EVALUATION OF AN ALTERNATIVE THORAX DEFLECTION DEVICE IN THE SID-IIs ATD

Jack Jensen
Jeff Berliner
Barbara Bunn
Hollie Pietsch
Occupant Safety Research Partnership
U.S.A.
Dan Handman
Boxboro Systems, Inc.
U.S.A.
Mike Salloum
Denton ATD, Inc.
U.S.A.
Dominique Charlebois
Suzanne Tylko
Transport Canada
Canada
Paper Number 09-0437

ABSTRACT

The use of a RibEye system in a SID-IIs crash dummy was evaluated. The SID-IIs is a small adult female side impact anthropomorphic test device. The RibEye is a non-contact optical system that uses triangulation to measure rib deflection.

This study quantified RibEye measurements using four evaluation environments. First, a SID-IIs thorax with an internal RibEye was impacted with a linear impactor and the measurements were compared to accelerometer and video measurements. Next, the RibEye was mounted in a vertical drop tower and impacted with a falling drop mass, simulating a purely lateral side impact. The RibEye measurements were compared to data from linear potentiometers, which are typically used in the SID-IIs. A similar drop tower test series was then conducted which included tests with the RibEye mounted at an angle to simulate oblique loading to a dummy during a side impact.

Lastly, a series of full vehicle crash tests were conducted to compare measurements from a SID-IIs dummy with a RibEye to a SID-IIs dummy with linear potentiometers.

The lateral drop tower tests indicated that peak deflections measured by the RibEye were generally within 1 mm of the linear potentiometer measurements. In the full vehicle crash tests, the RibEye and linear potentiometer measurements fell within the expected variability from crash test to crash test. User interface issues and the practicality of RibEye in the full vehicle tests are also discussed. In oblique loading tests, the RibEye revealed significant X-axis motions that cannot be measured by linear potentiometers as typically mounted in the SID-IIs thorax.

INTRODUCTION

The SID-IIs is a small adult female side impact Anthropomorphic Test Device (ATD). It was designed in the 1990s jointly by the three domestic U.S. auto manufacturers and First Technology Safety Systems working through the Occupant Safety Research Partnership (OSRP) of the United States Council for Automotive Research (USCAR). This ATD was designed to be a second-generation side impact dummy with improved biofidelity compared to existing side impact dummies. It was intended to be available for global harmonization of crash test regulations. The biofidelity of this ATD's beta version was reported by Scherer, et al. [1]

To simulate human anatomy, the SID-IIs uses a collection of steel bands called "ribs". The SID-IIs has one shoulder rib, three thoracic ribs, and two abdominal ribs, each made of Vascomax© steel with bonded dampening material. The dummy typically utilizes linear potentiometers (pots) (as specified in the Code of Federal Regulations – 49 CFR Part 572) to measure the amount of rib deflection for these six ribs during impact tests. The upper thoracic rib linear pot is shown in Figure 1 (with the shoulder rib pot removed).

The laboratories represented by the OSRP member companies as well as other laboratories have experienced data quality issues with these pots in the crash testing environment. Frequently, electronic noise and data dropouts have resulted from damage to the resistive elements inside the pots. The pots are mounted using spherical bearings to reduce any off-axis loading; however, the noise may have been due to inertial effects. Sources of this noise were investigated by Arbelaez, et al. [2]. An example of erroneous crash data recorded with the pots is shown in Figure 2. Thus, there was a need to investigate alternative technologies for measuring the motion of the impacted side of the SID-IIs ribs relative to the spine box.

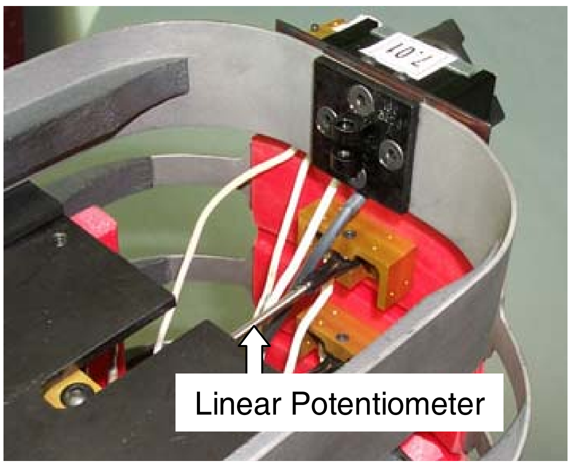

Figure 1. Linear pot mounted to thorax rib.

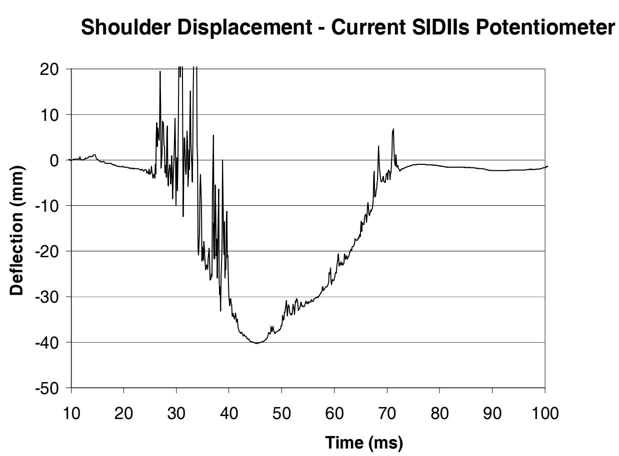

Figure 2. Sample crash data from a current SID-IIs linear pot.

RibEye Technology

RibEye is a new electro-optical technology that measures deformation of the ribcage in three dimensions at high speeds. The RibEye was designed to not affect the biofidelity of the dummy. RibEye uses light-emitting diodes (LEDs) placed at the desired measurement points, with three optical sensors mounted to the dummy spine. The sensors capture light from the LEDs and translate the light angle into a deflection measurement. Simple triangulation, as used in sailing and mapping, yields data on three-dimensional movement of all ribs. The RibEye sensor module is shown in Figure 3and the RibEye LEDs mounted on the SIDIIs ribs are shown in Figure 4.

Figure 3. RibEye sensor module.

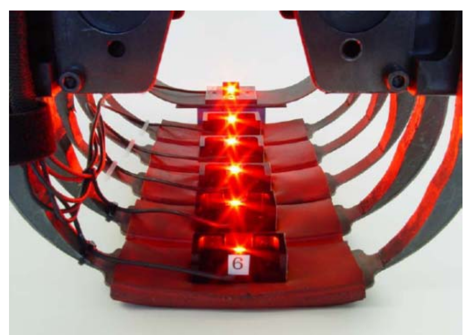

Figure 4. RibEye LEDs on SID-IIs ribs.

