CHARACTERIZATION OF WORLDSID RIB DIRECTIONAL DYNAMIC RESPONSE

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ABSTRACT

The objective of the present study was to quantify the response of an isolated WorldSID rib subassembly to quasi-static and dynamic loading at angles up to 30 degrees from lateral. A test fixture was designed consisting of two flat plates mimicking the WorldSID spine plate and was instrumented with two uniaxial load cells to measure independent loads transmitted by either the inner rib band or the thorax or abdomen ribs. The fixture and WorldSID rib subassembly were loaded in either a quasi-static or dynamic impact at 3, 4, or 5 m/s and at angles 0, ± 15, ± 30 degrees with respect to lateral, rotated about the Z axis. Quasi-static stiffness of the rib did not vary substantially with respect to loading direction for the first 30 mm of stroke. Dynamic stiffness was influenced by loading rate and loading direction, with highest impactor force found for -30 degrees (posterior). Using IR-TRACC deflections, stiffest response was demonstrated at anterior and posterior oblique loading. Maximum impulse to the spine plate load cells was observed at 0 degrees and also resulted in maximum IR-TRACC deflection. Optimized loading to maximize spine impulse while minimizing deflection was dependent on the chosen deflection measurement method (IR-TRACC or external deflection). Future work may characterize response using alternative injury metric measurements.

INTRODUCTION

In December 2015, the U.S. National Highway Traffic Safety Administration (NHTSA) issued a request for comment on considerations for upgrading the current New Car Assessment Program (NCAP) with new anthropomorphic test devices (ATDs), new injury metrics, and a new test mode. For side impact, the WorldSID 50th percentile male was proposed as the driver ATD in both the crabbed movable deformable barrier and oblique pole tests, replacing the current ES-2re and SID-IIs in these respective test modes. The WorldSID has been shown previously to better reproduce post-mortem human subject (PMHS) chest deflections compared to these ATDs [1].

The WorldSID thorax is uniquely designed to permit multidirectional deformation up to 30 degrees with respect to lateral [2]. Yet, the deformation responses to these extreme loading directions have not been reported. Therefore, the objective of the present study was to quantify the response of an isolated WorldSID rib subassembly to quasi-static and dynamic loading at angles up to 30 degrees from lateral.

METHODS

The test methods were developed to characterize the WorldSID rib response to varying impact loading rates and impact angles. A test fixture was designed to load a single WorldSID rib subassembly in a range of loading directions. The fixture (Fig. 1) consisted of two flat plates mimicking the WorldSID spine plate. The rib subassembly was mounted to these plates in a similar manner as they would be mounted in the ATD. Unlike the WorldSID spine plate, the fixture plate was instrumented with two uniaxial load cells to measure independent loads transmitted by either the inner rib band or the thorax or abdomen ribs. Although the rib forward end would be mounted to either the sternum or abdomen rib coupler in the ATD, in the test setup this end was allowed to freely translate. The angle of the fixture plate was adjustable about the rib Z axis, permitting variation in the direction of force applied.

With the WorldSID rib subassembly mounted to the fixture, the device was positioned in either a quasi-static test apparatus (Instron®) or a pneumatic dynamic linear impact apparatus. In both cases, force was applied using a flat resin impactor plate. Friction was increased using adhesive cloth tape; this was applied to reduce relative motion between the impactor face and the rib during loading. In quasi-static conditions, the loading rate was 1 mm/s and was applied until displacement achieved 50 mm. In dynamic conditions, a 3.45 kg impactor was accelerated to approximately 3, 4, or 5 m/s prior to contact with the rib. At each loading rate, the spine plate fixture was pre-positioned at 0, ±15, and ±30 degrees with respect to lateral. Rotation was applied about the IR-TRACC mounting location. A complete test matrix is shown in Table 1.

