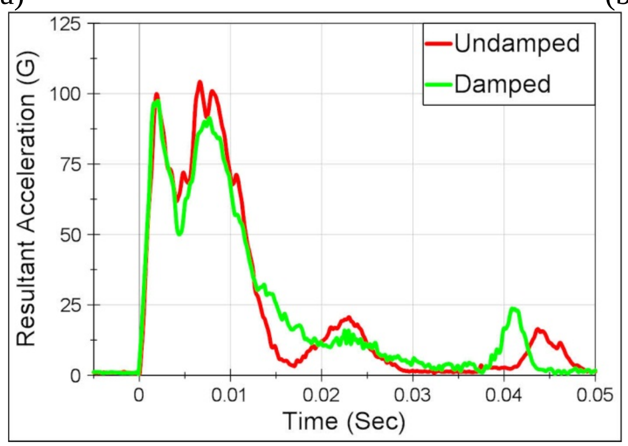
Resultant acceleration time histories for FTSS child headform impacts with undamped and damped accelerometers are shown in Figure 41. Head Injury Criterion (HIC) results are tabulated in Table 6.



(a)



(b)



(c)

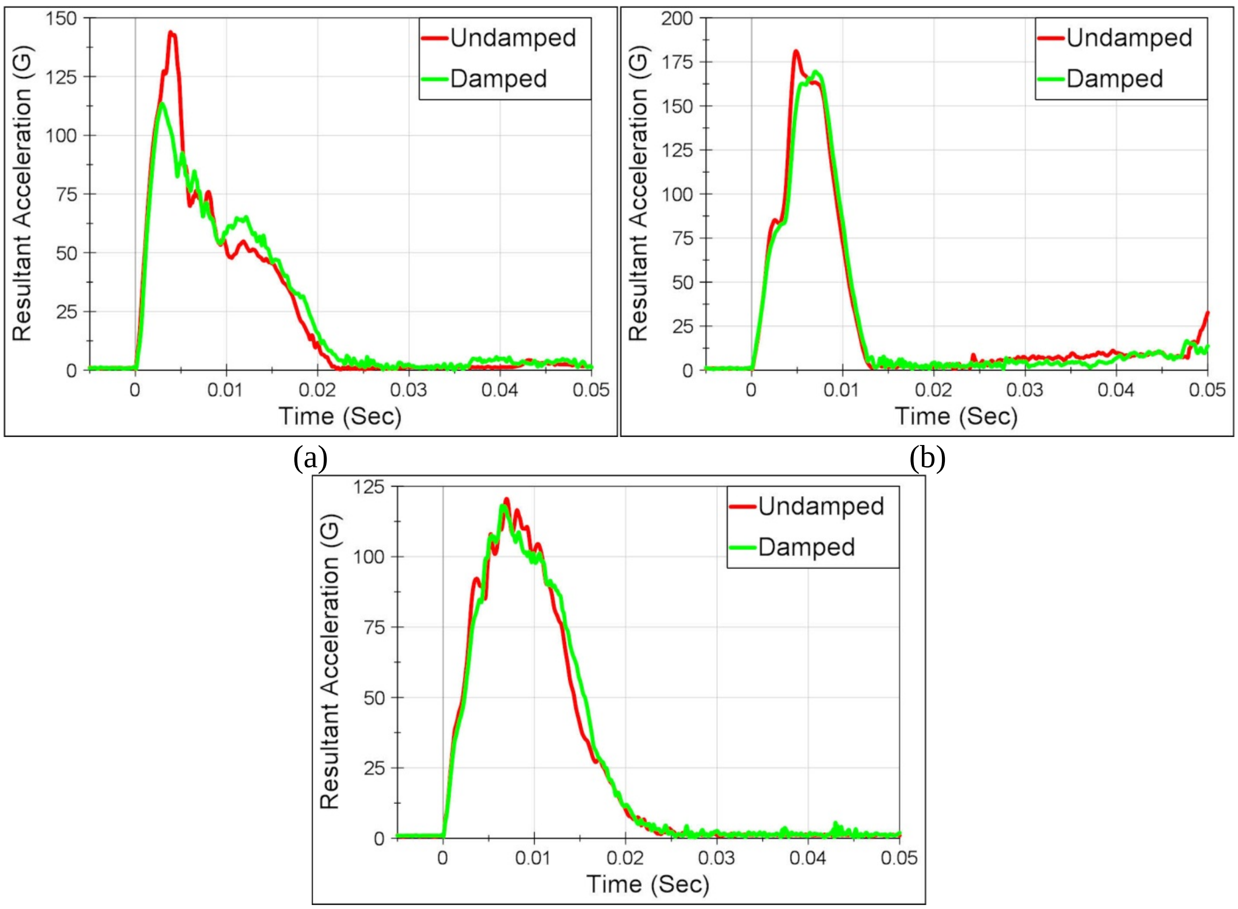
Figure 41. Kia Forte resultant acceleration time histories for the FTSS child headform impacts with undamped (red) and damped (green) accelerometers. Cowl (a), fender (b), and leading edge (c) results are shown.

Table 6. Phase III repeated impact results comparing undamped and damped accelerometers for the Kia Forte.