Unlike current methods, RibEye reports measurements with respect to the sensor location, as opposed to pots which simply report the stroke of its shaft. Also, RibEye constantly controls LED brightness to get accurate readings over a wide range of sensor-to-LED distances, which has not been done by previous optical methods.

LIMITATIONS

This evaluation was intended to quantify the accuracy of the RibEye measurements by exercising the system in several different loading conditions. This included linear impact tests, two series of drop tower tests and full vehicle crash tests. During each evaluation the RibEye measurements were compared to alternate measurements such as linear pots or video analysis.

For controlled laboratory tests such as drop tower and linear impact tests, differences in measured peak deflections between the alternate technologies of less than 1.5 mm were considered "good". This represents 2% of 75 mm, which was a typical displacement observed during these test evaluations. Those differences between 1.5 and 3.0 mm (2% - 4%) were considered "marginal".

This evaluation did not fully address all of the laboratory, user and durability issues associated with a new measurement technology. As an example, comments concerning the integration of RibEye to a data acquisition system are presented but a thorough analysis was not completed.

Previous testing had indicated the RibEye may susceptible to ambient light interference. Alternate dummy clothing had been proposed to address this issue by blocking ambient light from entering the dummy's chest cavity. However, this alternate clothing was not fully evaluated as part of this study.

For the purposes of this project, rib locations are referenced as Rib 1 through Rib 6. As an example, a reference to Rib 2 in this paper corresponds to thoracic rib 1 in the dummy (the second rib from the top in the dummy.)

LINEAR IMPACTOR TEST SERIES

A series of ten linear impactor tests was conducted to compare the response of the RibEye system in the thorax of the SID-IIs dummy with that of individual Y-axis mounted rib accelerometers and with high-speed video analysis. Most of these tests concentrated specifically on the in-line Y-axis motion of the ribcage.

Linear Impactor Test Methodology

The ribcage of a SID-IIs dummy was mounted to a reaction block via upper and lower mounting brackets as shown in Figure 5. The shoulder rib of the dummy was not included in these tests to improve photographic coverage, thus these tests concentrated on the remaining ribs of the thorax and abdomen. The mounting brackets were attached to the top and bottom of the dummy's spine box. The reaction block was bolted rigidly to the floor of the test facility. Ensolite foam pads for the thoracic and abdominal ribs were also included as part of the dummy's ribcage. Two or three high-speed video cameras were used during the testing (mounted off-board) to capture ribcage motion. Standard off-board lighting was used during the tests.

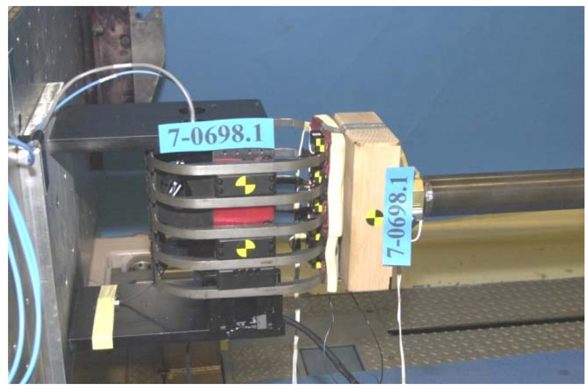

Figure 5. Targets on linear impactor.

The linear impactor machine was positioned to allow for pure in-line Y-axis loading. The intent was to exercise the RibEye system at a rib deflection rate similar to what is observed in typical side impact crash tests. This was estimated to be approximately 4.9 m/s (11 mph).

Test data was collected using three independent methods: 1) a RibEye system, 2) Endevco 7264C-2000 uniaxial accelerometers, and 3) TrackEye© video analysis using targets mounted to the spine box and ribcage. The accelerometers were mounted on each rib near the RibEye LEDs (5 total data channels). An accelerometer was also mounted to the loading ram to measure the input acceleration. The linear impactor face was a wood block. The spine box was assumed to be rigidly mounted to a non-moving fixture. The dummy's chest jacket and clothing were not used during the linear impactor testing so that the video cameras could adequately capture the ribcage motion.

Although RibEye measures deflections in all three axes, the primary focus of these tests was the Y-axis deflections. Each rib-mounted accelerometer was double-integrated to obtain the corresponding deflection of the individual rib. In addition, high-speed motion analysis techniques were used to measure the Y-axis deflection of each rib. The accelerometer and RibEye data were filtered according to the Society of Automotive Engineers (SAE) standard J211/1 [3].

Linear Impactor Test Results

Figure 6 shows the deflection time-history plot for abdominal Rib 5 for one of the ten linear impactor tests. Rib 5 generally had the best correlation among the RibEye Y-displacement, motion analysis, and the accelerometer calculations. The raw RibEye data (Y-axis deflection) is shown in blue; RibEye data filtered at CFC600, CFC180, and CFC60 are shown in green, red, and light blue, respectively. One source of noise in the RibEye measurements may have been the ambient lighting in this test series as there was no dummy clothing on the thorax. The unfiltered uniaxial accelerometer mounted to Rib 5 was doubled-integrated by two independent software packages (purple and yellow curves).

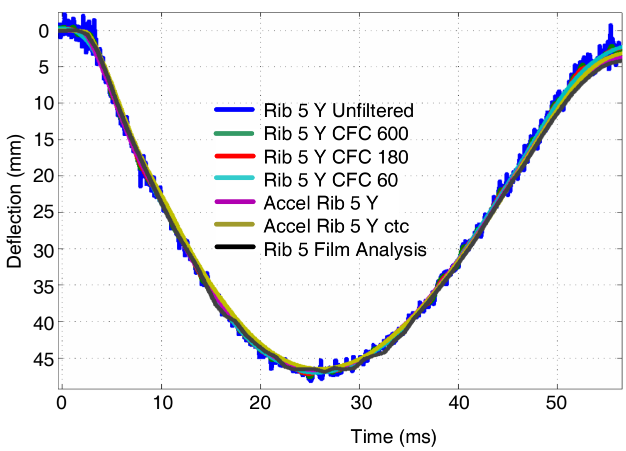

Figure 6. Sample linear impact test (Rib 5).

Figure 7 shows an enlargement of the peak deflections on Rib 5 during this test. The peaks for the filtered RibEye data were approximately 47 mm; accelerometer data peaks ranged from 46.5 to 46.7 mm; and the motion analysis peak was 46.7 mm. The effects of the various CFC filters on the RibEye raw data can clearly be observed.

The CFC filter of 180 appears to retain the useful waveform while reducing the noise in the signal. This is different than the recommended SAE filter class of 600 due to the additional noise in the RibEye signal for this test set-up. For the subsequent tests which did not use a dummy jacket, CFC class 180 was used for RibEye measurements, while the recommend SAE filter of 600 was used for tests using a dummy jacket (such as for the full vehicle crash tests.)

