THE NEED TO CONTROL BELT ROUTING FOR SILVER NCAP RATINGS

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ABSTRACT

In 2011 NHTSA made changes to the NCAP frontal full-width test rating that introduced a chest deflection metric. The dummy seating protocol did not specify routing procedures that consistently control shoulder belt positioning on the dummy. Thus, most NCAP tests were conducted with the D-ring in the fully up position, placing the shoulder belt far above the center chest potentiometer.

Sled and full-vehicle crash tests of a 2011 Dodge Caliber demonstrated that for the 5th percentile small female passenger dummy, the high D-ring position causes the belt to cross the chest above the location of the deflection potentiometer. The ribeye gauges show that this belt configuration produces deflection measurements that are higher than those measured by the center potentiometer.

The differences in chest deflection measurement caused by variations in belt routing are not trivial. For the Caliber, the NHTSA NCAP test produced a chest deflection of 11.8 mm, corresponding to a risk of serious chest injury for older females of 0.6%. A crash test conducted by IIHS under the same conditions but with the belt routed across the deflection potentiometer produced a chest deflection of 34.5 mm, corresponding to a risk of serious chest injury for older females of 44.7%.

INTRODUCTION

Beginning with Model Year 2011, NHTSA introduced a wide variety of changes to the nature and structure of the NCAP rating program [Federal Register 2008]. The more significant changes, as they apply to the measurement of chest injury risk in the portion of the program involving frontal crash protection, included:

- substituting chest deflection in place of chest acceleration to assess chest injury risk;
- including new chest injury risk functions for chest deflection;
- substituting a Hybrid III 5th percentile female dummy for the 50th percentile male dummy in the front right seating position; and
- positioning the right front passenger seat in the forwardmost position.

Other relevant changes in 2011 NCAP included:

- adopting a 15 ms HIC in place of the 36 ms HIC to assess head injury risk;
- expanding the body regions monitored to include the neck;
- selecting injury risk functions that shifted the emphasis from AIS 4+ injury risk to AIS 3+ injury risk in the case of the head, neck and chest;
- adding AIS 2+ injury risk in the case of the knee-thigh-hip (KTH) complex; and
- creating and applying a combined injury risk (CPI) metric to calculate overall injury risk to the above-mentioned four body regions.

The combined injury risk (CPI) metric was defined as follows:

CPI = 1 - (1-Phead)(1-Pneck)(1-Pchest)(1-Pkth)

where:

Phead = Probability of an AIS3+ head injury based on HIC

Pneck = Probability of an AIS 3+ neck injury based on Nij or axial force

Pchest = Probability of an AIS3+ chest Injury based on chest deflection

Pkth = Probability of an AIS2+ KTH injury based on femur Loads

The maximum combined injury risk for a five-star rating was set at 10 percent.

The chest injury risk function for the 2011 NCAP appears on p. 40026 of the 2008 Federal Register Notice. When compared with age-related risk curves developed by Laituri et al., the curve corresponds to a 35-year-old male [Laituri et al. 2005].

Subsequent to the introduction of the 2011 NCAP, Digges et al. [2013] proposed an NCAP rating system for seniors, subsequently known as a "Silver Rating." The suggested rating used chest injury risk functions based on the higher vulnerability of seniors to chest injuries and the higher risk of death associated with these injuries.

When exposed to frontal crashes, the injury risks for the elderly population differ from those of younger people in terms of both tolerance to impact and the body region most susceptible to life-threatening injuries. Numerous studies have shown that the chest region is much more vulnerable to life-threatening injuries for the older population [Augenstein et al. 2005, Kent et al. 2005, Ridella et al. 2012]. Augenstein et al. [2007] noted that elderly occupants in the right front seating position have fatality rates that are 42% higher than those of elderly occupants in the driver seat. Age dependent injury tolerances of the chest have been proposed by several researchers [Zhou et al. 1996, Laituri et al. 2005 and Prasad et al. 2010].