Table 1.
Test matrix

Test Nos.	Loading Angle (degrees)	Loading Rate (m/s)
1, 21	0	QS*
2, 22	0	3.0
3, 23	0	4.0
4, 24	0	5.0
5, 25	+15	QS
6, 26	+15	3.0
7, 27	+15	4.0
8, 28	+15	5.0
9, 29	+30	QS
10, 30	+30	3.0
11, 31	+30	4.0
12, 32	+30	5.0
13, 33	-15	QS
14, 34	-15	3.0
15, 35	-15	4.0
16, 36	-15	5.0
17, 37	-30	QS
18, 38	-30	3.0
19, 39	-30	4.0
20, 40	-30	5.0

* QS = quasi-static

For each test, data were collected from the following instrumentation: IR-TRACC deflection, IR-TRACC angle, rib reaction force, and inner band reaction force. Rib triaxial accelerations were also recorded but will be reported in future work. In the dynamic impacts, impactor linear acceleration was recorded and used to derive force and stroke. In the quasi-static tests, force and stroke we measure directly by LVDT and load cell. All data were filtered in accordance with SAE J211. Videography captured qualitative deformations at either 3000 Hz (dynamic tests) or 30 Hz (quasi-static tests).

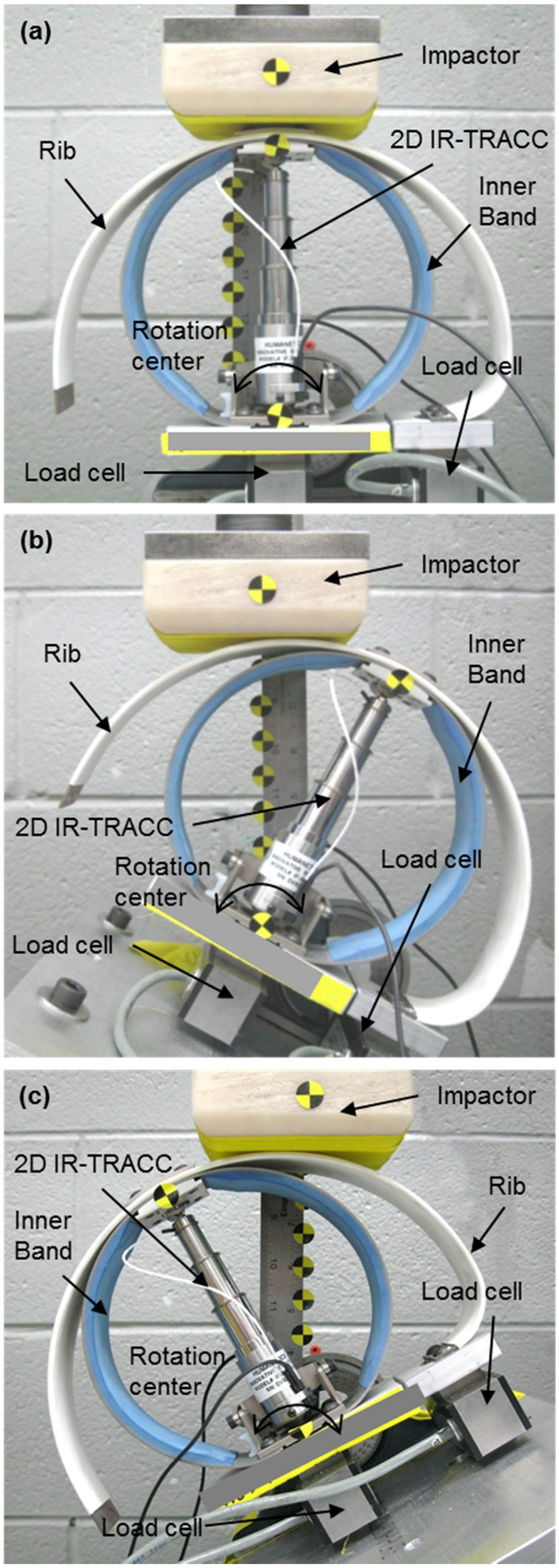

Figure 1. Isolated rib loading fixture positioned at (a) 0 degrees, (b) +30 degrees, and (c) -30 degrees with respect to lateral.