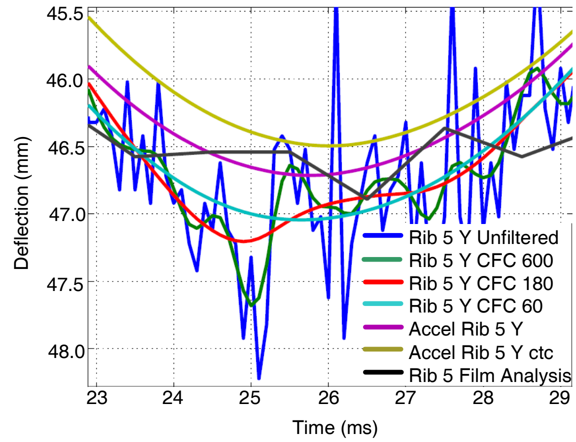

Figure 7. Peak deflections in sample linear impact.

Figure 8 shows an enlargement of the peak deflections on Rib 2 during one of the tests. Rib 2 generally had the lowest correlation among the RibEye Y-displacement, motion analysis, and the accelerometer calculations. The peaks for the filtered RibEye data were approximately 54 mm; accelerometer data peaks ranged from 50.2 to 51.0 mm; and the motion analysis peak was 52.3 mm. Again, the effects of the various CFC filters on the RibEye data are clear.

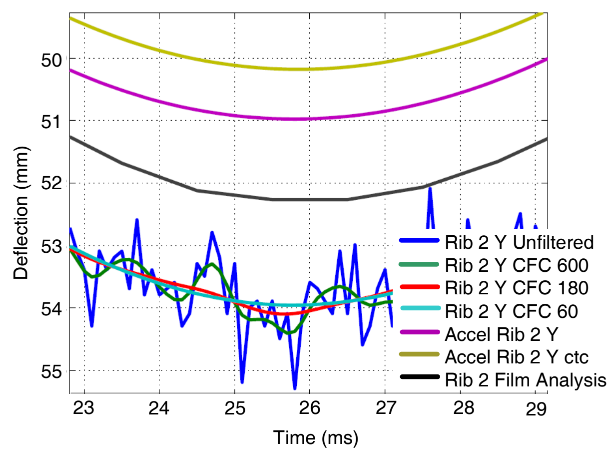

Figure 8. Sample linear impact test, Rib 2.

The difference in correlation between Rib 5 (with good correlation) and Rib 2 (with marginal correlation) prompted an investigation of the precision of the LED placement on the RibEye calibration fixture. Some inaccuracies in LED placement were found at all locations, which caused improper calibration of the RibEye system. This improper calibration resulted in the discrepancies between Rib 2 and Rib 5 in the linear impact test series.

A review of the film analysis of the targets mounted to the rigid spine box revealed motion in the Y-direction during the tests. As an example, approximately 2 mm of spine box motion was observed in one of the tests. Originally it was assumed that the spine box would be completely rigid, as it was attached to the reaction block. This motion contaminated the correlation of the RibEye data and video data (both of which were able to report relative displacement by compensating for spine box motion) to the accelerometer data (which could only report absolute displacement relative to the earth).

In addition, there were other suspect sources of inaccuracy in the linear impact testing. The rib targets were not fully visible for the duration of the film analysis, and the imager-to-target measurements were found to be suspect following the test series.

Linear Impactor Test Discussion and Limitations

This test series demonstrated that some ribs had good correlation between the RibEye and the alternative measurement techniques, while other ribs had marginal correlation. This was determined to be due to inadequacies of the test set-up and methodology. Thus the linear impact testing was most useful at identifying methodology issues that needed to be corrected for future testing to quantify the RibEye's precision more accurately. Specifically, the issues are:

- The placement of the RibEye LEDs on the calibration fixture was resolved, and the RibEye system was re-calibrated.
- Additional testing using film analysis requires 1) more accurate measurements of target-to-camera dimensions and 2) assurance that the targets remain visible for the duration of the test.
- The spine box needs to be completely rigid to compare displacements calculated from absolute measurements (such as data from the rib-mounted accelerometers, which record acceleration relative to the earth) to relative displacements (such as measured by RibEye).
- The RibEye signal is most appropriately filtered at class 180 rather than class 600 or 60 (for bench tests such as these that did not use a jacket.)

DROP TOWER TEST SERIES #1

The goal of this series of tests was to evaluate the accuracy of RibEye measurements under dynamic conditions that simulate high-speed rib motion during a side impact crash test. To achieve this goal, independent measurement instruments were needed for comparison.

Drop Tower Test Series 1 Methodology

This series of drop tower testing compared the RibEye to linear pots using the EuroSID rib drop test facility. A test fixture was designed that allowed for mounting the RibEye in multiple positions to measure either one axis or multiple axes of displacement. Although the SIDIIs ribs were not used, the fixture allowed for the mounting of the LEDs in locations representing their respective locations in the dummy (with respect to the sensors and to the other LEDs.)

The test fixture (Figure 9) consisted of upper and lower aluminum mounting plates, a RibEye system, four high-strength steel guideposts, three 6-inch linear pots, four brass bearings and two dampers. The guideposts (item 1) allowed the RibEye LEDs, which are attached to the underside of the upper aluminum plate, to glide up to 100 mm (about 65 mm free motion followed by 35 mm of restrained motion). The RibEye sensors (2) were affixed to the lower mounting plate. The stroke of the pots was aligned with the guideposts. The pot sample rate was set to 10 samples per ms.

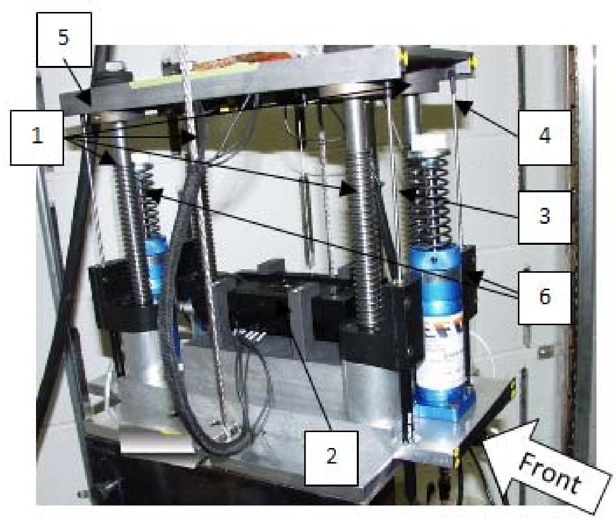

Figure 9. Drop tower fixture.