2010 Kia Forte			
Impact Location	HIC		Pct Diff (Damped Baseline)
	FTSS Child - Undamped	FTSS Child - Damped	
Cowl	597	516	+15.7%
Fender	1587	1540	+3.1%
Leading Edge	626	506	+23.7%

3.4.2. 2010 Buick LaCrosse

Resultant acceleration time histories for FTSS child headform impacts with undamped and damped accelerometers are shown in Figure 42. Head Injury Criterion (HIC) results are tabulated in Table 7.



(c)

Figure 42. Buick LaCrosse resultant acceleration time histories for the FTSS child headform impacts with undamped (red) and damped (green) accelerometers. Cowl (a), fender (b), and leading edge (c) results are shown.

Table 7. Phase III repeated impact results comparing undamped and damped accelerometers for the Buick LaCrosse.

2010 Buick LaCrosse			
Impact Location	HIC		Pct Diff (Damped Baseline)
	FTSS Child - Undamped	FTSS Child - Damped	
Cowl	686	636	+7.9%
Fender	1602	1482	+8.0%
Leading Edge	1026	1025	+0.1%

3.4.3. 2010 Acura MDX

Resultant acceleration time histories for FTSS headform impacts with undamped and damped accelerometers are shown in Figure 43. Head Injury Criterion (HIC) results are tabulated in Table 8. The adult headform was used at the WAD 1700 and fender locations. The child headform was used at the leading edge location.

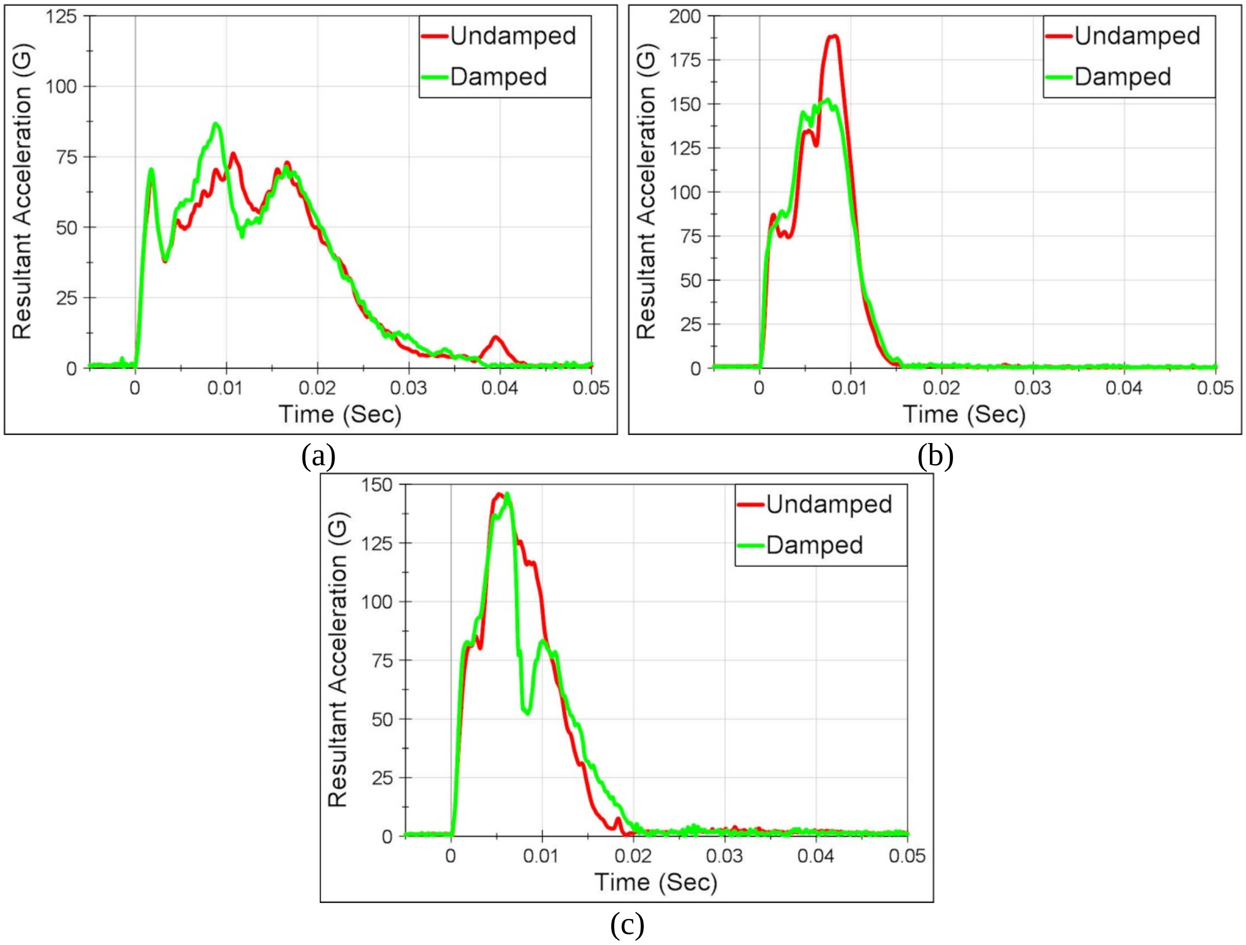


Figure 43. Acura MDX resultant acceleration time histories for the FTSS child (c) and adult (a & b) headform impacts with undamped (red) and damped (green) accelerometers. Cowl (a), fender (b), and leading edge (c) results are shown.

