APPLICATION OF MULTIPLE RIB GAGES TO IMPROVE CHEST INJURY MEASUREMENTS

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ABSTRACT

In 2011 the National Highway Traffic Safety Administration (NHTSA) made changes to the new car assessment program (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 full up position, placing the shoulder belt far above the center chest potentiometer, thereby loading the dummy's chest asymmetrically.

Previous research conducted with a Dodge Caliber, showed that differences in chest deflection measurement caused by variations in belt routing are not trivial. 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 the Insurance Institute for Highway Safety (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%. This indicated a need for a better belt positioning procedure to replace the vehicle body-based D-ring procedure. This improved positioning would ensure that the belt location relative to the chest deflection potentiometer could be more carefully specified and controlled.

The objective of this study is to investigate the use of supplementary chest deformation sensors, such as RibEye and IR-TRACCs for identifying belt fitment procedures which provide accurate chest readings by ensuring that the shoulder belt is routed near the dummy's center chest gage.

The present study examines in detail the chest deflections observed in the initial series of sled and full vehicle tests with the Dodge Caliber. In addition, the study examines the chest deflections observed in NHTSA and Transport Canada (TC) full frontal tests with dummies containing supplemental chest deformation sensors. The supplementary data took the form of Hybrid III 5th female dummies outfitted with either RibEye sensors or IR-TRACCs and Hybrid III 50th male dummies outfitted with IR-TRACCs.

The results indicate greater disparity between the center chest gage measurements and the supplemental RibEye or IR-TRACC readings when the belt routes higher on the dummy's neck, associated with the upper anchorage D-ring in the full up position. Effects of the D-ring positioning are lessened as the seat track is moved from full forward to midtrack for the 5th female dummy. Since the belt routes closer to the center gage, both the center gage and maximum RibEye measurements indicate more deflection than at the full-forward position. Other factors also contribute to these higher peak measurements.

For both the 50th male and 5th female right front passenger dummies, when the belt was routed closer to the dummy's design intention at the center gage, the center gage and left side supplemental (RibEye or IR-TRACC) measurements were similar. Additionally, when the belt was placed across the center of the dummy's chest, the supplemental sensors deflected quite uniformly across the chest.

Despite the promising test results of these supplemental chest measurement devices, currently, there is no US federal basis for calibrating or interpreting RibEye or IR-TRACC measurements in Hybrid III dummies, so using these devices to relate to injury risk remains problematic.

RibEye and IR-TRACC supplemental chest deflection technologies have the potential to better identify belt routings consistent with the design characteristics of the dummy chest and deflection sensor. This knowledge could be used to develop testing and belt placement protocols which support more meaningful and consistent estimates of chest injury risk. This, in turn, would greatly enhance the utility of NCAP programs to drive restraint system changes to further reduce real-world chest injuries.

BACKGROUND

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 compression in place of chest acceleration to assess chest injury risk;
- Including new chest injury risk functions for chest compression;
- Substituting a Hybrid III 5th percentile female dummy for the 50th male dummy in the front right seating position;
- Positioning the seat for the 5th percentile female right front passenger dummy in the full-forward position; and,
- Permitting the manufacturer to specify the shoulder belt anchorage height position for both dummies.

The variation of the chest deflection measurement according to belt position on the chest, relative to the chest deflection gage, has been noted by several researchers. In a 1991 paper, Horsch tested a restrained Hybrid III dummy and reported a 34% reduction in chest compression when the belt placed against the neck was compared with a similar test except with the belt placed 50 mm laterally away from the neck [Horsch 1991]. Other researchers have observed similar measured chest deflection reductions when the shoulder belt was moved away from the deflection gage [Tylko 2006, Yamanski 2011, Tylko 2012]. A 2017 study by Digges et al., demonstrated that in an US NCAP full width test of a Dodge Caliber, risk of serious chest injury increased from 0.6% to 15% based on the 64 mm difference in shoulder belt routing across the dummy's chest between the D-ring positioned at full-down and full-up. When considering an elderly risk curve, these differences magnify from a 0.6% risk with the belt routed at D-ring full up to 44.7% with the belt routed at D-ring full-down. This study concluded that a dummy landmark-based belt positioning procedure should be developed to replace the vehicle body-based D-ring procedure. Such a change would ensure that belt location relative to the chest deflection potentiometer could be more carefully specified and controlled.

Trends in test location of the driver and right front passenger upper anchorage D-ring changed significantly in the US after the introduction of the 2011 test protocol. Prior to 2011, NCAP full width tests were conducted with the 50th male, typically with the D-ring in the mid position. From 2011 onwards, the majority of vehicles have been tested with the D-ring positioned at full up position, both for the driver and passenger. This had the effect of routing the shoulder belt higher than the dummy's center chest gage. In Canada, closer harmonization of CVMSS 208 to FMVSS 208 did not occur until 2013. As a consequence, compliance tests prior to 2014 continued to be conducted with the 50th male at 48 km/h, typically with the D-ring in the mid-position. Historically, research tests with the 5th female were conducted typically at one of three speeds: 40 km/h, 48 km/h and 56 km/h, typically with D-ring in the full down position. Consequently, comparing chest deflections observed in Canadian and US tests, provides an opportunity to gain an appreciation of the influence of D-ring location on chest deflections measured by center chest gage.