The three pots were located at the left front corner of the plate (3), the right front corner of the plate (4), and the left rear corner of the plate (5). The spacing between the front pots was 130 mm and the spacing between the front and rear pots was 330 mm. The brass bearings minimized friction and provided alignment between the guideposts and the RibEye LED mounting plate. The adjustable dampers (6) and linear springs were mounted between the aluminum plates to cushion the LED plate, limit its movement, and absorb its energy. The initial position of the aluminum plate was about 60 mm above the dampening system and was held by spring loaded detents before impact. A block of expanded polystyrene foam was used between the impacting mass and the upper plate to minimize high frequency noise and inertial effects. Contact tape was used for the time zero signal for the RibEye, the pot data acquisition system, and the video imagers.

The EuroSID drop test fixture and 8-kg impact mass were used to accelerate the RibEye LED mounting plate. Four tests were conducted: one at 5 m/s, two at 7 m/s, and one at 10 m/s. These tests simulated pure lateral motion (Y-axis only). These tests are identified as test #s GT1 through GT4 (Table 1). The dampers were adjusted so that more restraining force was applied as the drop speed increased, preventing damage to the fixture. As a result of this adjustment, the maximum deflections did not necessarily increase with increasing drop speed.

High-speed imaging analysis was also conducted using TrackEye©. Originally the lighting set-up for the imagers interfered with the RibEye LED sensors. Thus, the imager speed was changed from 1000 frames per second (fps) to 500 fps to reduce the amount of light necessary. Also, the test fixture was surrounded by a light closeout to eliminate interference with the sensors. The closeout consisted of black opaque construction paper. Video analysis used four 16 mm (5/8 inch) targets over the length of travel. Resolution of the image was approximately 0.3 mm per pixel.

Drop Tower Test Series 1 Results

Data from pots at the front of the aluminum plate was averaged and compared to the closest RibEye LED, on Rib 1. (There were no actual dummy ribs used in these tests, however, the LEDs are referred to as Rib 1, Rib 2, to reference their positions on the plate.) Similarly, the pot displacement on the rear corner of the plate was compared to the RibEye LED at Rib 6. Table 1 reports the peak displacement and data analysis from this drop tower test series.

Table 1.
Peak Displacement for GT Test Series

	GT1, 5 m/s	GT2, 7 m/s	GT3, 7 m/s	GT4, 10 m/s
	mm			
Front pot avg.	81.3	79.2	79.0	69.6
Rib 1Y	81.3	79.3	79.4	70.1
Rib 2Y	81.8	79.5	79.5	70.1
Rib 3Y	81.7	79.5	79.7	71.2
Rib 4Y	82.1	79.9	80.1	71.2
Rib 5Y	82.5	80.0	80.4	71.2
Rib 6Y	82.7	80.0	80.7	71.0
Rear pot	82.1	79.9	79.8	70.6
Imaging Analysis	81.4	79.6	79.3	70.1
Mean	81.9	79.7	79.8	70.6
Std Dev	0.5	0.3	0.5	0.6
CV %	0.6	0.4	0.7	0.9

The first drop tower test, GT1, had good correlation between the RibEye system, linear pots, and imaging analysis. Figure 10 shows the peaks for the linear pots, imaging analysis, and RibEye measurements for Ribs 1 and 6. The difference between the maximum peak displacement of Rib 1 and the average of the front pots was 0.04 mm. (This difference is rounded to zero in Table 1.). The difference between the maximum peak displacement of Rib 6 and the rear pot was 0.6 mm. The standard deviation for the peak values in Figure 10 was 0.6 mm. Rib 6 and the front pots had the largest deviation, 1.4 mm. Rib 6 and the front pots were on opposite sides of the test fixture; thus this difference might have been caused by vibrations or tilting of the upper plate during impact.

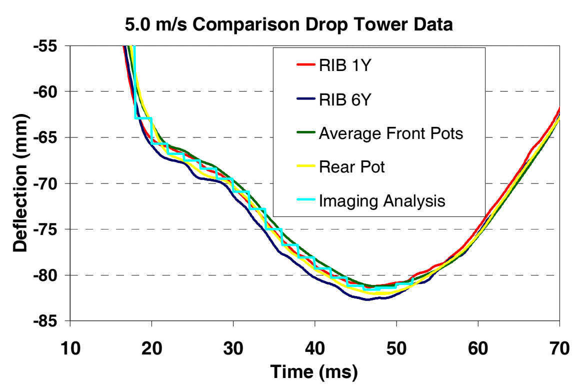

Figure 10. Drop tower Test GT1, 5 m/s.

Figure 11 shows the peak displacement measured from the RibEye LEDs (Ribs 1 through 6). The peak displacement difference between Ribs 1 and 6 was 1.4 mm.

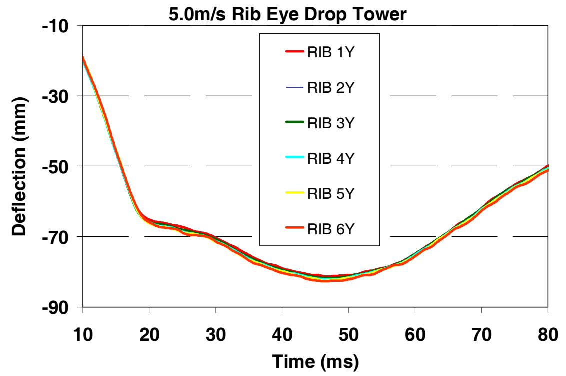

Figure 11. Drop tower Test GT1, 5 m/s.

For drop tower Test GT2, the impactor was raised to a height of about 2500 mm to increase speed to 7.0 m/s. The peak displacements between the RibEye system, corresponding linear pots, and imaging analysis is shown in Figure 12. The peak displacement difference between Rib 1 and the average of the front linear potentiometers was 0.1 mm. The peak displacement difference between Rib 6 and the rear potentiometer was 0.1 mm. The maximum displacement difference of 0.8 mm occurred between Rib 6 and the average of the front pots. The standard deviation for the measurements in Figure 12 was 0.3 mm. The maximum peak displacement difference of 0.7 mm occurred between Ribs 1 and 6 (Figure 13), which were on opposite sides of the RibEye plate.

.

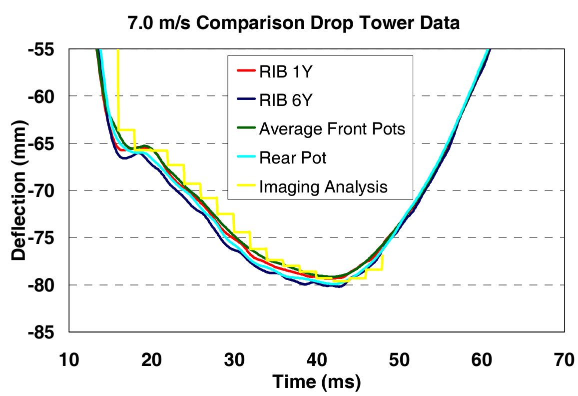

Figure 12. **Drop tower Test GT2,** 7 **m/s.**

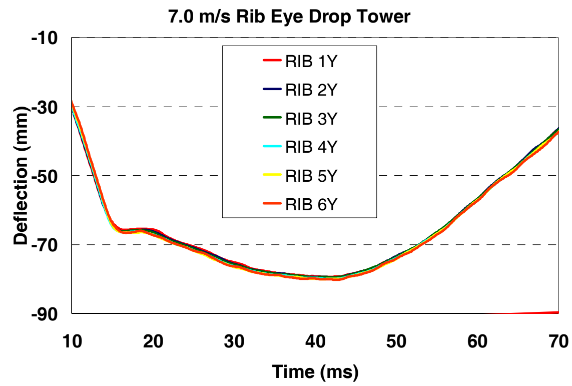

Figure 13. Drop tower Test GT2, 7 m/s.