With the resulting increased weighting of chest injuries relative to other body regions proposed by the authors, the accuracy of the chest injury estimates based on chest deflection from test data becomes critically important. Chest compression is measured by a single chest deflection gauge at the centerline of the sternum of the dummy. The path of the shoulder belt relative to the deflection gauge depends on belt anchor locations and particularly the location of the D-Ring, which is not specified in the NCAP test procedure relative to the location of the dummy chest deflection device. This could lead to unacceptable variability in estimated chest injury risk.

The variation of the chest deflection measurement according to belt position on the chest, relative to the chest deflection gauge, has been noted in passing by several researchers. Horsch et al. [1991], tested a belt-restrained Hybrid III dummy and reported a 34% reduction in chest compression when the belt was placed against the neck, compared with a similar test with the belt placed 50 mm laterally away from the neck. Similar 5th percentile female dummy driver and front right passenger reductions in chest compression were observed in controlled sled tests as belt placement moved from the shoulder region to the neck region [Tylko et al, 2006]. In sled tests with dummies in the rear seat, the shoulder belt configurations showed similar chest deflection reductions when the belt was moved away from the deflection gauge [Yamanski et al. 2011, Tylko et al. 2007, Tylko et al. 2012].

OBJECTIVE

The objective of the present research was to assess how variations in belt positioning across the chest, stemming from the location of the seatbelt upper anchorage D-ring and seat track position, influence a Hybrid III 5th percentile female dummy's chest injury measurements in sled tests simulating a 56 km/h full-width frontal NCAP pulse and matching full-scale rigid-barrier crash tests.

METHODOLOGY AND DATA SOURCES

The 2011 Dodge Caliber was selected for the sled tests and full-scale crash vehicle. This selection was based on a previous analysis of the effect of belt positioning, in which it was observed that NCAP and FMVSS 208 had differences in the specifications for the D-ring position that greatly affected the resulting chest deflection output in tests of the Caliber. [Haight et al., 2013]

Haight et al. compared the results of an FMVSS 208 test of a Caliber at 48 km/h, with that of an NCAP crash test at 56 km/h. In the FMVSS 208 test the D-ring was positioned in the mid position, while in the NCAP test the D-ring was positioned in the uppermost position (Figure 1). Higher chest deflection was observed in the lower speed FMVSS 208 test. Since the crash speeds were different, the test results were not directly comparable but pointed to the need to study belt geometry effects on chest deflections.

Figure 1. Shoulder belt routing of small female right front passenger dummy in official NCAP test of Dodge Caliber

The present research focused on a 5th percentile female dummy in the right front passenger seat in the 56 km/h NCAP condition. A Dodge Caliber buck was created by PMG Technologies and a series of sled tests were conducted using a crash pulse representing a 56 km/h full-frontal rigid barrier test. The time to fire airbags and seatbelt pretensions was matched to the official NCAP times.

The official NCAP test of the Caliber and a second full-scale vehicle test conducted by the Insurance Institute for Highway Safety in accordance with NCAP procedures were used to validate the results of the sled test series and demonstrate in a full vehicle crash environment the extent to which belt routing influences chest measures.

The sled test matrix examined combinations of D-ring positions and seat track locations on belt routing and resulting chest injury measures (Table 1).

Table 1.
Sled test matrix for small female right front passenger

	Seat track position	
D-ring height	*Forwardmost*	*Midtrack*
Highest	X (matching vehicle test)	X
Lowest	X (matching vehicle test)	X

The chest instrumentation for the PMG sled tests included both the center chest potentiometer, as used in the NCAP tests, and the ribeye. [Tylko et al., 2007]. This combination of instrumentation provided a comparison of the symmetry of the chest loading and the extent of the deflection away from the center gauge. However, the significance in terms of injury risk of the asymmetrical loading measured by the ribeye has yet to be determined.