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].

OBJECTIVE

The objective of this study is to investigate the use of supplementary chest deformation sensors, such as RibEye and IR-TRACCs for identifying belt fitment procedures which provide accurate chest readings by ensuring that the shoulder belt is routed near the dummy's center chest gage.

METHODS AND DATA COLLECTION

The Dodge Caliber platform 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. 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. The effect of belt geometry on chest deflections was studied in the 2017 paper by Digges et al. using a 5th percentile female dummy in the right front passenger seat in the 56 km/h NCAP condition.

For this study, 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. A matrix of tests is shown in Table 1. The time to fire airbags and seatbelt pretensions was matched to the official NCAP times. All dummies were positioned in the right front seat position and consumable vehicle components, such as airbags, were replaced after each test. Dummies were 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 belt routings relative to these target locations are shown in Figures 1 and 2. For the Hybrid III 5th female dummy, the chest instrumentation included both the center chest potentiometer, as used in the NCAP tests, and the RibEye. [Tylko et al., 2007]. Twelve RibEyes were positioned in accordance with the TC methodology described in the above paper. For the Hybrid III 50th male dummy, the chest instrumentation included both the center chest potentiometer and IR-TRACCs. The four IR-TRACCs are located at the left upper (LU), right upper (RU), left lower (LL) and right lower (RL) regions of the chest.

Table 1.
Sled Test Matrix

Seat track position	**D-ring position**	**Hybrid III 50th male**	**Hybrid III 5th female**
Full forward	*Full-up*		X
	Full-down		X
Midtrack	*Full-up*	X	X
	Full-down	X	X

In addition to the data obtained from the sled tests, additional RibEye and IR-TRACC data were obtained from TC and US full width vehicle tests. The additional data included:

- Five vehicle models (six tests) tested in NCAP-like 56 km/h rigid wall tests with a 5th female right front passenger fitted with RibEyes seated at midtrack (Keon, 2016);
- Four 56 km/h full width CMVSS 208 compliance tests with a 5th female right front passenger with RibEyes seated at full forward with D-ring full-down; and,
- Three 48 km/h full width CMVSS 208 compliance tests, each with two 5th female dummies, one with RibEyes, one with IR-TRACCs, seated in the rear outboard positions.

RESULTS

Sled Tests: Hybrid III 5th Female with RibEyes

Static comparisons of shoulder belt routing for the Hybrid III 5th female dummy sled test configurations are shown in Figures 1 and 2. The full forward seat track with D-ring full up condition, shown in Figure 1 (right), closely matches the NCAP test configuration, which places the top of the belt 116 mm above the center chest gage. Both moving the D-ring lower and moving the seat track rearward were effective at routing the shoulder belt closer to the center chest gage. In addition to the targets placed on the dummy's chest, 5th female dummies are constructed with two chest jacket holes that have the potential to help better orient belt routing relative to the dummy's design intention at the center chest gage.

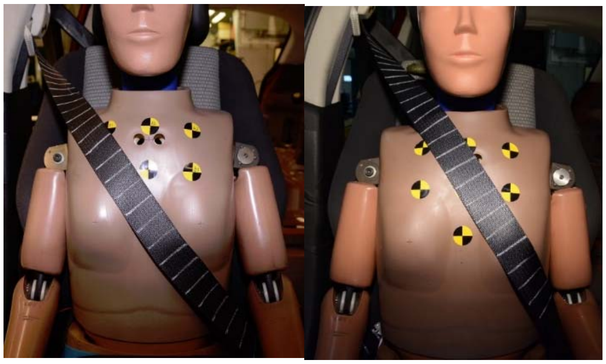

Figure 1. Forward Seat Position D-Ring Full-down (left) and Full-up (right)

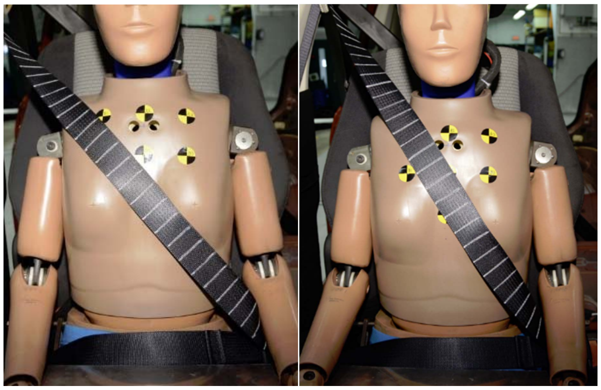

Figure 2. Mid Seat Position D-Ring Full-down (left) and Full-up (right)