The second 7.0 m/s test, GT3, confirmed that the transducers and/or sensors on the outer periphery of the test fixture had the greatest displacement differences.

Test GT4 was conducted at 10.0 m/s. The impactor was raised to approximately 4800 mm. Again, the maximum difference in peak deflection occurred between opposite sides of the fixture: 1.4 mm between Rib 6 and the average of the front linear pots (Figure 14). The maximum difference between the RibEye system and the high-speed imaging analysis was 1.1 mm. The maximum difference between the linear pots and the high speed imaging analysis was 0.5 mm. The imaging analysis peak displacement correlated better to the linear pots and RibEye measurements for Ribs 1 through 3, probably due to the proximity of the imaging targets being analyzed. Figure 15 shows just the RibEye data for all six ribs in Test GT4

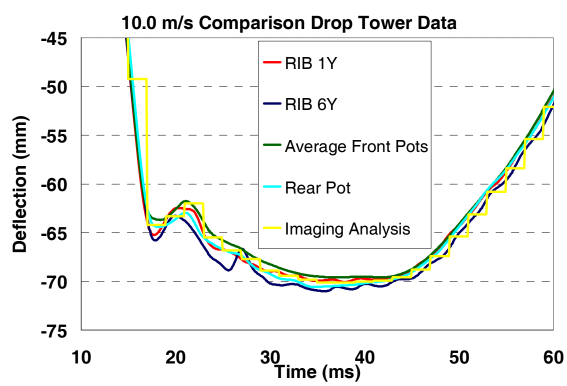

Figure 14. Drop tower Test GT4, 10 m/s.

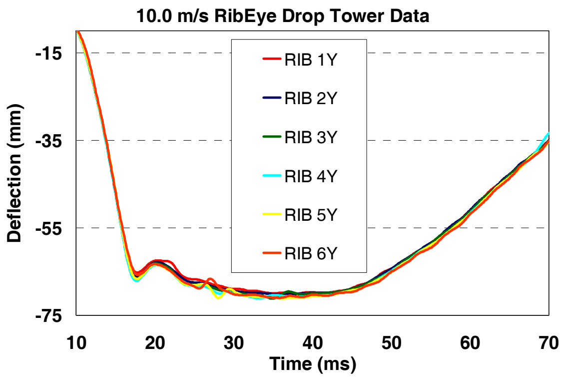

Figure 15. Drop tower Test GT4, 10 m/s.

Drop Tower Test Series 1 Discussion

This test series demonstrated that the RibEye, linear pots, and high-speed imaging had good correlation. The comparison of the pots and their closest rib LED indicated good correlation (within 0.6 mm.) The largest deviations between the front pots and Ribs 3 through 6 (1.4 mm to 1.6 mm) occurred during the 10 m/s test. This larger deviation was attributed to tilting of the plate during the impact. Comparison of the three data sets shows that as the LED plate moved along the Y-axis, the plate tilted rearward, so that the rear of the plate traveled further than the front of the plate.

As seen in Table 1, when the test speed increased, the deflection readings decreased. This was due to the higher setting on the adjustable dampers at higher speeds.

DROP TOWER TEST SERIES #2

This test series included single axis and multiple axes testing of the RibEye.

Single Axis Methodology

The set-up for this series of drop tower tests was similar to that used in the first drop tower series. Five tests were conducted to evaluate pure lateral motion: two at 5 m/s, two at 6 m/s, and one at 7 m/s. For this series, however, there was no film analysis conducted.

Single Axis Results and Discussion

The first drop tower test, DT1, suggested good correlation between those RibEye measurements and the measurement of the closest linear pots (Table 2). Rib 6 and the front pots had the largest deviation, 2.9 mm.

For these tests the accuracy of the system was comparable to the results of the first drop tower test series – that is, RibEye measurements between Ribs 1 and 6 were within 3 mm, and the difference was likely due to tilting of the plate as confirmed by the pot measurements. Comparing the LED that was closest to a pot, the difference was less than 0.5 mm.

Table 2.
Peak Displacement for Single Axis Test Series

	DT1, 5 m/s	DT2, 5 m/s	DT3, 6 m/s	DT4, 6 m/s	DT5, 7 m/s
	mm				
Front pot avg.	78.6	79.9	66.5	65.3	70.5
Rib 1Y	78.7	79.9	66.1	65.0	71.2
Rib 2Y	79.3	80.4	66.8	65.6	71.2
Rib 3Y	79.9	80.8	66.8	65.6	71.2
Rib 4Y	80.0	80.4	67.0	65.9	71.2
Rib 5Y	80.6	81.5	67.5	66.1	70.1
Rib 6Y	81.5	81.9	67.2	66.0	70.0
Rear pot	81.2	81.6	67.3	66.2	69.2
Mean	80.0	80.8	66.9	65.7	70.6
Std Dev	1.1	0.8	0.5	0.4	0.8
CV%	1.4	1.0	0.7	0.6	1.1

Multiple Axis Methodology

For the multiple axis drop tower tests, the test set-up was modified to simulate oblique loading in a SID-IIs dummy. This was done by tilting the RibEye sensors about the X-axis 10 degrees and about the Z-axis 20 degrees, exposing the RibEye to displacements in all three axes. The RibEye LEDs were not moved or tilted. Figure 16 is an illustration of the test fixture with the RibEye sensors (item 1) in an oblique position supported by the compound mounting block (2).

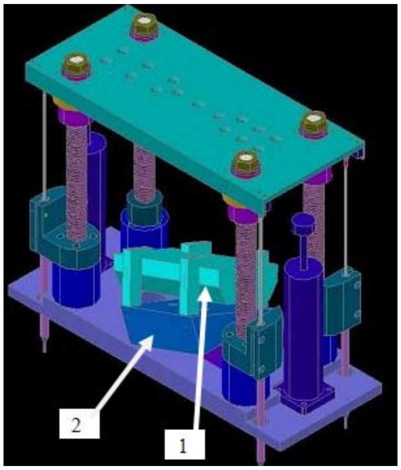

Figure 16. Test fixture illustration.