The small female dummy's chest was marked with a grid of targets to observe the differences in belt routing and measure distance from the belt to the center chest potentiometer, which at rest is located at the lowest center target. The target locations are shown in Figure 2. This grid was applied to both the dummies in the sled tests and full-vehicle test. Figures 3-4 show the routing of the shoulder belt relative to the chest target grid for the sled tests. Figure 5 shows the routing of the shoulder belt relative to the chest target grid for the full-vehicle test conducted by IIHS.

The test conducted by IIHS was the same as the official NCAP test with one exception: The D-ring height of full down was chosen instead of the full-up position used in the official NCAP test of the Caliber.

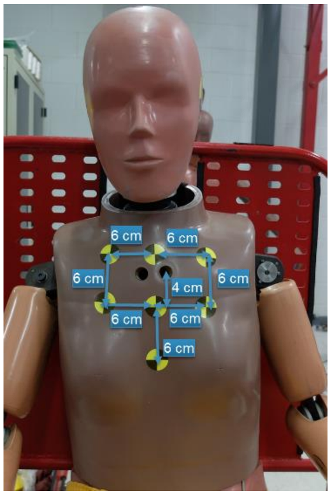

Figure 2. Small female dummy chest target grid for observing variation in belt routing relative to center sensor

Figure 3. Sled tests of small female dummy, forwardmost seat position: D-ring full-up (left), full-down (right)

Figure 4. Sled tests of small female dummy, midtrack seat position: D-ring full-up (left), full-down (right)

Figure 5. IIHS-conducted Caliber test of small female dummy with forwardmost seat position and D-ring full-down

RESULTS

Upper anchorage D-ring location and seat track location had a significant effect on belt routing and resulting chest deflection measured at the center potentiometer both in sled tests and full-vehicle tests. A comparison of belt routing differences and associated peak center chest deflections for the sled tests is shown in Tables 2-3.

Table 2.
Distance of shoulder belt above center chest sensor grid target for sled test matrix (mm)

	Seat position	
D-ring height	*Forwardmost*	*Midtrack*
Highest	116	60
Lowest	52	38

Table 3.
Sled test peak chest deflections (mm)

	Seat position	
D-ring height	*Forwardmost*	*Midtrack*
Highest	20.4	33.8
Lowest	29.8	36.8

In the sled tests, the additional chest measurements with the ribeye were compared to the peak center chest deflection sensor used for NCAP rating. Figures 6-9 show the chest deflection histories of the center chest potentiometer and individual ribeye deflections for each of the sled test conditions. For both the forwardmost and midtrack seat positions, when the belt is routed closer to the center potentiometer (D-ring full-down), the ribeye sensors are better aligned with the measurement from the center potentiometer, while in the tests where the belt is routed further away (D-ring full-up), the ribeye measurements are greater than the center potentiometer and more dispersed.

The full-vehicle tests validated the relevance of the sled test series. A comparison of belt routing and resulting chest deflections between the sled and full-vehicle tests is shown in Table 4. Since the chest grid was not present on the official NCAP test dummy, measures of PBU and PBL were also compared as height of the belt relative to the dummy torso. A comparison of sled test and full-vehicle chest deflection histories is shown in Figure 10. A comparison of sled-test shoulder belt loading is shown in Figure 11. The chest deflections for NCAP and IIHS tests are in Figure 12 and injury risks associated with the NCAP and IIHS vehicle tests are shown in Table 5.