Table 8. Phase III repeated impact results comparing undamped and damped accelerometers for the Acura MDX.

2010 Acura MDX			
Impact Location	HIC		Pct Diff (Damped Baseline)
	FTSS - Undamped	FTSS - Damped	
WAD 1700 (adult)	503	505	-0.4%
Fender	1696	1519	+11.7%
Leading Edge	1283	969*	+32.4%

*Post-test inspection of the hood structure showed a spot weld separation directly below the impact point.

3.5. Child vs Adult Response at WAD 1700

Resultant acceleration time histories for the FTSS child and adult headform impacts at the WAD 1700 of the Acura MDX are shown in Figure 44. Head Injury Criterion results for the child and adult headforms are 550 and 503, respectively.

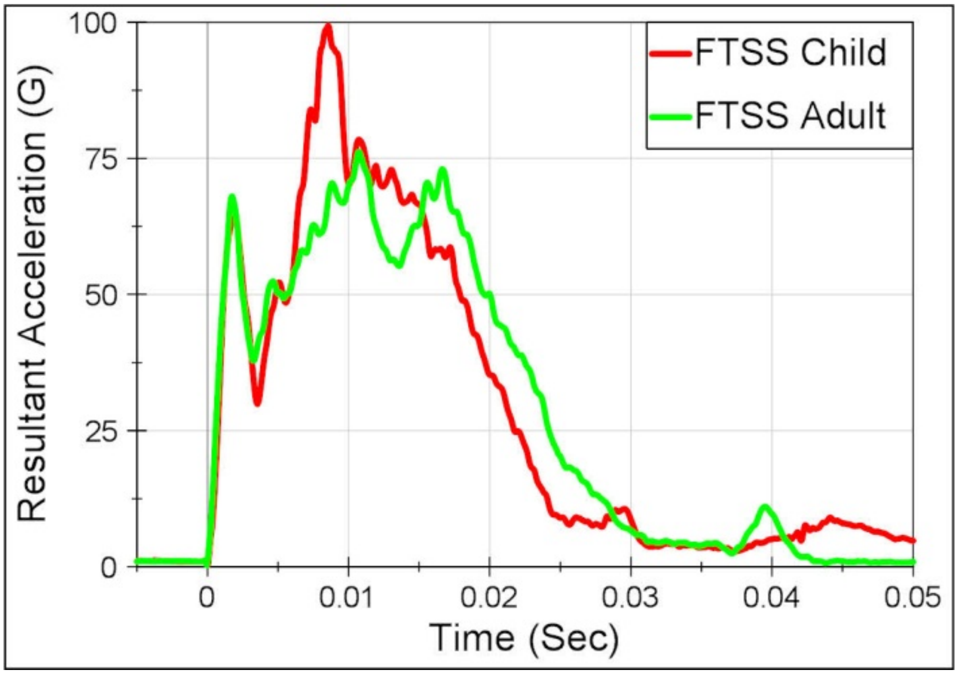


Figure 44. FTSS child and adult resultant acceleration time histories at the WAD 1700 of the Acura MDX.

4. Discussion

4.1. Phase I Discussion – Impact Point Definition

In Phase I of this study, a launch area survey was conducted to determine the differences between the 3D point of first contact (3D POFC) protocol, which is how NHTSA has interpreted the GTR test procedure in the past, and the aiming point (AP) protocol, which was NHTSA's original interpretation of the 2D measuring point (2DMP) protocol specified in the proposed GTR amendment with respect to launch area and HIC outcome.

4.1.1. Launch Area Assessment

The launch area using the 3D POFC protocol was observed to coincide with the GTR-defined test zone for all vehicles and for both child and adult headforms. For every point along the test zone boundary, it was possible to position the headform so that its point of first contact coincided with any given target point on the test zone boundary. However, this was not the case with the AP protocol. Due to the impact angle of the headform and relative curvature of the headform and vehicle, the first point of contact of the headform when it was aligned with the target point did not coincide with that target point. As shown by the launch area assessment, the first point of contact using AP along the test zone boundary was in front of both the front and rear boundaries and inward of the side boundary. This combination of shifting and shrinking caused a 5.7% average decrease in launch area when using AP. Although 5.7% seems small, the areas that are no longer reachable are near the cowl and fender, which are among the hardest parts of the hood.

The launch area using the 2DMP protocol can be assumed to be a hybrid of the 3D POFC and AP protocols. The front and rear boundaries of the actual launch area using this protocol would be similar to 3D POFC. The side boundary would be similar to AP. Therefore, as with AP, 2DMP would not include the rigid fender areas.

It is important to note that this study is not suggesting revision of the test zone itself as defined by the boundaries specified by the GTR, based on the findings for the three different targeting protocols. The purpose instead was to assess what portion of that GTR test zone for a given vehicle would essentially be unreachable if a particular protocol were used.