Only two pots were used in the multiple axis tests because the third pot failed and no replacement was available. The two pots were mounted on the front left and rear right of the fixture. The way the RibEye was mounted on the block, the Rib 1 LED was closest to the rear pot and Rib 6 LED closest to the front pot (the opposite of the first drop tower series).

Multiple Axis Results

Three tests were conducted, all at 5 m/s. The compound angle change of the sensors resulted in the pure Y displacements (with respect to the pots) being measured as X, Y, and Z displacements by the tilted RibEye sensors. Thus, the RibEye data were converted from its coordinate system to the potentiometer coordinate system, so that the pot data and the converted RibEye Y data could be compared.

Figure 17 shows Rib 1 LED data in the RibEye coordinate system (1X, 1Y, and 1Z) and the same data converted to the pot coordinate system (X~, Y~, and Z~). Data from other ribs showed similar results. Figure 18 shows all rib Y data (Ribs 1-6) in both the RibEye and the pot coordinate systems. Figure 19 is an enlarged view of all rib Y data. It was expected that there is two groupings of curves, one represents the Y deflection in the RibEye coordinate system the other is the same data converted to the pot coordinate system. Table 3 summarizes rib Y data converted to the pot coordinate system.

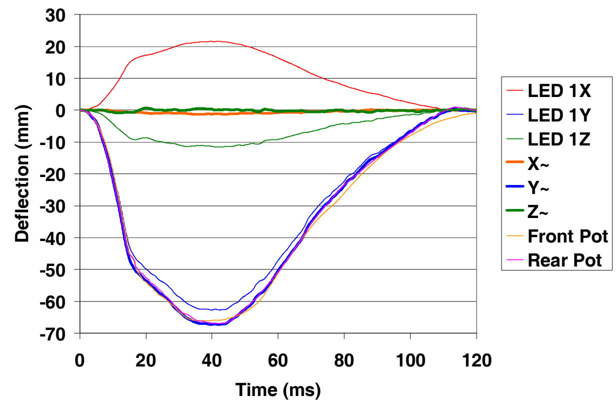

Figure 17. Rib 1 LED data.

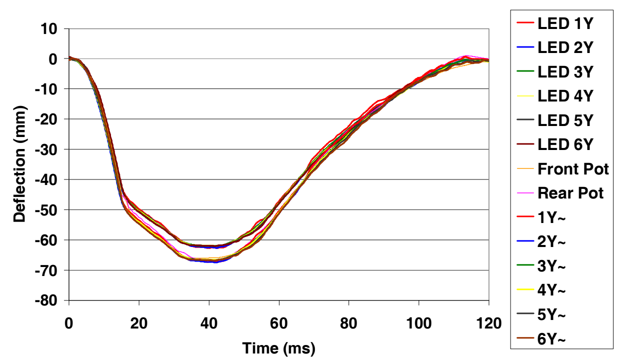

Figure 18. All rib Y data.

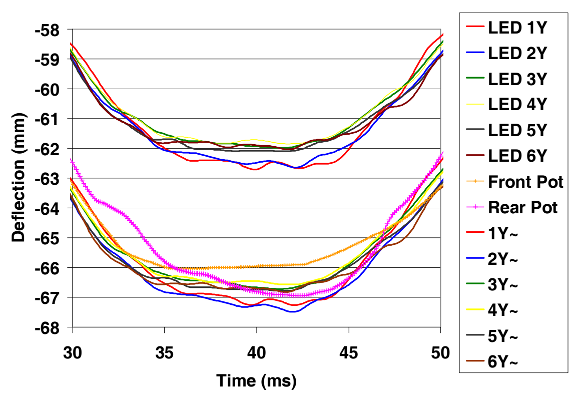

Figure 19. Enlargement of all rib Y data.

Table 3.
Peak Displacement for Multiple Axis Test Series

	CP1	CP2	CP3
	mm		
Rear pot	64.9	66.9	66.7
Rib 1Y~	65.7	67.3	67.0
Rib 2Y~	65.9	67.5	67.2
Rib 3Y~	65.0	66.7	66.5
Rib 4Y~	64.5	66.6	66.4
Rib 5Y~	64.7	66.8	66.6
Rib 6Y~	64.8	66.8	66.6
Front pot	63.3	66.0	65.9
Mean	64.9	66.8	66.6
Std Dev	0.8	0.5	0.4
CV%	1.2	0.7	0.6

Multiple Axis Discussion

The maximum difference between a RibEye converted Y measurement and the closest pot measurement was 1.5 mm (test CP1: the front pot and Rib 6Y~). However, the other tests demonstrated good correlation.

The RibEye X and Z data, converted to the pot coordinate system, showed differences in displacements of less than 1 mm. Because the RibEye sensors were rotated for this series, the LEDs are moving through the sensor's field of view at an oblique angle. The true displacement of the LEDs however, is in line with the linear pots. Thus the RibEye X and Z data, converted to the pot coordinate system, would theoretically be zero. The actual converted measurements of less than 1 mm suggest accurate RibEye measurements in multiple axes.

FULL VEHICLE CRASH TEST COMPARISON SERIES

Methodology

Full-vehicle paired crash tests were conducted to investigate the three-dimensional capability of the RibEye and to compare chest deflection measurements obtained with the RibEye to those obtained with linear pots.

The vehicle sample included 10 paired tests, which included a mix of crossover vehicles and passenger vehicles. The vehicles were all model year 2007-2008 and equipped with side curtain airbags and seat-mounted airbags for the driver position, with the exception of one vehicle model where only the curtain airbag was available for the driver. Comparisons were conducted in both the driver seat position and the rear struck side passenger seat position. There were three paired tests at the driver position and seven paired tests in the rear passenger position (Table 4).

Table 4.
Number of paired tests
by configuration and seat position

	IIHS	FMVSS 214 MDB	FMVSS214 Pole
Driver	2	--	1
Rear Passenger	2	5	--

Notes: IIHS tests: perpendicular impact at 50 km/h
FMVSS 214 tests: crabbed barrier, 27 degrees at 54 km/h
Pole test: 15 degrees angle at 32 km/h

One SID-IIs (Build Level D) dummy was instrumented with linear pots, while the second was modified to accommodate the RibEye measurement system. Both dummies underwent pendulum tests to verify that the rib sets had comparable responses. Other instrumentation included head, spine, and pelvis accelerometers, as well as acetabulum and pubic load cells. The data was acquired and filtered according to SAE J211-1 [3] standards and the film footage was recorded at 1000 fps.

The dummies were positioned as per the IIHS or FMVSS 214 seating procedure in the driver seat. No specific protocol was followed for the rear seat; however, an attempt was made to position the dummies similarly and their positions were verified using a Platinum Faro arm ©.