The peak deflections recorded from the standard center gage and supplemental RibEye sensors for the sled test series with the 5th female dummy are shown in Table 2. Only x-direction data was compared to the center gage. The readings from the right RibEye number 6 were frequently lost and so were not reported in the Table. In the case of the test with the mid seat position D-ring full down, the left maximum RibEye readings occurred later than the center gage reading. However, the difference between measurement at the time of maximum center pot reading and the time of maximum RibEye readings was small. The spread between the maximum and minimum RibEye readings was also relatively small. Figures 3 to 6 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 peak RibEye measurements are greater than the center potentiometer and more dispersed.

Table 2.
Chest Deflection Measurements from Sled Tests of 5th Female with Varying Seat and D-ring Positions

	Seat track	**Full forward**		**Mid track**	
	D-ring	**Full-up**	**Full-down**	**Full-up**	**Full-down**
Central Pot		-20.4	-29.8	-33.8	-36.8
Max RibEye		*-30.2*	*-30.4*	*-37.2*	*-36.9*
RibEye Left	*Rib 1*	*-30.2*	*-30.4*	*-37.2*	*-36.4*
	Rib 2	*-28.9*	*-29.6*	*-37.0*	*-35.7*
	Rib 3	*-27.7*	*-29.4*	*-36.6*	*-36.1*
	Rib 4	*-25.6*	*-28.8*	*-36.3*	*-36.4*
	Rib 5	*-23.9*	*-28.4*	*-36.0*	*-36.8*
	Rib 6	*-22.2*	*-27.6*	*-35.1*	*-36.9*
RibEye Right	*Rib 1*	*-14.4*	*-26.5*	*-25.9*	*-31.4*
	Rib 2	*-12.7*	*-24.2*	*-23.8*	*-29.2*
	Rib 3	*-11.1*	*-22.4*	*-21.8*	*-27.2*
	Rib 4	*-9.6*	*-21.4*	*-21.0*	*-26.8*
	Rib 5	*-8.1*	*-19.7*	*-19.8*	*-25.8*

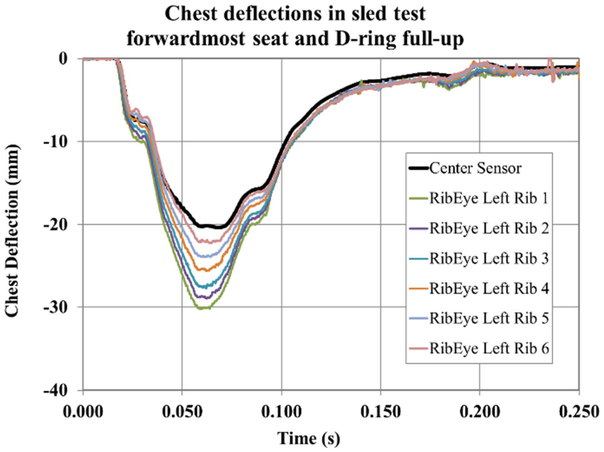

Figure 3. Chest deflection comparison for sled test: forwardmost seat position and D-ring full-up

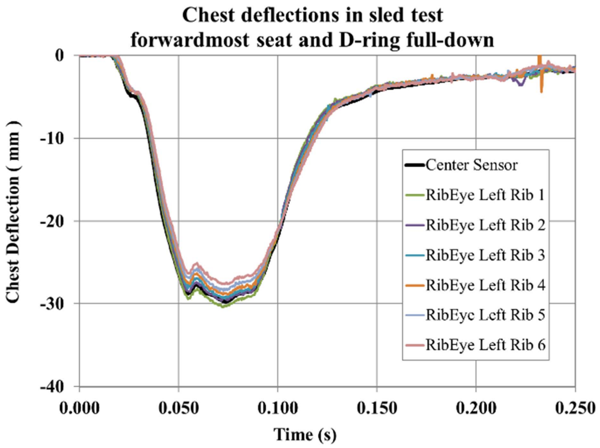

Figure 4. Chest deflection comparison for sled test: forwardmost seat position and D-ring full-down

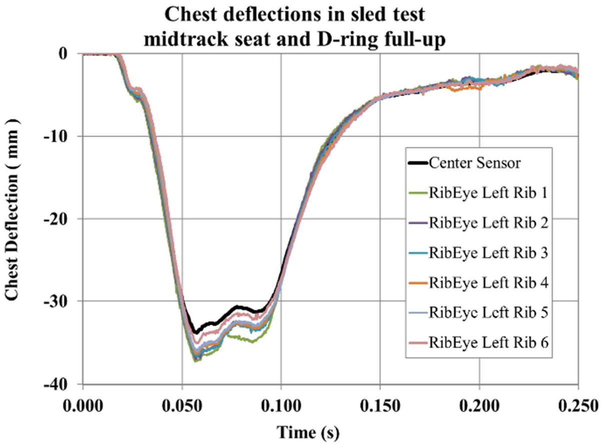

Figure 5. Chest deflection comparison for sled test: midtrack seat position and D-ring full-up