RESULTS

All testing resulted in n = 210 channels of data traces. A data summary for thorax and abdomen ribs is shown in Tables A.1 and A.2 in the Appendix. Data were compared with respect to loading rate and with respect to loading direction.

Quasi-Static Tests

Quasi-static stiffness results are shown in Figure 2. Qualitatively, external stiffness of the chest did not vary substantially with respect to loading direction for the first 30 mm of impactor stroke. Observations for the abdominal rib were similar and omitted for brevity. Force deflection response was most linear when applied at -30 degrees, resulting in a stiffness of 20.0 N/mm and $R^2 = 0.999$. Response was least linear when applied at 0 degrees, resulting in a stiffness of 18.8 N/mm and $R^2 = 0.814$. Comparing all directions, the rib subassembly was stiffest at -15 degrees: 22.5 N/mm and $R^2 = 0.982$.

Lateral spine reaction force with respect to IR-TRACC is shown in Figure 3 for each loading direction. IR-TRACC rib deflection was dependent on loading direction. Although impactor stroke was the same for each loading case (50 mm), measured deflection varied by more than 50% from 24.2 (in -30 deg) to 47.8 mm (0 deg). Further, peak lateral spine load also varied with respect to loading direction. Peak loads varied from 791 N at +15 degrees to 1261 N at -30 degrees.

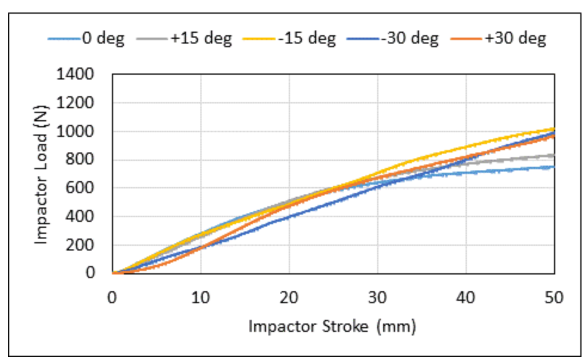

Figure 2. Quasi-static force-stroke response of the thorax rib subassembly in different loading directions.

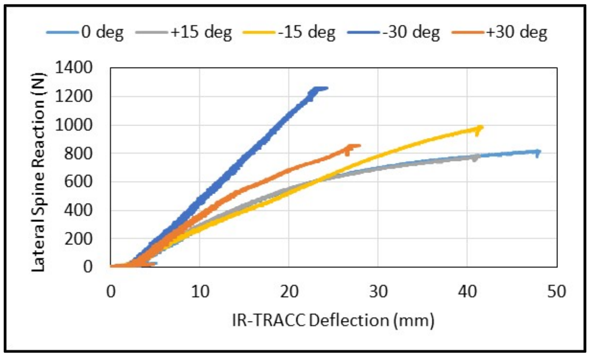

Figure 3. Quasi-static response of IR-TRACC measured rib deflection with respect to lateral spine reaction force thorax rib subassembly in different loading directions.

Dynamic Tests

Rib force responses are shown with respect to impactor stroke in Figure 4 for thorax rib tests. Only responses at + 30, -30, and 0 degrees are shown for clarity. Force and stroke responses demonstrated dependence on loading rate and on loading direction. With increased impactor velocity, peak stroke increased from approximately 25 mm to approximately 45 mm. Strokes were least at -30 degrees and greatest at +30 degrees. Force response trends varied depending on the stroke region. Over the initial 10 mm of stroke, stiffness increased with loading rate. Rate dependence was greatest at 0 degrees, at which response varied by more than 100% between 3 m/s and 5 m/s. Rate dependence was least apparent at -30 degrees, at which stiffness varied by 38% over the initial 10 mm of stroke. Stiffness also was dependent on load direction beyond 30 mm impactor stroke. Impactor force at -30 degrees increased to 2238 N at max stroke but did not exceed 1200 N at 0 degrees. Examining the stiffness over 10-30 mm impactor stroke, rib subassembly stiffness did not appear to vary substantially based on loading direction. Within this stroke range, impactor force generally fell within 500-700 N.