The impact velocity for the IIHS barrier was 50 km/h ± 0.4 km/h; FMVSS 214 and pole impact were 54 ± 0.13 km/h and 32 ± 0.9 km/h, respectively. The impact points for the IIHS barrier tests were within 2 mm of the target, the FMVSS 214 barrier impact points were within 28 mm, and the pole impacts were within 7 mm of the target.

These full vehicle tests utilized the standard jacket for the SID-IIs dummy. A prototype jacket was available to reduce ambient light interference. However, since the purpose of the study was to evaluate dummy measurement capability, it was thought inadvisable to conduct tests with different jackets. Furthermore, since the dummy was not subject to direct light exposure in the test vehicle, measurement interference was not anticipated.

Calculations for Equivalency

Since the RibEye measures deflection in axes and the linear pots measure the compression of the pot shaft, some calculations were required to obtain comparable measurements. The initial position of the pots and the LEDs needed to be identified to make these calculations. The spatial relationship of the LED and the pot are shown in Figure 20, where the top dot represents the initial position of the LED on the rib.

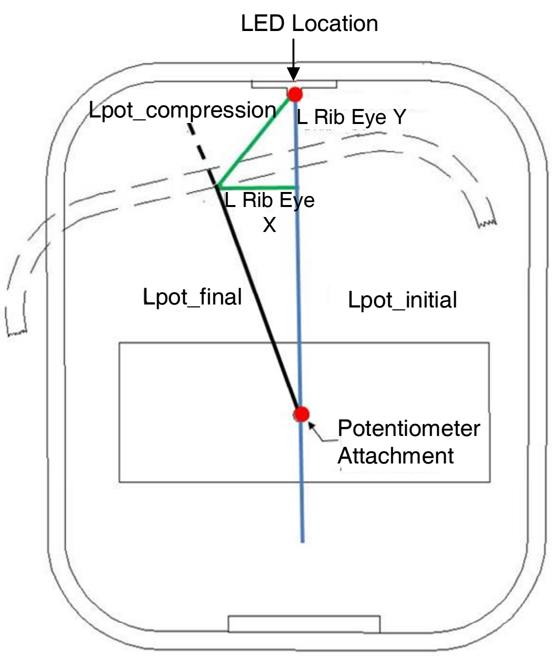

Figure 20. RibEye to pot conversion.

The mathematical relationship between the two instruments is defined by Equation 1, where $L_{pot\_initial}$ is the distance between the attachment point of the pot on the rib and the corresponding attachment point on the spine box. This distance is on average 120 mm. $L_{pot\_compression}$ represents the calculated RibEye equivalency to the linear pot. $L_{RibEyeX}$, $L_{RibEyeY}$, and $L_{RibEyeZ}$ are values recorded by the RibEye along the X-axis, Y-axis, and Z-axis, respectively.

(1.)

$$L_{pot\_compression} = L_{pot\_initial} - \mathrm{sqrt}\left[(L_{pot\_initial} - L_{RibEyeY})^2 + L_{RibEyeX}^2 + L_{RibEyeZ}^2 \right]$$

Results

Two principal deflection patterns were found in this study: 1) a uni-axial deflection, where the major contributor of the deflection was along the Y-axis and deflections in X-axis and Z-axis were insignificant; and 2) a multi-axial deflection, where the major contributor of the deflection was in the fore-aft direction with a less important lateral or vertical component.

Uni-axial deflection was most frequently observed in perpendicular or purely lateral loading environments such as the driver position in the IIHS configuration. Multi-axial deflections were observed in the oblique or combined loading environments such as rear passenger for IIHS tests and both rear and front occupants for FMVSS 214 barrier and pole test configurations.

As shown in Figures 21-23 the differences between the peak measurements of the RibEye dummy and the standard dummy for Ribs 2, 3, and 4 were 1.7 mm, 3.7 mm, and 0.3 mm respectively. Unlike the controlled drop tower tests where the linear pots and RibEye were measuring the same impact, these reported differences reflect different crash tests. Thus the differences noted not only reflect on the crash test to crash test repeatability but also repeatability between RibEye and linear pot measurements. The shapes of the curves suggest good test to test repeatability.

Figure 24 presents an example of the X, Y and Z components for the same rib (Rib 3) shown in Figures 22 as measured by the RibEye. As described, the principal direction of loading in this sample case was perpendicular or almost completely lateral. This was characterized by the peak deflection occurring in the lateral or Y-axis with negligible fore-aft or vertical contributions to deflection.

Multi-axial deflection was most frequently observed in oblique loading conditions. As an example, Figure 25 illustrates the time histories for the corrected RibEye deflection and the corresponding pot deflection for Rib 3. The peak deflection measurement of the pot was equivalent to the corrected RibEye measurement. There was greater difference in shapes of the traces as compared to the more lateral test conditions because the oblique loading of the ribs may have been causing greater variability in the rib motion. Differences may be more apparent because the overall magnitude of the

Y-deflection was significantly lower for the oblique conditions.

The corresponding three deflection components for Rib 3 as measured by the RibEye are shown in Figure 26. In this loading environment the RibEye indicated that a fore-aft deflection of 33.1 mm was present in addition to the 20.1 mm of lateral deflection.

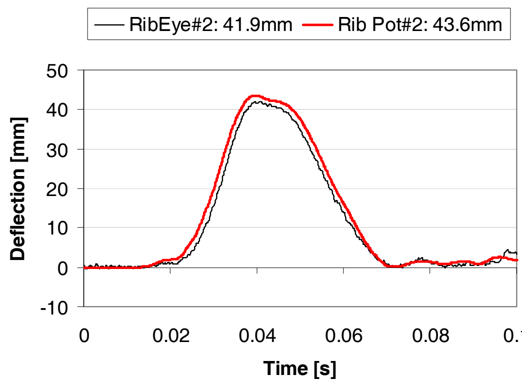

Figure 21. Rib 2 deflections measured for driver in an IIHS test.

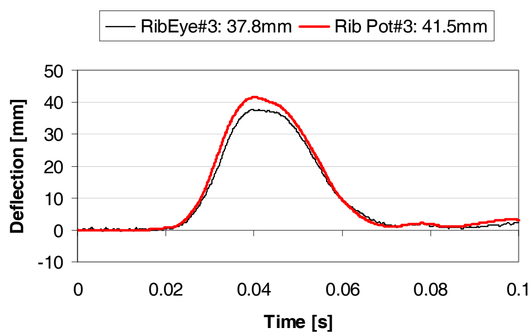

Figure 22. Rib 3 deflections measured for driver in an IIHS test.