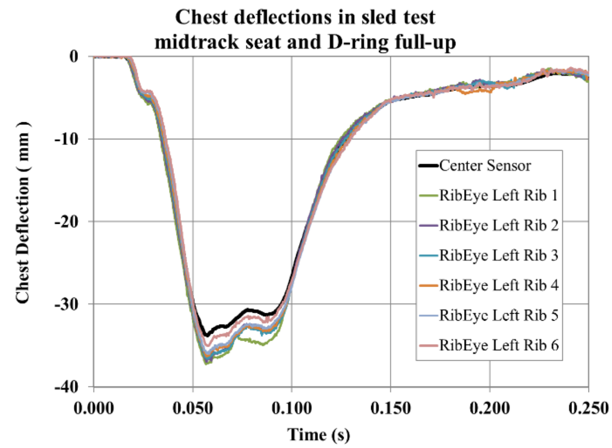

Figure 8. Chest deflection comparison for sled test: midtrack seat position and D-ring full-up

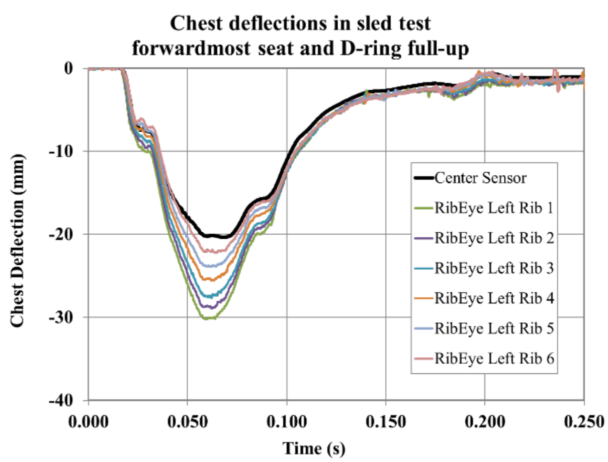

Figure 6. Chest deflection comparison for sled test: forwardmost seat position and D-ring full-up

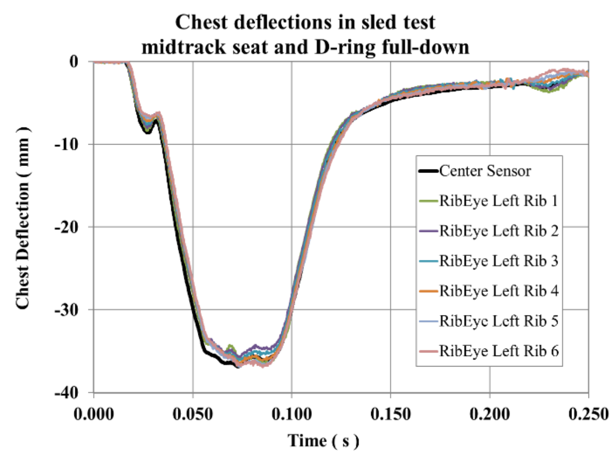

Figure 9. Chest deflection comparison for sled test: midtrack seat position and D-ring full-down

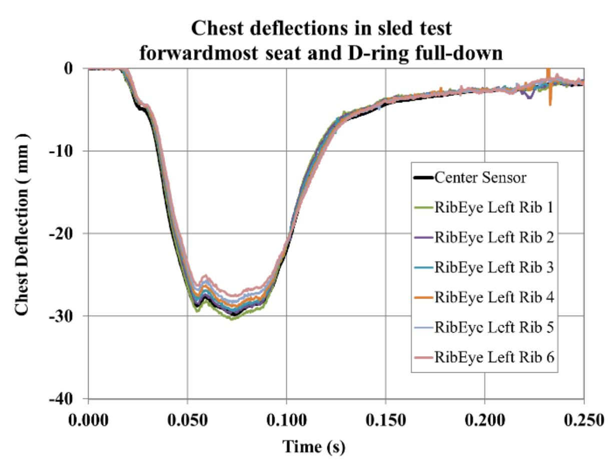

Figure 7. Chest deflection comparison for sled test: forwardmost seat position and D-ring full-down