Spine reaction force with respect to IR-TRACC deflection is shown in Figure 5 for thorax rib tests. Again, only +30, -30, and 0 degree responses are shown for clarity. Similar to impactor forces and strokes, spine reactions and deflections also demonstrated dependence on loading rate and on loading direction. Spine reaction force at 0 degrees and at +30 degrees reached approximately 1150 N at 5 m/s. In contrast, spine reaction force at -30 degrees

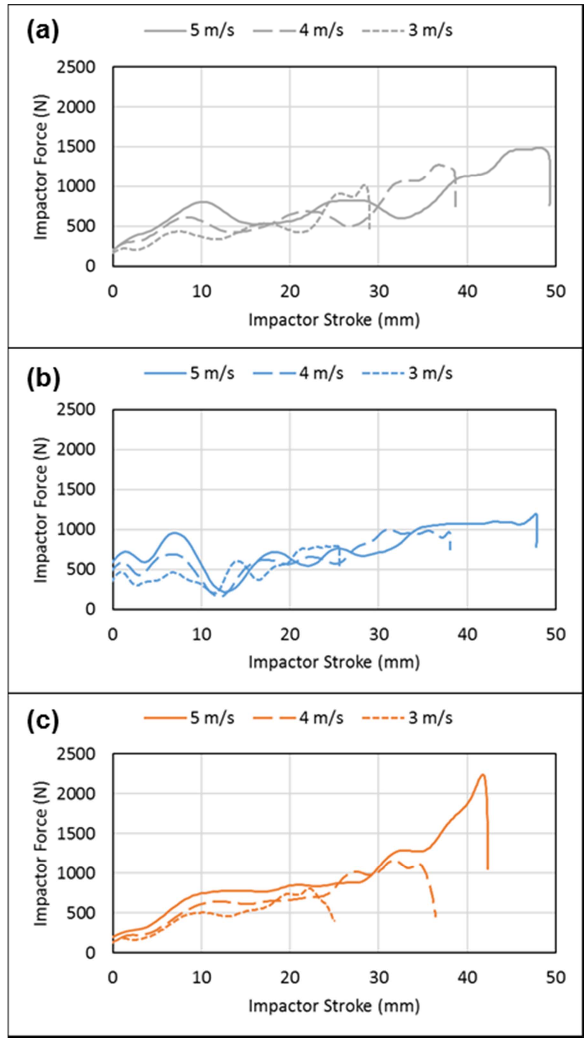

Figure 4. Select force-stroke responses of the WorldSID thorax rib in dynamic impact at (a) +30 degrees, (b) 0 degrees, and (c) -30 degrees.

was 25% higher (1398 N) than at 0 degrees. Further, IR-TRACC deflections varied by more than 50% compared to 0 degree load direction. Both -30 and +30 degree directions demonstrated similar deflection results.