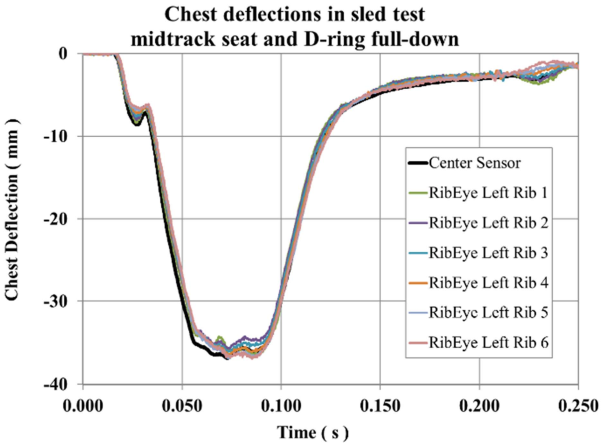

Figure 6. Chest deflection comparison for sled test: midtrack seat position and D-ring full-down

Sled Tests: Hybrid III 50th Male with IR-TRACCs

Static comparisons of shoulder belt routing for the Hybrid III 50th male dummy sled test configurations are shown in Figure 7. The midtrack seat position with D-ring full up condition, shown in Figure 7 (right), places the top of the belt well above the center chest gage. Moving the D-ring lower was effective at routing the shoulder belt overlapping the center chest gage.

Figure 7. Belt Routing 50th Male Dummy D-ring Down (Left) and D-ring Up (Right) – Dodge Caliber

Peak deflections recorded from the standard center gage and supplemental IR-TRACC sensors for the sled test series with the 50th male dummy are shown in Table 3. Figures 8 and 9 show the chest deflection histories of the center chest potentiometer and individual IR-TRACC deflections for each of the sled test conditions. In the sled test with the D-ring full down, which routes the shoulder belt closest to the center chest gage, the center gage measured the maximum peak deflection and the 4 IR-TRACCs measured very similar peak values, ranging from 27.5 to 32.4 mm. These close readings indicate the chest is being loaded symmetrically, focused on the center sternum. In contrast, the sled test with the D-ring full-up and the belt routed significantly higher than the center gage showed the greatest peak deflection at the left upper IR-TRACC location, with a wide range of peak values from each sensor location, ranging from 8.7 to 29.9 mm.

Table 3.
Chest Deflection Measurements from Sled Tests of 50th Male with Varying D-ring Positions

	Seat track	**Mid track**	
	D-ring	**Full-up**	**Full-down**
Central Pot		27.1	42.6
IR-TRACC Left	*Upper*	29.9	32.4
	Lower	26.9	34.5
IR-TRACC Right	*Upper*	13.2	32.4
	Lower	8.7	27.5
Difference between upper locations		16.7	0
Difference Left upper to lower		3.0	-2.1

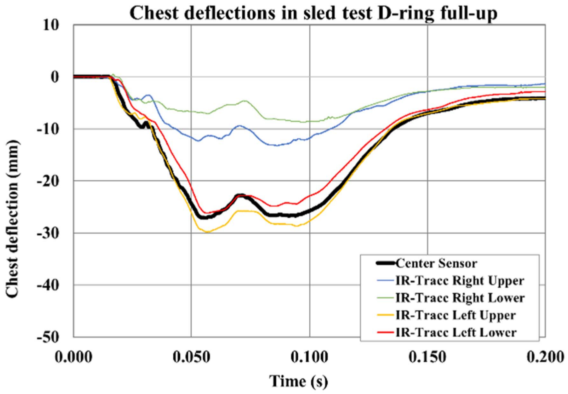

Figure 8. 50th Male Dummy IR TRACC Measurements for NCAP Sled Test with Mid-position Seat and D-ring Up (Dodge Caliber)

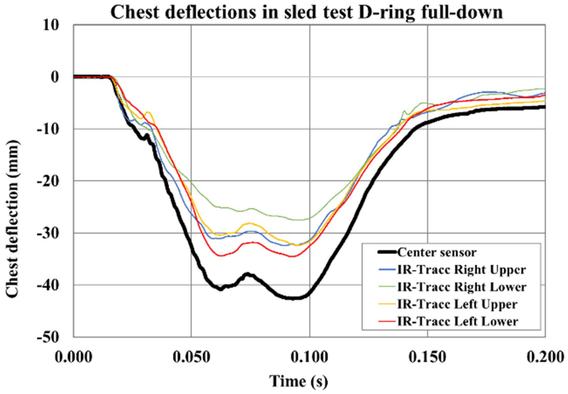

Figure 9. 50th Male Dummy IR TRACC Measurements for NCAP Sled Test with Mid-position Seat and D-ring Down (Dodge Caliber)