The side boundary of the launch area was affected the most by the targeting protocol. However, the degree to which the launch area was affected depended significantly on that vehicle's geometry (Figure 45-46). The Forte and LaCrosse had the most edge curvature in the YZ plane, and thus the largest difference in launch area between the AP and 3D POFC targeting protocols was observed on those vehicles. While the difference in launch area steadily increased from front to back of the hood for the LaCrosse, an abrupt change in the difference occurred about halfway up the hood in the Forte. The Tucson was similar to the Forte, except that the transition was not as prevalent and the difference along the full hood was not as significant as with the Forte. There was negligible difference between targeting protocols along the hood for the Odyssey, Grand Cherokee, and Acura, all of which contained a very traditional flat hood contour (Figure 46).

Figure 45. The Kia Forte (top), Buick LaCrosse (center), and Hyundai Tucson (bottom) have more of a clamshell-like geometry and the hood is steeper along the sides compared to traditional flat hood designs. The side boundaries of the hood test zone lie on these steeper side portions of the hood, which produces different launch area side boundaries for the different targeting protocols.

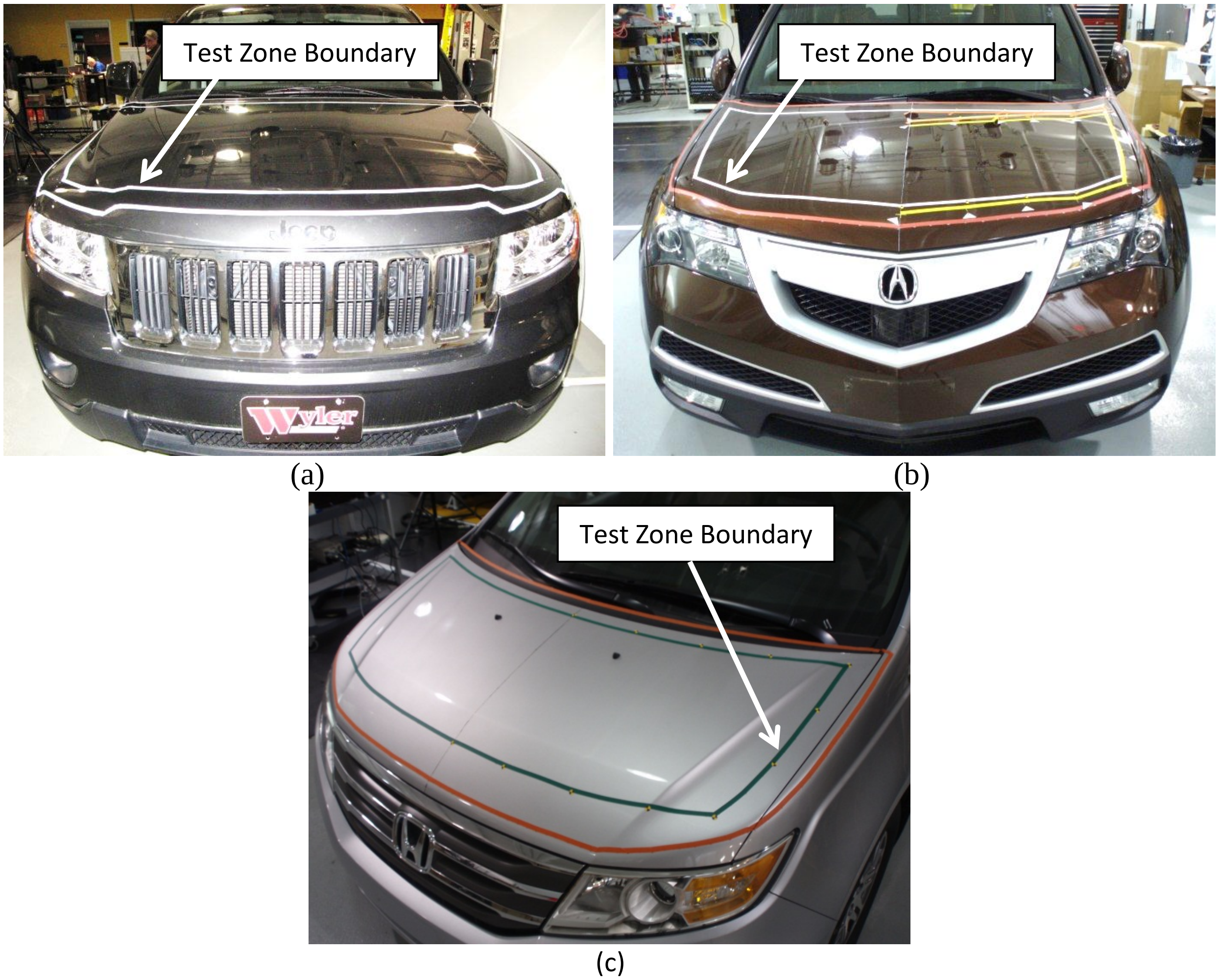


Figure 46. The Jeep Grand Cherokee (a), Acura MDX (b), and the Honda Odyssey (c) have relatively flat hood contours. The side boundaries of the hood test zones lie on relatively flat portions of the hood, which produces similar launch area side boundaries for the different targeting protocols.

The difference in launch area between the targeting protocols was not as large in the rear (bonnet rear reference line, BRRL) or front (bumper leading edge, BLE) as along the sides. Near the BRRL, the AP protocol pushed the rear edge of the launch area forward. If the AP targeting protocol was selected, some revised definition of the BRRL and/or some more stringent HIC limit may be required to account for the decrease in reachable test area. For the BLE, the aim point targeting protocol actually increases the launch area. However, this increase in launch area would not be allowed because the first contact would be outside of the test zone.