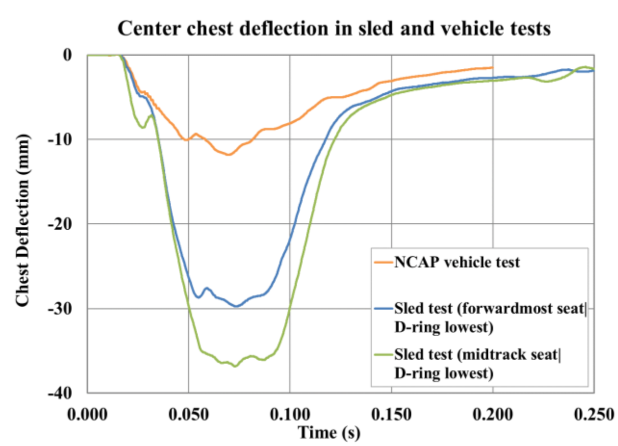

Figure 10. Center chest deflection comparison of sled tests to NCAP vehicle test

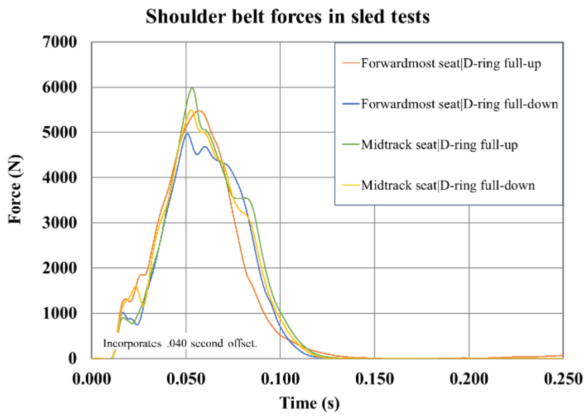

Figure 11. Comparison of shoulder belt forces in sled tests

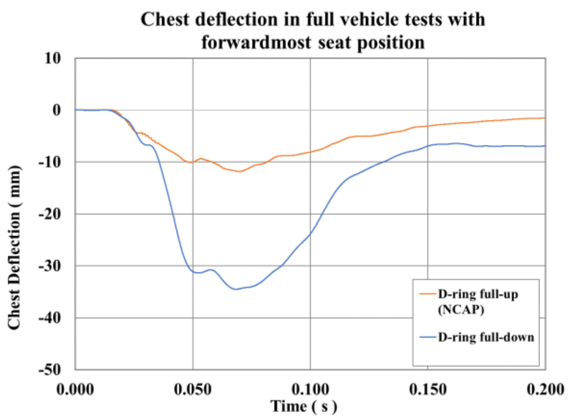

Figure 12. Center chest deflection comparison for full-vehicle tests with varied D-ring positions

Table 4.
Comparison of matched sled test and full-vehicle test setup and resulting chest deflections (mm)

	Forwardmost seat position			
	D-ring full-up		**D-ring full-down**	
	Sled test	*Full vehicle (NCAP)*	*Sled test*	*Full vehicle*
Distance from belt to center sensor	116	N/A	52	46
PBU-dummy lap plate to belt upper edge	367	364	260	268
PBL-dummy lap plate to belt lower edge	285	292	180	195
Maximum chest deflection	20.4	11.8	29.8	34.5

Table 5.
Vehicle test peak center chest deflections and associated injury risks

	NCAP Test High D-ring	**IIHS Test Low D-ring**
Chest Compression	11.8 mm	34.5 mm
	Injury Risk	*Injury Risk*
Young (35YO) Occupant Risk (NCAP Rating Based)	0.6%	15.0%
Older Female Risk; 5% Dummy (Digges 2013; Prasad 2010)	0.6%	44.7%

DISCUSSION

A key research question addressed in this paper is the degree to which locating the belt away from the center chest potentiometer changes the chest injury measurement. In this typical small car, adjusting the upper anchorage D-ring location across the vehicle's range results in large differences in routing across the small female dummy's chest. The forwardmost seat position with a full-up D-ring results in the belt touching the lower neck, while the forwardmost seat position with a full-down D-ring results in the belt lying across the dummy's shoulder, well away from the neck. Of more significance is the difference in position of the belt relative to the center potentiometer, depicted in this study as the lowest centered grid target. With the seat forwardmost, the lowest D-ring position achieves a much closer routing to the center potentiometer, 64 mm closer than the full-up D-ring condition, and the belt itself overlays the senor.