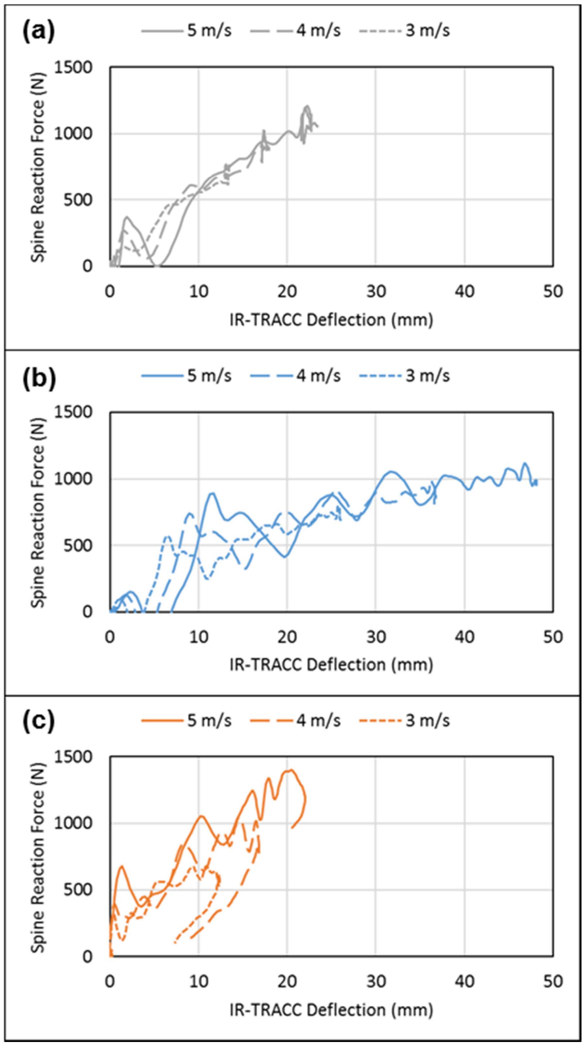

Figure 5. Select force-stroke responses of the WorldSID thorax rib in dynamic impact at (a) +30 degrees, (b) 0 degrees, and (c) -30 degrees.

DISCUSSION

The purpose of the present study was to investigate the quasi-static and dynamic response of an isolated WorldSID rib subassembly to different loading rates and loading directions. The WorldSID dummy was developed to meet ISO 9790 biofidelity corridors for chest and abdomen deflection performance [3]. The overall construction of the thorax and abdomen ribs was designed for robust performance in ± 30 degree oblique loading and the rib design has not changed substantially since the original prototype was released [2]. The present study demonstrated robust performance of the rib at these extreme loading directions.

Rib responses varied with respect to both loading rate and loading direction. In both quasi-static and dynamic conditions, oblique loading demonstrated higher peak force response compared to lateral loading: +25% for +30 degrees, +94% for -30 degrees (Figs. 2 and 4). External stroke responses for 0 degrees and +30 degrees were similar but were reduced by approximately 5 mm for -30 degrees. The increased force likely resulted in part from increased deformation and loading of the outer rib near the spine mount (Fig. 1). Shown in Figure 6 are peak forces measured by the spine plate load cells. As loading direction rotated toward posterior, loads measured at the outer rib mounting location increased by between 150 N (3 m/s) and 350 N (5 m/s). This increase generally did not include a commensurate decrease in inner band force, particularly at the higher impact velocities, thereby increasing total force. However, this alone does not account for the increased total force response at -30 degrees, suggesting that other causes should be investigated.

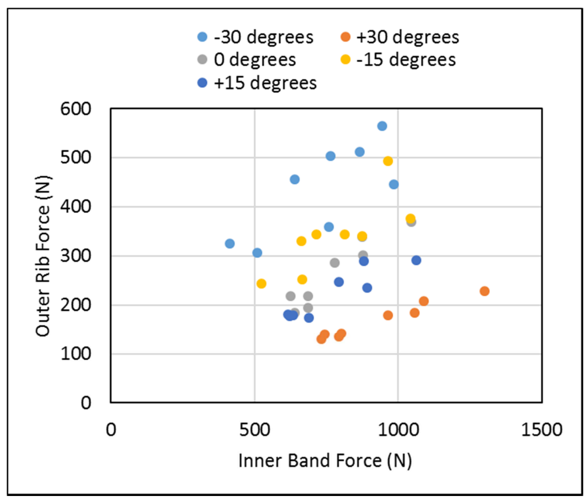

Figure 6. Outer rib force vs. inner band force for all impact directions and velocities.

Side impact injuries are generally governed by contact characteristics between a nearside occupant and the intruding door until the occupant and door attain equal velocity [4]. Therefore, structure and restraint designs may be employed to increase the lateral momentum of the dummy while minimizing injury metrics. In this study, such a strategy would be identified by maximized spine reaction impulse and minimized rib deflection. Shown in Figure 7 are impulse results (using spine load cell time traces) with respect to two rib deflection measures: IR-TRACC deflection and external deflection as indicated by impactor stroke. Also shown are linear fit relationships for each loading direction. Based on a strategy to maximize impulse and minimize injury metrics, a loading condition with larger slope would be preferred. Yet, the present study demonstrates that this relationship is dependent on the chosen injury metric. Considering IR-TRACC deflection, oblique loading directions demonstrated larger slope: 1.1300 (-30 degrees) vs. 0.6366 (0 degrees). Considering external deflection represented by impactor stroke, lateral loading demonstrated larger slope than all other loading directions. This finding agrees with previous work, which found that impact angle affected rib deflection results, particularly when considering the IR-TRACC measurement [5].