4.1.2. Impact Tests

HIC values for both 3D POFC and AP protocols and the percent differences between the two protocols are tabulated in Table 9. Adult head impacts are shaded in gray. Highlighted in red text are tests in which a lower HIC value was observed when using the AP protocol. Values in black text are tests in which a higher HIC value was observed when using AP. A general trend exists in which a lower HIC value was recorded when impacts were performed at the rear or side boundaries using AP whereas a higher HIC value was recorded when impacts were performed at the front. There were three cases (highlighted by a black box) in which the HIC values using AP at the rear boundaries were greater than or equal to the values observed with 3D POFC. However, these are not necessarily more severe impacts because the actual first contact points when using AP can be impacted with 3D POFC as well.

Table 9. HIC values and percent differences for the 3D first contact and aiming point protocols.

Description	3D POFC HIC	AP HIC	%Difference Between Methods (3D POFC is baseline)
2010 Kia Forte			
Rear, Passenger Side	597	498	-17%
Front, Driver Side	626	703	12%
Side, Passenger Side	***1587***	***927***	***-42%***
2010 Buick LaCrosse			
Rear, Passenger Side	686	640	-7%
Front, Driver Side	1026	1041	1%
Side, Driver Side	***1602***	***888***	***-45%***
2011 Honda Odyssey			
Rear, Driver Side, Inboard	1358	1103	-19%
Front, Driver Side, Outboard	1302	1379	6%
Front, Passenger Side, Inboard	1129	1280	13%
Side, Passenger Side, Inboard	***731***	***623***	***-15%***
2010 Hyundai Tucson			
Rear, Driver Side, Inboard	461	460	0%
Rear, Passenger Side, Outboard	1036	1173	13%
Front, Driver Side, Inboard	638	670	5%
Side, Driver Side	***1484***	***1171***	***-21%***
2010 Acura MDX			
Rear, Driver Side, Outboard	***1100***	***875***	***-20%***
Rear, Driver Side, Inboard	550	487	-11%
Rear, Passenger Side, Outboard	***1696***	***1472***	***-13%***
Front, Driver Side, Inboard	1283	1326	3%
Front, Passenger Side, Outboard	785	812	4%
2011 Jeep Grand Cherokee			
Rear, Driver Side, Inboard	491	443	-10%
Rear, Passenger Side, Outboard	877	1430	63%
Front, Driver Side, Inboard	651	874	34%
Side, Driver Side	***979***	***898***	***-8%***

*Tests in ***Italics*** indicate equivalence between 2DMP and AP protocols

At the front test zone boundary, AP places the point of first contact of the headform in front of and outside the defined test boundary and closer to the harder points of the bonnet leading edge. This forward shift produces an average 10% higher HIC value for AP than for 3D POFC.

At the rear test zone boundary, AP places the point of first contact of the headform in front of the defined boundary and away from the harder points of the cowl. This forward shift produces an average 12% lower HIC value for AP than for 3D POFC. At the side test zone boundary, AP places the point of first contact of the headform away from the hard fender and closer to the raised contours of the hood. These raised contours and corner-like surfaces of the hood were actually found to be really soft areas, producing anywhere from 8% to 45% lower HIC values (an average 26%) for AP than for 3D POFC.

Impacts were not performed using 2DMP because it was observed from the launch area survey that it is essentially equivalent to 3D POFC along the front and rear boundaries and to AP along the side boundaries. Therefore, the HIC values using 2DMP at the front and rear test zone boundaries and near the centers of the test zones were assumed to be similar to the HIC values that would be produced using 3D POFC. The HIC values near the side boundaries using 2DMP were assumed to be similar to the values that would be produced using AP.

All tests passed the HIC 1700 requirement for the GTR-defined relaxation zones. Therefore, it was shown that it is feasible to comply with the GTR while using either 3D POFC or AP protocols. It should be noted, however, that vehicle manufacturers typically design to around 80% of performance criteria to assure compliance margin. This would mean that HIC values of 1360 or greater would be considered a failing test in internal OEM design evaluations. Four of the 3D tests and three of the aiming point tests were greater than HIC 1360, and one of the tests had HIC greater than 1360 with either method (Acura MDX rear, passenger side). For the seven side boundary impact points denoted by italics in Table 9, the 2D method (assumed same as aiming point method) resulted in 8% to 45% lower HIC than when using the 3D first contact method. The Kia and Buick hoods had the most curvature at the fender location (Figure 45), resulting in a large difference in HIC between aiming point and first contact point. For the Kia, "first contact" was 42% higher, but was still only 1587. For the Buick, "first contact" was 45% higher (1602). Note in the reproducibility section using two headforms for the Kia and Buick fender impacts that the HIC differences were 0.2% and 6.5%. The MDX fender impact difference was 10.1%. Given these results, it is estimated that 10% would be the maximum variation expected and thus it’s conceivable that these impacts could exceed 1700 in some cases.