Moving the dummy's seat location from forwardmost to midtrack inherently brings the belt routing closer to the center potentiometer. Full-up D-ring was 56 mm closer and full-down D-ring was 14 mm closer, with both positions achieving some overlap of the belt with the sensor. This trend suggests that the forwardmost seat position makes the belt routing geometry more sensitive to variables, especially the D-ring positioning. Should NHTSA proceed with a midtrack position for NCAP testing in the future, belt routing in general would be expected to become more controlled.

Belt routing between sled tests and their matched vehicle tests was considered consistent, making a direct comparison between sled and full-vehicle tests valid. The routing in the IIHS test and its paired sled test were similar. There were slight differences in the NCAP test and matching sled test routing. While the belt touched the dummy's neck in both tests and PBU/PBL values were similar, from photographic evidence it appears the sled test had slightly less overlap on the neck than the corresponding NCAP test. The exact difference in belt routing cannot be determined since the NCAP test did not provide additional comparative measures, but it is probable that the higher location of the NCAP belt means it crosses the chest even further away from the deflection gauge, which may account for the lower NCAP chest compression reading.

A comparison of shoulder belt forces from the four sled test conditions confirms that the deflection variations in the test series were dictated by belt placement and seat position. The maximum belt load was in the range of 5,000 N plus or minus 500 N. The higher belt loadings corresponded to the higher anchorage locations and the resulting lower chest deflections.

The variations in chest deflections observed in this study have much to do with dummy design. As with any measuring instrument, a dummy needs to be used in the confines of its calibration and intended use. The Hybrid III dummy calibration procedure involves a 15.25 cm (6") diameter cylinder impacting the dummy chest centered upon the chest deflection potentiometer. This calibration test was based on a similar test that established the compression response corridors for the human chest, and was the basis for the dummy chest design [Kroll 1974]. Although real-world occupants may position their belts so they cross the chest in a variety of locations, a dummy, with only a central deflection sensor, produces an excessively wide range of measurements when an equivalent latitude of belt positioning is permitted, as in the NCAP test.

The ribeye deflection measurements provide an evaluation of asymmetry in loading of the chest by the restraint system. In configurations in which the belt is routed farther away from the center potentiometer (D-ring full-up conditions), there is a large difference in the peak center sensor and peak ribeye sensors. For example, in the forwardmost seat D-ring full-up condition, the maximum center chest deflection is 20 mm and the highest ribeye deflection is 30 mm, with peak deflections ranging from 22 to 30 mm for the remaining locations. This trend was also true for the midtrack seat D-ring full-up condition but less pronounced, (peak differences of 33.5 mm vs. 37 mm), likely because the belt is routed more closely in this condition. In contrast, when the belt is routed closer to the center sensor (D-ring full-down conditions), the center sensor and ribeye deflection sensors are similar in magnitude, with a maximum of approximately 30 mm in the forwardmost seat track condition and 37 mm for the midtrack seat condition. This suggests highly symmetric loading of the chest by the restraint.

Currently, the ribeye has both advantages and disadvantages for evaluating chest injury. The use of the ribeye appears to be a positive addition to evaluating symmetry of chest loading, especially when used in a way that reflects the dummy's chest compression calibration procedure and intended use. However, the evaluation of chest injury risk measurements in locations away from the center deflection sensor may be problematic, due to limitations of biomechanical data about the human chest response under similar loading.

Results from these sled tests suggest that positioning the seat at midtrack and lowering the D-ring height to the lowest setting achieved the best belt routing over the dummy's center chest potentiometer, producing symmetric loading across the chest. This configuration creates belt routing that more closely corresponded to the dummy calibration procedure for chest compression response and intended use [NHTSA 2008].