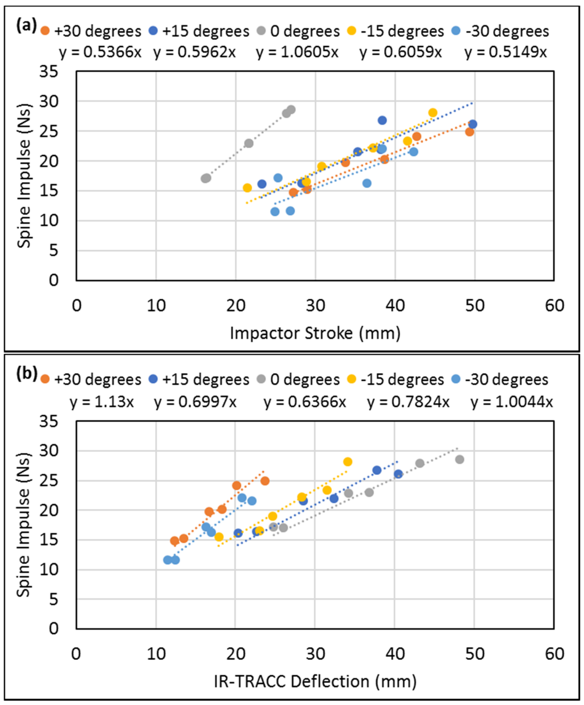

Figure 7. Spine impulse with respect to (a) peak impactor stroke and (b) peak IR-TRACC deflection for all dynamic tests.

Contemporary chest injury metrics proposed for the WorldSID consider only the IR-TRACC peak deflection regardless of loading direction [6]. Yet injury response has been shown to be dependent on obliquity of chest deformation. PMHS sled tests with 20 and 30 degree anterior oblique wall have shown increased chest deflections and different injury patterns compared to pure lateral loading [7]. Injury response of the chest to posterior oblique loading may differ from lateral loading but is not well understood [8]. WorldSID biofidelity studies have considered both anterior and posterior oblique loading directions but have not considered angles over the entire span of the present study [5] [9]. Based on these findings, further investigation may be needed to identify optimal restraint conditions for the WorldSID dummy.

LIMITATIONS

Several limitations should be considered when interpreting the results of this study. First the isolated rib subassembly testing did not replicate fully the boundary conditions of the rib in the assembled WorldSID dummy. The struck side of the rib was loaded directly by a resin impactor with a cloth surface. In contrast, the rib in the assembled dummy is beneath both a foam rubber pad and a fabric dummy suit. Although the boundary condition employed in the present study did not represent fully the damping of these materials in the dummy, this approach avoided confounding results with relative sliding motion between the struck rib and the impactor. In addition, the spine boundary condition in the present study was a rigid mount and the sternum was omitted. This support differed from a dummy spine, which could translate in response to applied load. This rigid boundary condition increased deflections by eliminating residual kinetic energy. Lastly, this study was limited by sample size. Only 1 rib for thorax and abdomen was used for all testing, and each test was conducted once. This type of study is useful for observing general trends but limits the predictive capability of any regression between variables.

CONCLUSIONS

The present study characterized WorldSID rib response to quasi-static and dynamic loading. Force and stroke responses were dependent on loading rate and on loading direction. Load distribution between the outer rib and the inner band was also affected by loading direction, with the outer rib force increasing as direction moved more posterior. A strategy to maximize impulse and minimize injury metrics was dependent on the chosen measurement method, suggesting that future work is needed to determine an optimal restraint strategy.