In addition to the geometric profile causing larger or smaller HIC differences, the underhood structures in each vehicle, especially along the hood-fender interface, give some indication about why smaller or larger HIC differences were observed between the two targeting methodologies. Many hoods are now constructed to be lightweight with an extra web-like layer of sheet metal for added rigidity. In order to soften the hoods for pedestrian safety while maintaining added rigidity, crush spaces are built into these web-like layers (Figure 47). As can be seen in Figure 47, many crush spaces exist throughout the underside of hoods and it is assumed that a low HIC would result from a headform impact to one of these areas. However, there are many points throughout the hood where the crush area boundaries meet and are joined to the hood (via spot welds and/or glue), resulting in thicker, more rigid areas. A small shift in headform impact (i.e.

the use of different targeting methods) near one of these rigid crush area boundaries may cause large differences in HIC values due to the sudden change in hood rigidity. Hoods are attached to the vehicle using hinges that deform when impacted (Figure 48). Depending on where and how the hinge area of the hood is impacted, small or large differences in HIC can occur depending on the targeting protocol employed.

Figure 47. Crush spaces on the underside of hoods.

Figure 48. The hood hinge for the Acura MDX is normally unbent. Circled in red is a bent and deformed hood hinge as result of a head impact.

More clearance exists between the hood and the engine components due to a raised hood or a lowered engine bay (Figure 49). The increased space between the hood and engine components prevents any secondary hard impacts that the headform may see with the engine components after impacting the hood.

Figure 49. Increased space in the engine bay between engine components and the hood.

The combinations of the top fender edge width and hood-fender geometry also contribute to the differences in HIC when moving small distances inboard along the sides of the hood. Depending on the top fender edge width, head impacts near the hood-fender border can result in similar or different HICs. If the stiffness of the hood-fender border drastically changes when moving inboard a small distance (becoming softer due to more open space), a large decrease in HIC will be observed. If the hood-fender border stiffness only slightly changes when moving inboard, more similar HIC results will be observed. The steepness of the hood-fender geometry can also determine whether a head impact would occur more inboard towards the soft hood (lower HIC) or more outboard towards the rigid fender (higher HIC).

4.2. Phase II Discussion – Headform Reproducibility

4.2.1. Vehicle Testing

Tables 3 and 4 showed that the percent differences of the two child headforms for the Kia Forte and Buick LaCrosse were below 6.5% at all impact locations, indicating good reproducibility between the two headforms. The percent differences of the two child headforms for the Acura MDX were much larger than for the other two vehicles (Table 5). In the WAD 1700 test, the HIC values were quite low with respect to the requirements and thus a large difference may not be as critical from a compliance standpoint. In addition, there was some pre-existing fender deformation on the struck side in the FTSS damped test that was not present for the Cellbond damped test. The difference in acceleration time history shown in Figure 37(a) is likely due to this pre-test deformation. The large variation in the leading edge test for the MDX was influenced by a spot weld separation discovered in the hood structure following the FTSS damped test (Figure 37c). This damage was deemed to be the most valid explanation of the abrupt decrease in the acceleration trace in the FTSS damped test (Figure 36).

In comparing headform/accelerometer variation for vehicle tests with and without a subsequent hard contact, it appeared that headform variability was less than accelerometer variability in both cases. In cases with a subsequent hard contact (for example, the Forte leading edge from Figures 35(c) and 41(c)), the amplitude of the percent difference was typically higher when comparing accelerometer schemes than it was when comparing headforms. The lone exception was the LaCrosse leading edge location (0.1% damped vs. undamped, 2.7% FTSS vs. Cellbond).

4.2.2. Headform Certification Testing

The FTSS headforms were certified with undamped accelerometers and the Cellbond headforms were certified with damped accelerometers. Figure 50 compares the resultant acceleration traces of the Cellbond and FTSS child headforms. Figure 51 compares the resultant acceleration traces of the Cellbond and FTSS adult headforms. Table 10 tabulates the peak resultant accelerations for all of the certification tests conducted on a Part 572, rigid steel plate which is consistent with the GTR9 procedure. The results are similar for both headform manufacturers and for both accelerometer schemes, indicating that the different combinations are repeatable and reproducible. Note that in Table 10, we showed that the FTSS/undamped and Cellbond/damped combinations had a similar amount of variation (1.4% vs. 2.0%) in repeated head drop tests. Therefore, differences in vehicle impact results for a given impact point are likely to be attributable more to the vehicle or test setup rather than differences in the headform structures. Note that the severity of the certification test is within the range of the peak accelerations obtained in vehicle testing.