The findings of this study are in general agreement with earlier tests looking at varying shoulder belt configurations for rear seat occupants. Yamasaki and Uesaka, 2011, reported an increase of nearly 18 mm in chest deflection due to the belt routing effect over the dummy chest. Similar effects have been reported by Tylko and Bussières, 2012.

Better control of belt routing is necessary for future comparative evaluations of chest injury to be meaningful. If the future NCAP seating protocol includes a seat track change from forwardmost to midtrack as proposed, belt routing may improve. However, neither the current or future NCAP seating procedures specify D-ring position.

Table 5.
Recent NCAP D-ring position by vehicle make and model

Test No.	Vehicle Make	Model	Year	SEAT BELT UPPER ANCHORAGE
9793	HYUNDAI	ELANTRA	2017	UPPERMOST (D & P)
9763	FORD	FUSION	2017	UPPERMOST (D & P)
9762	FORD	ESCAPE	2017	UPPERMOST (D & P)
9745	KIA	SPORTAGE	2017	UPPERMOST (D & P)
9939	NISSAN	MURANO	2016	UPPERMOST (D & P)
9808	HONDA	CIVIC	2016	FIXED
9801	BUICK	CASCADA	2016	FIXED
9761	LEXUS	RX350	2016	UPPERMOST (D & P)
9757	NISSAN	VERSA NOTE	2016	UPPERMOST (D & P)
9696	VOLVO	XC90 T8	2016	UPPERMOST (D & P)
9662	CHEVROLET	SILVERADO	2016	UPPERMOST (D & P)
9649	TOYOTA	PRIUS	2016	UPPERMOST (D & P)
9593	HONDA	CIVIC	2016	UPPERMOST (D & P)
9592	TOYOTA	PRIUS C	2016	FIXED
9591	TOYOTA	TACOMA	2016	UPPERMOST (D & P)
9563	KIA	OPTIMA	2016	UPPERMOST (D & P)
9561	CHEVROLET	MALIBU	2016	FIXED
9557	VOLVO	XC90 T6	2016	UPPERMOST (D & P)
9553	VOLKSWAGEN	GOLF SPORTWAGEN	2016	UPPERMOST (D & P)
9552	VOLKSWAGEN	PASSAT	2016	UPPERMOST (D & P)
9512	JEEP	RENEGADE	2016	1 NOTCH BELOW UPPERMOST (D) 2 NOTCHS BELOW UPPERMOST (P)
9511	NISSAN	VERSA	2016	UPPERMOST (D & P)
9508	CHEVROLET	COLORADO	2016	UPPERMOST (D & P)
9503	DODGE	CHARGER	2016	UPPERMOST (D & P)
9494	MAZDA	CX-3	2016	UPPERMOST (D & P)
9493	CHRYSLER	300	2016	UPPERMOST (D & P)
9492	HONDA	CRV	2016	UPPERMOST (D & P)
9487	LEXUS	ES 350	2016	UPPERMOST (D & P)
9484	FORD	F250 PICKUP	2016	UPPERMOST (D & P)
9350	HYUNDAI	TUCSON	2016	UPPERMOST (D & P)
9326	HONDA	PILOT	2016	UPPERMOST (D & P)
9296	HONDA	HR-V	2016	UPPERMOST (D & P)
9295	NISSAN	MAXIMA	2016	UPPERMOST (D & P)
9252	ACURA	ILX	2016	UPPERMOST (D & P)
9157	KIA	SORENTO	2016	UPPERMOST (D & P)
9156	MAZDA	6I	2016	UPPERMOST (D & P)
9136	MAZDA	CX-5	2016	UPPERMOST (D & P)

Manufacturers appear to be choosing a full-up D-ring position. From a query of recent NCAP test setup information, of 33 vehicles with adjustable D-rings, 32 were tested with the upper belt anchorage for the right front passenger in the uppermost position and none tested at lowermost (Table 5). The remedy is not as easy as specifying a lower D-ring position, since manufacturers can simply redesign the D-ring height adjustment range to achieve a certain routing. What is currently full up could be redesigned as the full down position in future models to essentially achieve a similar belt-routing pattern. A dummy-based procedure should be developed to ensure the belt routes across the sensor in a way that corresponds to the intended use of the dummy.