Comparison to Other Frontal Crash Test Data

Full scale crash test data from NHTSA in a 56 km/h full width test condition were examined for the effect of seat position on the peak chest deflections for the right front passenger 5th female dummy (Table 4). In the research tests, the dummy's seat track was moved to midtrack, but all other aspects of the seating remained the same, including the D-ring at full up position. Moving the seat track from full forward to midtrack resulted in the shoulder belt routing 5 to 45 mm closer to the center chest gage, based on PBU standard clearance measurements. The seating change produced chest deflections that were 5 to 13 mm greater. Numerous other factors may have contributed to these deflection differences, as the change in seat position would also results in different interactions with airbags, seatbelts and knee bolsters.

The PBU measurement is the vertical distance between a horizontal reference plate in the dummy lap and the upper edge of the belt, measured at the centerline [NHTSA 2012]. Since the measurement does not rely directly on dummy landmarks, it is subject to variations with dummy positions. As can be observed in Table 4, while chest deflection increases between NCAP and Research tests were observed as the PBU values decreased, no clear relationship between the magnitude of the change in the PBU measurement and the change in chest deflection was observed. The increases in chest deflection associated with moving the seat from full forward to mid-track position ranged from 45% to 162%. However, the largest deflection increase was associated with one of the lowest changes in PBU.

Figures 10 and 11 show the RibEye and center gage traces for the 5th female dummies in the Malibu #1 research test. The traces in Figure 10 are from the right front passenger dummy, seat in midposition and D-ring full-up. The traces in Figure 11 are for the rear seat dummy. For this dummy, the D-ring is fixed and belt force limiting is not present. The traces in Figure 11 display a close spread of the RibEye reading suggesting symmetric loading of the chest and improved belt routing relative to the center pot.

The traces in Figure 10 have a wider spread of readings, suggesting less symmetric chest loading than observed for the rear dummy. However, the chest load distribution for this right front passenger is better than that observed in the Caliber sled test with the dummy seated full forward and the D-ring full up ((Figure 3), showing closer, but not as good as, the agreement than observed with the seat mid-track and the D-Ring full up (Figure 5).

Table 4.
Chest Deflection and Shoulder Belt Measurements Research and NCAP of 5th Females in Right Front Seat

	PBU Belt to Reference (mm)			**Chest Deflection (mm)**		
Vehicle	**NCAP**	**Research**	**Change**	**NCAP**	**Research**	**% Change**
Chevrolet Malibu #1	320	305	-15	9.0	13.9	54%
Chevrolet Malibu #2	320	285	-35	9.0	17.6	96%
Toyota Highlander	325	280	-45	9.2	22.6	146%
Ford F-150	310	295	-15	7.9	20.7	162%
Mazda3	335	300	-35	12.2	17.7	45%
Honda Fit	300	295	-5	14.5	24.4	68%

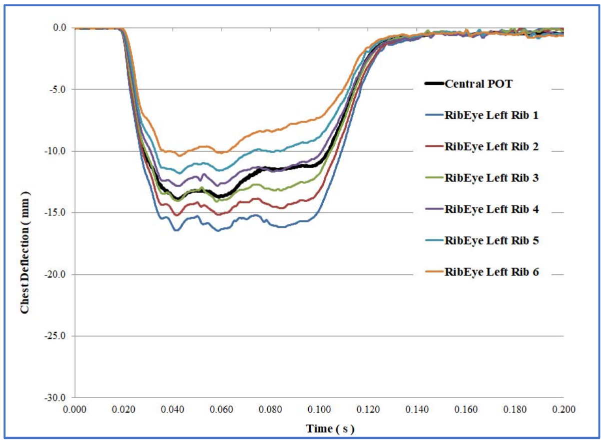

Figure 10. Right Front Passenger Chest Deflections Observed in NHTSA Test of Chevrolet Malibu #1 (9332): Mid-Seat / D-Ring: Full-Up

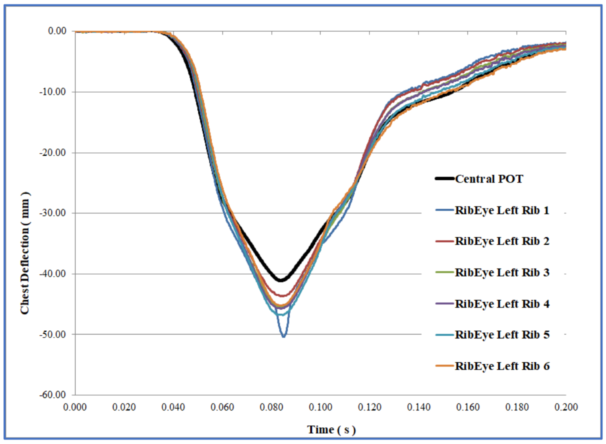

Figure 11. Right Rear Passenger Chest Deflections Observed in NHTSA Test of Chevrolet Malibu #1 (9332)