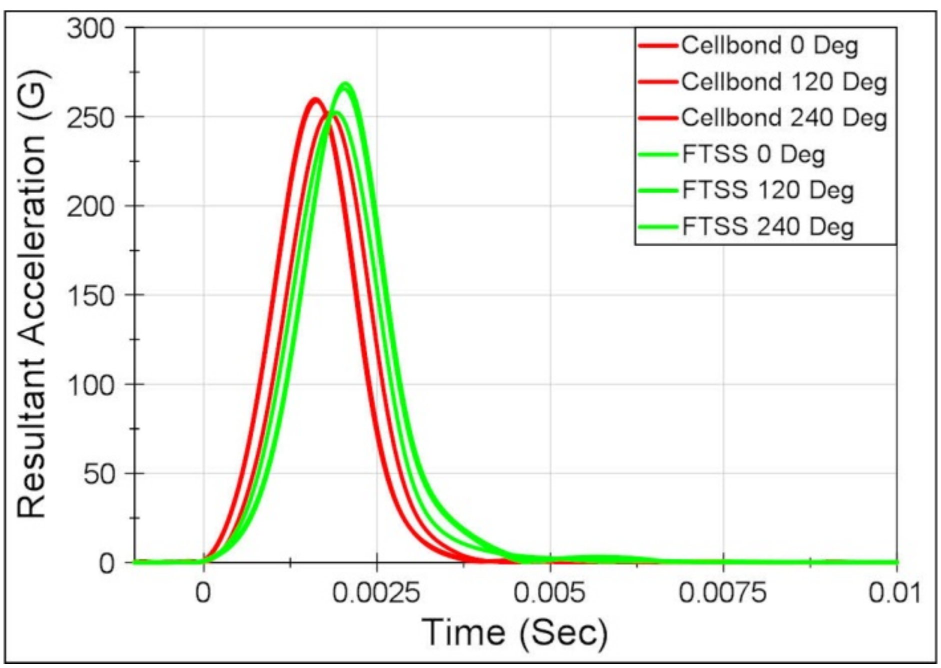


Figure 50. Resultant acceleration results from the headform certification tests for the Cellbond (red) and FTSS (green) child headforms.

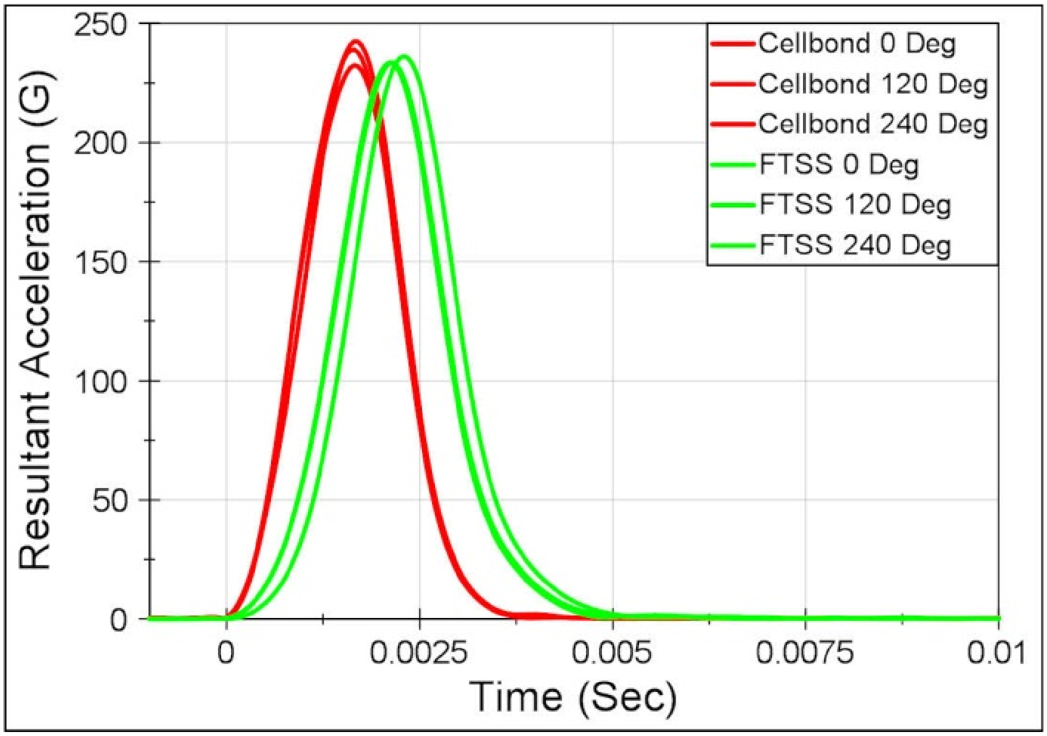


Figure 51. Resultant acceleration results from the headform certification tests for the Cellbond (red) and FTSS (green) adult headforms.

Table 10. Peak resultant acceleration results for the Cellbond and FTSS child and adult headforms.

	Rotation	Peak Acceleration (G)	
		Cellbond	FTSS
Child	0 Deg	259	252
	120 Deg	260	266
	240 Deg	252	269
Average		257	262
%Difference		2.0%	
Adult	0 Deg	243	236
	120 Deg	239	234
	240 Deg	232	234
Average		238	235
%Difference		1.4%	

4.2.3. Headform Construction Differences

Figures 17-20 illustrate the structural differences between the Cellbond and FTSS headforms. While both headforms meet the GTR specifications for mass, diameter, and seismic mass location with respect to the headform center of gravity, there are some definite discrepancies both internal and external. Even with these discrepancies, the headforms displayed reproducible results. There was a need to slightly modify the Cellbond headforms with a thin steel back plate to assure connectivity and centering with the impactor launch plate. This provision could be spelled out in the drawing or PADI document to assure that such a revision is allowable as long as it doesn't move the mass, moment of inertia, or diameter out of the GTR specification. The FTSS child headform has a steel back plate, but the sphere that interfaces with the headskin is aluminum as specified in the GTR. As long as the headform meets the mass, external geometry, accelerometer seismic mass location, and moment of inertia requirements, the launch system interface material in the headform structure appears to be inconsequential for the acceleration response.