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DISCLAIMER

Any views or opinions expressed herein are those of the authors and do not necessarily reflect those of Toyota Motor North America.

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APPENDIX

Table A.1.
Peak results for thorax rib subassembly tested in all loading rates and loading directions.

Angle	Target Velocity	Impactor Force	Impactor Stroke	Rib Force	Inner Band Force	Spine Force	Impactor Impulse	Spine Impulse	IR-TRACC Stroke	IR-TRACC Angle
(deg)	(m/s)	(N)	(mm)	(N)	(N)	(N)	(Ns)	(Ns)	(mm)	(deg)
30	QS	968	50.0	129	732	859	-	-	27.9	-15.4
	3	1016	29.0	141	745	785	16	15	13.5	-10.0
	4	1273	38.7	179	964	1052	21	20	18.3	-13.9
	5	1489	49.4	208	1089	1208	26	25	23.7	-17.7
15	QS	835	50.0	180	616	791	-	-	41.5	-12.5
	3	823	28.3	177	622	798	17	16	22.6	-6.1
	4	1046	38.2	247	793	1023	22	22	32.4	-9.1
	5	1129	49.7	289	880	1125	27	26	40.4	-12.4
0	QS	751	50.0	184	641	820	-	-	48.1	3.5
	3	795	25.6	218	626	798	16	17	26.0	2.4
	4	1000	38.1	286	779	990	22	23	36.8	4.1
	5	1196	47.9	339	875	1118	27	29	48.1	6.5
-15	QS	1018	50.0	330	663	990	-	-	41.7	16.1
	3	906	28.9	243	525	704	15	17	23.0	10.6
	4	1269	37.3	343	815	1024	20	22	28.3	14.3
	5	1751	44.7	494	966	1302	25	28	34.1	18.4
-30	QS	991	50.0	503	766	1261	-	-	24.4	22.7
	3	807	25.0	325	414	680	13	12	12.5	19.5
	4	1160	36.5	456	641	1044	17	16	16.9	26.3
	5	2238	42.3	564	946	1398	21	22	22.1	30.6

Table A.2.
Peak results for abdomen rib subassembly tested in all loading rates and loading directions.

Angle	Target Velocity	Impactor Force	Impactor Stroke	Rib Force	Inner Band Force	Spine Force	Impactor Impulse	Spine Impulse	IR-TRACC Stroke	IR-TRACC Angle
(deg)	(m/s)	(N)	(mm)	(N)	(N)	(N)	(Ns)	(Ns)	(mm)	(deg)
30	QS	1063	50.0	141	803	944	-	-	27.4	-15.3
	3	1021	27.3	135	793	859	15	15	12.4	-10.1
	4	1350	33.8	184	1058	1133	20	20	16.7	-13.3
	5	1624	42.8	228	1300	1388	25	24	20.2	-16.4
15	QS	825	50.0	179	634	813	-	-	40.3	-11.9
	3	913	23.3	174	689	856	16	16	20.3	-5.8
	4	1169	35.4	234	891	1103	22	22	28.5	-9.1
	5	1365	38.4	291	1062	1327	27	27	37.8	-12.6
0	QS	876	50.0	194	688	882	-	-	48.9	2.3
	3	889	24.2	218	687	867	16	17	24.8	2.6
	4	1079	34.8	302	879	1079	22	23	34.2	3.7
	5	1296	44.2	369	1046	1239	26	28	43.1	4.9
-15	QS	1081	50.0	343	716	1059	-	-	42.4	15.5
	3	999	21.5	252	665	882	15	15	17.9	10.8
	4	1257	30.8	340	876	1174	19	19	24.7	19.3
	5	1577	41.6	375	1044	1366	23	23	31.5	25.0
-30	QS	1379	50.0	512	867	1379	-	-	25.3	22.2
	3	820	26.8	306	511	768	13	12	11.5	17.3
	4	1289	25.4	359	758	1090	17	17	16.3	21.9
	5	2119	38.4	446	986	1407	21	22	20.8	26.6