The differences in belt routing observed in this study have a significant influence on chest deflections and their associated predicted injury risk, especially when considering risks for elderly occupants. A comparison of the two vehicle crash tests, the official NCAP test (D-ring full-up and forwardmost seat position), with the belt routed high, touching the dummy's neck, and the IIHS conducted test (D-ring full-down and forwardmost seat position), with the belt routed close to the chest sensor, highlights the importance of controlled routing to dummy sensor output. The NCAP test deflection of 11.8 mm is associated with a low risk of AIS 3+ injury — 0.6% using the NCAP risk curve (occupant age 35). In contrast, with improved belt routing, the IIHS test deflection of 34.5 mm is associated with a relatively higher risk of 15%. A combined body region risk of less than 10% is needed for a 5-star rating.

In contrast, applying the Prasad risk curve for older female occupants to the IIHS test deflection of 34.5 mm produces the substantially higher chest injury risk of 44.7%.

CONCLUSIONS

In 2011 NHTSA made changes to the NCAP frontal full-width test rating that included the introduction of a chest-deflection metric. However, the dummy seating protocol did not specify routing procedures that consistently control shoulder belt positioning on the dummy. Thus, most NCAP tests were conducted with the D-ring in the full-up position, placing the shoulder belt far above the center chest potentiometer used for rating.

Sled and full-vehicle crash tests of a 2011 Dodge Caliber demonstrated that for the 5th percentile small female right front passenger dummy, the official NCAP setup of forwardmost seat position and D-ring full up places the shoulder belt high on the chest, away from the center potentiometer, producing low chest deflections due to dummy construction.

Sled test combinations in which the seat was moved to midtrack or the D-ring lowered to full down improved the belt routing relative to the center potentiometer significantly, increasing maximum chest deflections and utilizing the dummy in a condition more like the one it was designed for. However, another vehicle with a different belt geometry (higher D-ring) could nullify this observation.

The patterns of belt routing and chest deflection in this study are in general agreement with other studies focused on rear-seat occupants and varying shoulder belt configurations.

The ribeye chest measurement system was a good indicator of symmetry in shoulder belt chest loading. For belt placement away from the center potentiometer, the ribeye indicated a wide range of deflections with the maximum deflection greater than the center potentiometer. For belt placement close to the center potentiometer, the ribeye and center sensor indicated similar deflections.

This study suggests a vehicle's NCAP chest rating is highly dependent on shoulder-belt routing. In the official NCAP test (D-ring full up), the belt routed across the dummy's neck and produced a chest deflection of 11.8 mm. In the IIHS test (D-ring full down), the belt routed across the center sensor and produced a chest deflection of 34 mm. Based on the Prasad older female chest injury risk function for the 5th percentile female the AIS 3+ injury risk increases from 0.6% with the NCAP routing to 44.7% with the routing from the IIHS test. [Digges et.al. 2013, Prasad et al., 2010]

Meaningful comparative vehicle assessments can only be made if the belt routing across the dummy's chest is done consistently and correctly from test to test. This is especially relevant to a Silver NCAP Rating because the chest injury risk for older occupants is 4-5 times that of younger occupants [Digges et al., 2013] and therefore should carry more weight.

A dummy landmark-based belt positioning procedure should be developed to replace the vehicle body-based D-ring procedure. This would ensure that belt location relative to the chest deflection potentiometer can be more carefully specified and controlled.

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