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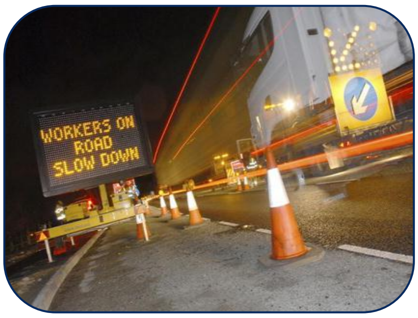

CLIENT PROJECT REPORT CPR1317

Global Impact Dummies - Assessment Concerning WorldSID in Future Regulatory Applications

Final Report

J A Carroll, O Goodacre and D Hynd

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J Nelson (Project Manager)	JNelson	M Edwards (Technical Referee)	Mervyn Edwards.

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Executive Summary

The WorldSID 50th percentile male crash test dummy (WorldSID-50M) was developed by a world-wide collaborative effort to produce an advanced world-harmonised side impact dummy. More recently, the WorldSID 5th percentile female dummy (WorldSID-5F) was developed. The design of the 5F dummy was based on the 50M design with the objective to create a family of dummies that give a consistent direction to the design of vehicle safety structures and restraint systems.

In parallel with the development of the WorldSID-5F, Transport Canada commissioned a new rib compression instrumentation package, called RibEye, to be installed in their 50M dummy. The WorldSID-50M RibEye system measures rib compression at three locations on each rib, instead of the single-point measurement on each rib with the 1D and 2D IR-Traccs fitted as standard in the 50M and 5F dummies, respectively. Both the RibEye and IR-Traccs use an optical measurement system as opposed to physical measurements such as are provided by a string potentiometer or Linear Variable Differential Transformer (LVDT). However, whereas the RibEye is a purely optical system with no physical connection between the measured point on the rib cage and the spine, IR-Traccs incorporate a telescoping rod to shield the optical components and therefore retain a mechanical linkage from the measured point to the base.

In order to allow the WorldSID dummies to be used in vehicle regulations, Global Technical Regulation Informal Groups have directed a WorldSID Technical Evaluation Group to document the performance of the WorldSID-50M and 5F. This effort is to include identification of outstanding issues that may make the WorldSID dummies unsuitable for particular applications.

To contribute to the global evaluation of the WorldSID dummies now being undertaken, the EC let the project, described in the following report, with the following objectives:

- Review the status of the validation of the RibEye instrumentation:
- Contribute to the assessment of WorldSID-5F biofidelity by:
    - Contributing to ISO WG5 work to scale side impact biofidelity test conditions in order to make them suitable for a small female dummy
    - Contributing pendulum impactor or sled biofidelity tests to complement the biofidelity testing carried out by other contributors to the GTR WorldSID Informal Group
- Contribute to the development of injury risk functions for the WorldSID 5F by:
    - Contributing to ISO WG5 work defining injury risk functions for the WorldSID-5F
    - Contributing pendulum impactor or sled injury risk tests to complement the biofidelity testing carried out by other contributors to the GTR WorldSID Informal Group. NB: it was hoped that these tests could be conducted with a WorldSID-5F especially fitted with a RibEye system for this purpose, because this may allow a greater deflection range to be measured and therefore more injury-level tests to be conducted to improve the Aprosys injury risk functions.

It should be noted that this last objective, to use a RibEye system in the 5th percentile female WorldSID was changed during the course of the project. Unfortunately, events and development barriers meant that there was no prospect of a WorldSID-5F being fitted with RibEye, at least within the duration of the project. This meant that the project tasks which involved testing the WorldSID 5F RibEye system could not be undertaken within the project timeframe. Instead more effort was directed towards those tasks which involved biofidelity and injury risk testing with the standard 2D IR-Tracc thorax and abdomen instrumentation.

The WorldSID-5F test programme carried out for the EC by TRL consisted of 26 sled tests and 51 pendulum impacts.

Within these tests the WorldSID-5F generally performed as expected. The dummy biofidelity was shown to be outside of the ISO requirements in a number of areas. However, this performance has been demonstrated previously with the Revision 1 release of the dummy and may still represent an improvement over other, currently available, side impact dummies.

Test-to-test use of the dummy was straight forward and no significant issues occurred with the data acquisition system. However, durability is a problem when trying to achieve test severities needed in the development of injury risk functions. Sled tests were limited to impact speeds less than required for the higher severity biofidelity tests. This meant that many measurements needed for use in evaluating biofidelity or contributing to injury risk function development could only be provided via extrapolation from lower severity tests. This is far from ideal because it assumes that the behaviour of the dummy varies progressively and predictably with loading severity. This may not be true when testing close to the extremes of the mechanical tolerance for the dummy where, for instance, the dummy could be stiffer as it approaches maximum compression. It is the expectation of the authors that this limitation means that robust injury risk functions may be difficult to generate with the current dummy build level.

Results of the work carried out for this project have now been presented to the WorldSID Informal Group (IG). Based on the discussions held there, Humanetics (the WorldSID dummy manufacturer) has proposed to revise the dummy on the basis of this test work and similar findings from other groups participating in the IG. With a new design release further checks of biofidelity will be necessary. Depending on the exact modifications made an opportunity may come about to experimentally evaluate the dummy at higher severities and contribute more information to the development of improved risk functions.

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1 Introduction

1.1 Background

The WorldSID 50th percentile male crash test dummy (WorldSID-50M) was developed by a world-wide collaborative effort that was managed by the ISO WorldSID Task Force under a tri-chair representing Europe, the Americas, and Asia-Pacific. The European FP4 and FP5 projects SID-2000 and SIBER both contributed extensively to the development and evaluation of the WorldSID-50M. With an overall ISO biofidelity rating of 7.6 the WorldSID-50M offers a biofidelity improvement over other currently available side impact dummies such as the BioSID, ES-2, EuroSID-1 and USDOT-SID (EEVC WG12, 2009).