An improved understanding of how the position of the D-ring is influencing quantification of chest injury risk, at the fleet level, can be achieved by comparing the deflections observed in TC compliance tests at 56 km/h with those observed in NCAP tests of the same vehicle platform for the subset of TC tests run with the RibEye. A direct platform comparison of the 5th female dummy deflections observed on the right front passenger side in TC tests with the D-ring in the full down position with those observed in NCAP tests with the D-ring in the full up position is possible for four TC tests with the RibEye. A detailed comparison of the responses observed in these four platform tests is provided in Table 5. A comparison of the chest deflections observed is depicted in Figure 12.

From the results presented in Table 5, it can be seen that the NCAP deflections were consistently lower than those observed in the TC tests. In the case of Platform 1, the reduction was of the order of 60%, similar to the reduction in the deflection value observed in the Caliber car and sled tests when the D-ring was moved from the full down position to the full up position, the typical NCAP setting. We can also observe that the TC chest pot values consistently show close agreement with maximum Ribeye values measured on the left side of the dummy. These results suggest the belt routing provided by the lower D-ring more consistently places the belt close to the chest sensor.

Table 5 also includes a calculated metric which has the potential of highlighting belt routings above the chest sensor, the "implied chest stiffness" value. This value is calculated by dividing the maximum shoulder belt force value by the maximum chest pot value. As the D-ring is moved from the full down position, shoulder belt routing moves away from the chest sensor, reducing the magnitude of the measured pot deflection, but not the applied belt force. All four of the NHTSA NCAP tests produced implied chest stiffness values above 200, while all four of the TC tests produced values below 175.

Table 5.
Response Comparisons - Front Right Passenger (5th Female) / 56 km/h Full Frontal
TC (D-Ring Lowermost) vs NHTSA (D-Ring Uppermost)

Vehicle Model	**Test**		**Center chest gage (mm)**		**RibEye (mm)**	**Shoulder Belt Force (N)**		**Chest Implied Stiffness N/mm**	
	TC 208	*NHTSA*	*TC 208*	*NCAP*	*TC 208*	*TC 208*	*NCAP*	*TC 208*	*NCAP*
Platform #1	17-110	9157	22.5	9.0	24.9	2,357.80	3,272.10	104.8	363.6
Platform #2	17-108	7564	14.2	7.4	16.4	2,453.70	2,453.70	172.8	331.6
Platform #3	17-172	9296	16.0	11.8	17.4	2,621.90	3,029.00	163.9	256.7
Platform #4	16-146	9552	22.9	20.5	28.5	3,725.90	4,323.90	162.7	210.9

It may be observed that Platform 1 and 2 both show large differences between the center chest pot readings from the two D-ring conditions (Figure 12). In the TC tests, the max RibEyes deflections are slightly higher than the D-ring down center pot deflections. Platform 3 shows similar trends, but the difference between the center pots is less. For Platform 4, the difference between center pots is less and the differences between the center pot and the RibEye is greater. The observations suggest that the range of D-ring adjustment makes less difference on Platform 4 and, to some extent, on Platform 3. The high RibEye reading for Platform 4 indicates that, even with the D-ring full down, the belt is not over the center pot and the chest is loaded asymmetrically. A review of the picture of dummy placement confirmed that the shoulder belt remained close to the neck in the D-ring full down test.