4.3. Phase III Discussion – Accelerometer Scheme

Tables 6-8 indicate that using damped accelerometers usually results in a decrease in HIC outcome. The differences tended to be larger in softer hood areas. The stiffer points as indicated by higher HIC values resulted in differences of 3.1%, 8.0%, and 11.7%. It appears that either damped or undamped accelerometers are suitable for hood tests from a testing standpoint, in that the acceleration traces for each show no evidence of resonant frequencies or excessive vibration. Signal analysis showed very little difference in the frequency content of the damped and undamped accelerations, and this similarity is evident from the acceleration time histories in Figures 41-43. It appears that damped accelerometers only provide added signal stability in high frequency impacts such as the windshield. However, the lower measurements with the damped accelerometers may require a more stringent HIC requirement in a hood test than if undamped accelerometers were used. Regardless of which type of accelerometer is selected, the type and frequency characteristics of the accelerometer used should be spelled out explicitly in regulatory text. If there is an option to use either, it may require additional considerations given the tendency to lower HIC values with damped accelerometers shown in this study.

4.4. Adult vs. Child Headform Response at WAD 1700

The GTR language specifies that any points forward of the WAD 1700 line should be tested with the child headform, and any points rearward of WAD 1700 tested with the adult headform. There is no provision for testing *at* the WAD 1700 line. In order to evaluate how a child vs. adult headform would do at WAD 1700, both were tested on the Acura MDX. The child response (HIC=550) was slightly higher than the adult response (HIC=503) when both were equipped with undamped accelerometers (Figure 44). This consistency indicates, for this specific point, that there is not a danger of bottoming out with the higher mass adult headform. A concern would be that, given the +/- 10 mm tolerance on impact point, that either headform could be used from 1690 to 1710 mm, and that a countermeasure in that area may be tuned for one specific headform.

5. Conclusions

- The launch area prescribed by the 2D measuring point protocol (2DMP) was found to be equivalent to the 3D point of first contact (3D POFC) protocol launch area edges at the front and rear boundaries of the test zone, but equivalent to the launch area edges prescribed by the aiming point protocol (AP) at the side boundaries.

- Use of the aiming point as opposed to the 3D point of first contact resulted in a 5.7% decrease in launch area. Because of the equivalence of the 2D measuring point and aiming point at side boundaries of the test zone and equivalence of the 2D measuring point with the 3D point of first contact at the front/rear boundaries, the difference in launch area between 2D measuring point and 3D point of first contact is expected to be between 0% and 5.7%. While this difference appears small, the difference tends to be in the hardest hood locations where head contacts would result in more serious injury.

- All tests, regardless of targeting protocol, met the HIC 1700 requirement. However, several of the points were above HIC 1360, which is a common OEM design limit associated with 20% compliance margin.

- Differences in HIC using various targeting protocols at the same hood locations and same headform configuration were attributed to vehicle-by-vehicle variation in hood contour along with the presence/type of pedestrian countermeasures contained under the hood.

- Testing with two different headforms at the same impact points resulted in less than 10% difference in HIC, with the exception of two impacts on the Acura MDX. The first exception occurred in a very soft hood area with relatively low HIC (603 with Cellbond, 505 with FTSS) with neither close to the GTR HIC limit, and the second large difference was a result of a hood spot weld separation in one of the two tests.

- Differences between Cellbond and FTSS headforms were found, which required some modification to the Cellbond back plate to hold the headform in place prior to the test. However, both headforms met the GTR specifications and showed good reproducibility.

- Undamped accelerometer headform impacts resulted in higher HIC values than with damped accelerometers. The difference ranged from -0.4% to +23.7%. Again, the largest differences were at low HIC locations or due to the spot weld failure. The highest HIC locations showed differences of 3.1%, 8.0%, and 11.7%, which are in the same range as headform reproducibility differences.

- Tests done with child and adult headforms at WAD 1700 showed consistent HIC values, indicating that for this specific point, the pedestrian countermeasure provides equal benefit for child and adult.

6. References

Kessler, J., Development of countermeasures to reduce pedestrian head injury. In *Experimental Safety Vehicles Conference*, pp. 784–796, 1987.

Kessler, J. and Monk, M., NHTSA pedestrian head injury mitigation research program –Status report. In *Experiment Safety Vehicles Conference*, pp. 1226–1236, 1991.

MacLaughlin, T. and Kessler, J., "Pedestrian Head Impact Against the Central Hood of Motor Vehicles - Test Procedure and Results," SAE Technical Paper 902315, 1990.

Mallory, A., Stammen, J., and Meyerson, S., Pedestrian GTR testing of current vehicles. In *Experimental Safety Vehicles Conference*, ESV Paper No. 07-0313, 2007.

Pritz, H. "Experimental Investigation of Pedestrian Head Impacts on Hoods and Fenders of Production Vehicles," SAE Technical Paper 830055, 1983.

Stammen J.A., Saul R.A., Ko S.B. "Pedestrian Head Impact Testing and PCDS Reconstructions," Seventeenth International Technical Conference on the Enhanced Safety of Vehicles (ESV), June 2001.

United Nations Economic Commission for Europe, Transport: Vehicle Regulations; 1998 Agreement on Global Technical Regulations, Appendix to Global Technical Regulation No. 9 Pedestrian Safety (ECE/TRANS/180/Add.9/Appendix 1), Geneva, Switzerland, 2009.