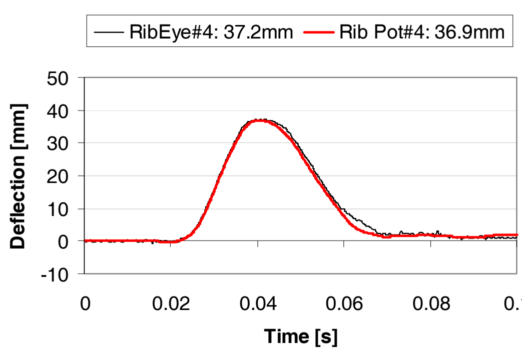

Figure 23. Rib 4 deflections measured for driver in an IIHS test.

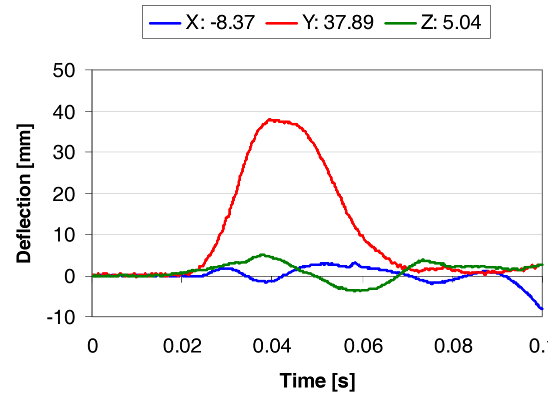

Figure 24. Deflection components as measured by the RibEye for driver in IIHS test.

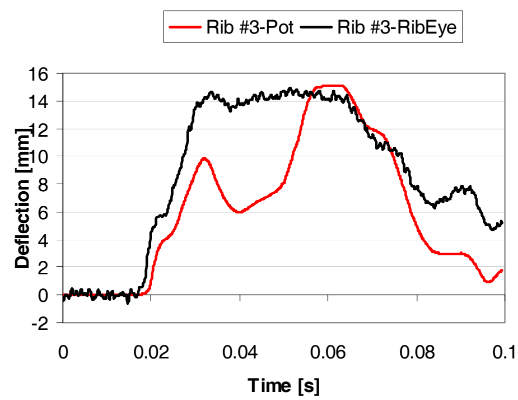

Figure 25. Deflection of rib 3 as measured with the linear pot and the RibEye for driver in FMVSS214 pole test.

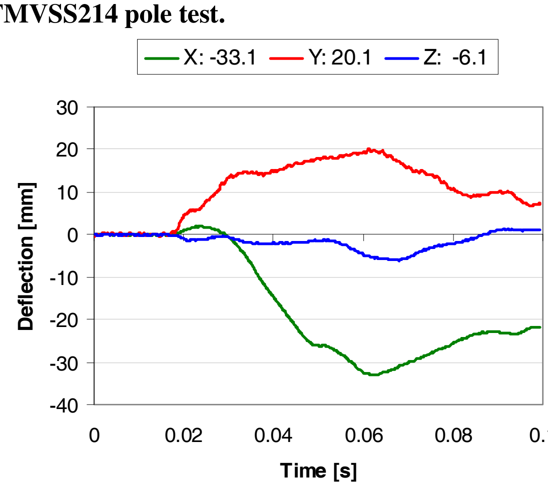

Figure 26. Three components of deflection for rib 3 as measured with the RibEye for driver in FMVSS214 pole test.

Discussion

The RibEye system was reliable and did not present any durability issues throughout the vehicle crash test series. In contrast, the significant loading associated with certain tests did cause damage to the linear pots both at the attachment point and in the wiring, resulting in noise and loss of data.

For the full vehicle crash tests, the proposed dummy clothing designed to block ambient light from entering the chest cavity was not used. Standard dummy clothing was used. However, of the ten full vehicle crash tests using RibEye, only one test had saturated signals and it occurred after 100 ms post impact (after the region of occupant interest.) Some laboratory testing had been completed to demonstrate the effectiveness of the new clothing, but that evaluation is not reported here.

Another possible limitation of the RibEye system is that the software application was not integrated with a data acquisition system. This required a parallel set-up to the central data acquisition system and was time consuming. Integrated software that interfaces with the standard data acquisition systems would greatly improve the usability of the RibEye in the laboratory environment.

Under controlled paired crash configurations, the RibEye demonstrated the ability to measure rib motion in three directions with respect to the spine box. The deflection as measured by the RibEye in the Y- direction was found to correlate well with that of the linear pots. It should be noted, however, that currently used thorax injury risk curves for side impact utilize lateral deflections only. Additional research may be necessary to fully understand the 3-dimensional aspects associated with thoracic and abdominal injury.

SUMMARY

The initial linear impactor test series was useful at identifying testing shortcomings that were corrected for the subsequent tests.

In the drop tower test series, which were conducted at different laboratories, the RibEye measurements, the linear pots, and high-speed imaging demonstrated good correlation (within 1.5 mm difference). The worst case difference between a peak RibEye measurement and the corresponding peak pot measurement was 1.5 mm, and occurred during an oblique test. Many of the other measurements demonstrated much better correlation (significantly less than 1.5 mm difference.)

The RibEye system is designed to measure deflections in all three dimensions. A limited amount of oblique tested demonstrated the ability to measure displacements in both the Y and X directions.

The full vehicle crash tests demonstrated similar peak value measurements between the RibEye dummy and the standard dummy. During FMVSS 214 and pole impact tests, the RibEye revealed significant X-axis deflection that cannot be measured by linear pots.

A full durability analysis was not completed on the RibEye, however in the limited amount of testing conducted there were no durability issues identified. The linear pots, however, did exhibit some damage during some of the full vehicle crash tests.

Although there were not significant ambient light interference issues with RibEye during the full vehicle crash tests, further analysis of the redesigned clothing may be necessary.

ACKNOWLEDGEMENTS

The authors wish to acknowledge John Athey, Daryl Black, Lynn Byers, Dawn Firth, Ryan Goocher, Lynn Byers, Kim Malone, Craig Morgan, and Marianna Sierra Ramerez.

REFERENCES

1. Scherer, R., Kirkish, L., McCleary J., Rouhana, S.W., Athey, J.B., Balser, J.S., Hultman, R.W., Mertz, H.J., Berliner, J.M., Xu, L., Kostyniuk, G.W. 1998. “SID-IIs Beta+ Prototype Dummy Biomechanical Responses”, SAE 983151, Warrendale, PA, Society of Automotive Engineers.
2. Arbelaez, R.A., Brumbelow, M., Wang, Z., Van Ratingen, M. 2006. “A New Calibration Specification for Linear Displacement Transducers”, SAE 2006-01-0719, Warrendale, PA, Society of Automotive Engineers.
3. Society of Automotive Engineers, “Instrumentation for Impact Test, Part 1, Electronic Instrumentation”, SAE J211/1, Warrendale, PA, July 2007.
4. National Highway Traffic Safety Administration, Reference No. 572.185, Subpart U.