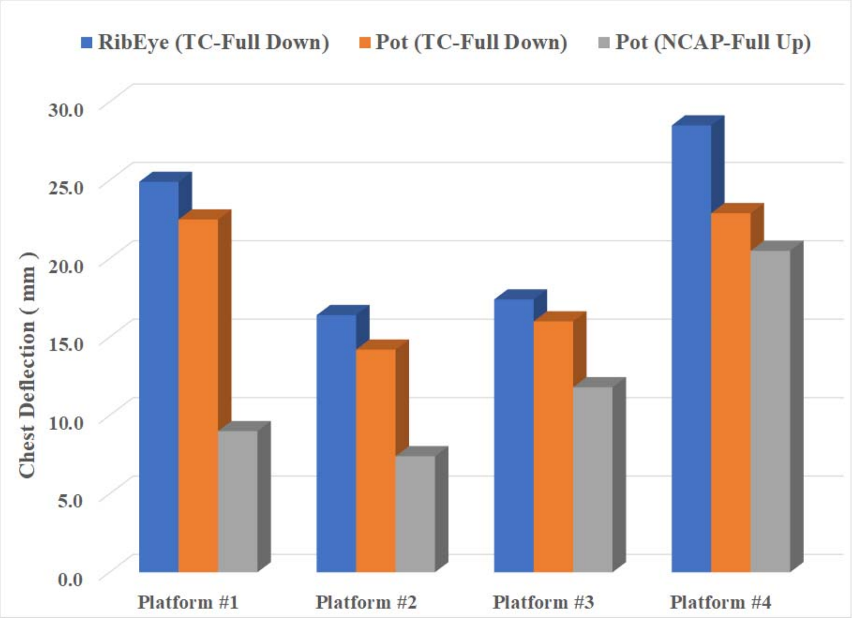

Figure 12. Right Front Passenger (5th Female) Chest Deflections as a Function of Vehicle Platform, D-Ring Location and Monitoring Technology

Included among the 48 km/h TC CMVSS 208 compliance tests reviewed were three tests in which a rear seated 5th female fitted with IR-TRACCs was accompanied by a rear seated 5th female fitted with RibEyes. These tests provide a convenient environment for the comparison of chest deflection pattern, as quantified by the IR-TRACC with that quantified by the RibEye. To facilitate the comparisons in terms of mirror images, the deflections from ribs 1 and 2 of the Ribeye were averaged to produce an upper quadrant value and the deflections from ribs 5 and 6 were averaged to produce a lower quadrant value. This was possible for left side quadrant values. In the case of the right side of the Ribeye, rib 6 values were typically lost. As such, the lower right quadrant values simply reflect right rib 5 values. For completeness, the average deflections of RibEye ribs 3 and 4 were also computed. The IR-TRACC data, the computed quadrant data and the central pot data from this series of tests are summarized in Table 6. All measurements are in millimeters.

From the results presented in Table 6, it can be observed that there was generally agreement in the quadrant deflections between the IR-TRACC and the RibEye. This was particularly true when one compared the left side quadrant values of the rear left dummy (IR-TRACC) and the right side quadrant values of the rear right dummy (RibEye). Here the maximum difference was only 3.2 mm. The differences in the central pot deflection values were more pronounced and consistently higher with 8.3 mm in test TC08-135. The source of the difference was not readily evident. The peak shoulder belt forces and the peak lap belt forces measured in the two rear seating positions differed less than 100 N in this test. However, the implied chest stiffness values of the RibEye chest ranged from 160 to 169 in this test series, while the corresponding values for the IR-TRACC ranged from 190 to 207. So the more elevated chest pot values observed with the Ribeye may simply have been an attribute of a slightly more compliant chest assembly. It may also have been associated with a difference in belt routing.

Table 7 summarizes the differences between the max gage readings. The first row, top-center, shows the difference between the top IR-TRACC or RibEye and the center gage for the three TC tests in Table 6. The second row substitutes the bottom IR-TRACC or RibEye for the top ones. The third row is the difference between the two top sensors. An examination of differences in readings of these four gages provides insight into the uniformity of loading of the chest. Large differences between the upper gages suggest the belt is close to the neck. Large differences between the upper and lower gages suggest asymmetric chest loading. This data suggests that the belt on the RibEye Test 139 dummy was positioned closest to the center gage. For this dummy, the difference between the RibEye gages and the center gage was small and the difference between the upper gages was much smaller than for the other dummies. The upper gage reading was slightly lower than the center gage and the lower gage was slightly higher. These characteristics were observed in the Caliber sled tests when the D-ring was full down and the belt routing was optimum.

The TC data indicates that either the RibEye or the IR-TRAC would be useful in determining the degree to which the belt passes over the center gage.

Table 6.
RibEye, IR-TRACC and Center Gage Measurements from TC Tests of 5th Females in Rear Seat

		Rear Left Dummy			**Rear Right Dummy**		
		IR-TRACC			**RibEye**		
	Sensor location	*Right Side*	*Center*	*Left Side*	*Right Side*	*Center*	*Left Side*
TC08-135	*Upper*	49.7		29.9	28.1		49.7
	Center		39.5		26.3	47.8	49.7
	Lower	46.0		22.8	22.6*		54.5
TC08-139	*Upper*	40.1		24.5	23.4		33.4
	Center		30.6		20.7	35.0	33.7
	Lower	34.8		16.0	19.2*		36.0
TC08-140	*Upper*	38.2		21.9	19.2		35.5
	Center		27.9		15.8	29.8	34.0
	Lower	31.9		13.3	13.0*		32.6

* Excludes rib #6.

***Table 7*.**
Difference in Measurements for RibEye, IR-TRACC and Center Gage, TC Tests of 5th Females in Rear Seat

Gage Locations	IR-TRACC Test 135	RibEye Test 135	IR-TRACC Test 139	RibEye Test 139	IR-TRACC Test 140	RibEye Test 140
Top-Center	10.2	1.9	9.5	-1.6	10.3	5.7
Bottom-Center	6.5	6.7	4.2	1.0	4.0	2.8
Upper Right-Left	19.8	21.6	15.6	10	16.3	16.3

DISCUSSION

Static measurements of dummy position and belt routing across the 5th female and 50th male dummies' chests indicate that a relatively small adjustment of the upper anchorage D-ring location can have a significant effect on shoulder belt location across the dummy's chest. The worst-case scenario is the 5th female dummy with the seat track full forward, where the adjustment of the D-ring in a Dodge Caliber exemplar vehicle can create variation in shoulder belt location of up to 64 mm. This study found that moving the seat track to midtrack lessened the effect of the D-ring adjustment variation but did not completely solve it. The 50th male dummy showed less dramatic differences than the 5th female in belt routing, but observations were large enough to suggest dynamic performance could be affected.

Both chest sensor measures at the standard center gage and supplemental RibEye and IR-TRACC devices detected variation in symmetry/asymmetry of the belt routing across the dummy's chest. The 2017 Digges et al. study showed that the center gage measured an additional 23 mm of deflection when the belt was adjusted closer to the sensor in a pair of full vehicle tests. Similar observations were made through this sled test series, where the 50th male dummy measured an additional 16 mm of deflection with the belt positioned across the center chest rather than above. The 5th female dummy measured an additional 8 mm of deflection with the belt positioned across the center chest with seat track at full forward. For the 5th female, the effect was less at the midtrack seat position, with the variation in D-ring position only accounting for a difference of 3 mm of center chest deflection.

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 within 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 and IR-TRACC deflection measurements provide an evaluation of asymmetry in loading of the chest by the restraint system. For 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 was 20 mm and the highest RibEye deflection was 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 35 mm vs. 37 mm), likely because the belt was routed more closely in this condition. In contrast, when the belt is routed closer to the center sensor (D-ring full down condition), the center sensor and RibEye deflection sensors were 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, supplemental deflection measuring devices like RibEye and IR-TRACCs offer advantages for evaluating chest injury. Their use 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 devices have their limitations. 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 for both the 5th female and 50th male dummies, 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 corresponds to the dummy calibration procedure for chest compression response and intended use [NHTSA 2008].

Additionally, the 5th female dummy measured greater chest deflections at midtrack compared to full forward in this study's sled tests and other NHTSA and TC observations, suggesting that vehicles are not optimized for this condition. The dummy's position, farther away from the frontal airbags and knee bolsters, places more reliance on the belt system to absorb crash energy. Testing at midtrack position covers a larger segment of the population and is expected to advance protection for right front passengers.

This study suggests a vehicle's NCAP chest rating is highly dependent on shoulder-belt routing. 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 nor the proposed future NCAP seating procedures specify D-ring position. 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.

CONCLUSIONS AND RECOMMENDATIONS

Proposed changes to future US NCAP, such as testing the right front passenger 5th female dummy at midtrack seat position, have the potential to reduce some of the shoulder belt routing variation observed in tests of the dummy at full forward. More consistent belt routing near the center chest gage would ensure more repeatable and accurate evaluations of chest injury risk.

Supplemental chest measurement devices, IR-TRACCs and RibEyes, were able to detect that when the shoulder belt was routed close to the center sensor, the dummy's chest was loaded symmetrically and when the shoulder belt was routed higher up on the neck, the dummy's chest was loaded asymmetrically. In conditions where the belt was routed close to the center sensor, the peak measure from the supplemental sensor was similar to the center chest pot, while in conditions where the belt was routed higher than the sensor, the peak measures from the standard and supplemental devices were disparate and the supplemental sensor locations measured a wide range of results.

The implied chest stiffness metric, calculated from shoulder belt loads and center gage chest deflections, may be useful in future evaluations of symmetry of belt routing. High implied chest stiffness values were associated with the high D-ring test condition in NHTSA NCAP tests.

Supplemental chest deflection measuring devices should be investigated further because they appear effective at identifying asymmetric belt loading conditions. More research must be devoted to understanding their biomechanical relationship to human injury tolerance.

This study suggests a vehicle's NCAP chest deflection measurement used for rating is highly dependent on seat position and shoulder-belt routing. Better control of belt routing is necessary for future comparative evaluations of chest injury to be meaningful. At the least, future NCAP seating procedures should specify the D-ring position at full down for tests with the 5th female.

A dummy landmark-based belt positioning procedure should be developed to replace the vehicle body-based D-ring procedure that would ensure that belt location relative to the chest deflection potentiometer can be more carefully specified and controlled. For example, a minimum distance between the belt edge and the dummy chest holes should be established.

Additional studies are needed of how RibEye and IR TRACC perform in tests involving restraint systems with a variety of technical advancements. Involvement of ISO Working Group 5 and the HBSS of the SAE for further evaluation of these technologies is encouraged.

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