More recently, the WorldSID 5th percentile female dummy (WorldSID-5F) was developed by the European FP6 project APROSYS. The design of the 5F dummy was based on the 50M design with the objective to create a family of dummies that give a consistent direction to the design of vehicle safety structures and restraint systems. In order to determine biofidelity requirements for the 5F, the biofidelity requirements for the 50M were scaled by APROSYS using standard techniques. Eggers (2009) reported that the WorldSID-5F has an overall ISO biofidelity rating of 7.6, equal to the 50M. Other aspects of the WorldSID-5F dummy performance, such as repeatability and reproducibility (R&R), were intended to be comparable with the WorldSID-50M performance.

However, there are several differences between the 50M and the 5F dummies that are worthy of note, including:

- The spine box is the same width in both dummies. Because the overall width of the 5F is smaller than the 50M, the depth of the ribs in the 5F is a smaller proportion of the total torso width than is the case for the 50M. This means that there is proportionally less compression range available in the 5F.
- During the SIBER project, it was identified that the one-dimensional (1D) IR-Tracc (Infra-Red – Telescoping Rod for the Assessment of Chest Compression) rib compression instrumentation used in the WorldSID-50M underestimated the actual rib compression, and therefore the injury risk, particularly in oblique or off-axis loading conditions (Hynd *et al.*, 2004). The APROSYS project therefore took the opportunity to develop and evaluate improved rib compression instrumentation for the 5F dummy. Several options were evaluated, and a two-dimensional (2D) IR-Tracc system was designed for the dummy.
- Due to the reduced shoulder depth it was not possible to use the same arrangement of load cell and rib compression instrumentation in the shoulder rib of the 5F as had been used on the 50M. Furthermore, new biofidelity data for the upper arm had become available. The shoulder and upper arm of the 5F were updated to suit the available space and to meet the latest biofidelity target.

In parallel with the development of the WorldSID-5F, Transport Canada commissioned a new rib compression instrumentation package, called RibEye, to be installed in their 50M dummy. The WorldSID-50M RibEye system measures rib compression at three locations on each rib in three dimensions (3D), instead of the single-point measurement on each rib with the 1D and 2D IR-Traccs. This should improve the injury risk assessment for oblique and off-axis loads. Furthermore, the z-axis motions are also measured. Edwards *et al.* (2010) reported that this system offered significant advantages over other rib deflection measurement systems, although several issues related to the integration of the RibEye in the dummy, robustness and calibration were also noted.

1.2 Project Objectives

The objectives of this project were to:

- Task 1: Review the status of the validation of the RibEye instrumentation:
    - Document the evidence for the performance of the RibEye system as a measurement instrument
    - Briefly review the available injury information that could be used to enhance the prediction of injury risk using the additional information measured by RibEye, and
    - If necessary, test the performance of the RibEye system in the WorldSID 5F
- Task 2: Contribute to the assessment of WorldSID-5F biofidelity by:
    - Contributing to the ISO WG5 work to scale side impact biofidelity test conditions
    - Contributing pendulum impactor or sled biofidelity tests to complement the biofidelity testing carried out by other contributors to the GTR WorldSID Informal Group
- Task 3: Contribute to the development of injury risk functions for the WorldSID 5F by:
    - Contributing to the ISO WG5 work to define injury risk functions for the WorldSID-5F, including the scaling of test results to the 5F
    - Contributing pendulum impactor or sled injury risk tests to complement the biofidelity testing carried out by other contributors to the GTR WorldSID Informal Group. NB: it was hoped that these tests could be conducted with a WorldSID-5F fitted with a RibEye system, because this may allow a greater deflection range to be measured and therefore more injury-level tests to be conducted to improve the Aprosys injury risk functions. Using the RibEye would also allow both 1D and 2D IR-Tracc risk functions to be calculated if these are chosen for the regulatory version of the dummy.

It should be noted that this last objective, to use a RibEye system in the 5th percentile female WorldSID was changed during the course of the project. Both the WorldSID-50M and 5F dummies were originally developed by FTSS. However, in the merger between FTSS and Denton, the successor company, Humanetics, became the exclusive manufacturer of the WorldSIDs. Preliminary discussions had been held with FTSS Delft and Boxboro Systems (who manufacture the RibEye) regarding the feasibility of implementing a RibEye system in the 5F. These discussions were placed on hold when FTSS Delft went into administration in January 2011. Discussions restarted at the beginning of March, once the transfer of responsibility for work on WorldSID had transferred to Humanetics. At the 5th WorldSID GTR Informal Group meeting in Brussels in March, TRL presented the current status of these negotiations. As distributor of dummy-based RibEye systems at that time, Humanetics presented on the RibEye system, including announcing an upgrade from the model used on the Transport Canada dummy (8700) to the model 10000. This system reportedly had the following improvements:

- Greater field of view, which should improve the measurement range
- Better durability of the connectors to the data acquisition system
- Updated control via the data acquisition system, or the RibEye software

As both WorldSID-5F manufacturer and RibEye distributor, the representative from Humanetics confirmed that technical and funding issues meant that implementing RibEye in the WorldSID-5F was not a priority for them, and would be unlikely to happen in the near term. Since this point there has been no change in this situation. As a result there was no prospect of a WorldSID-5F being fitted with RibEye within the duration of the project. This meant that the project tasks involving testing the WorldSID-5F RibEye system could not be undertaken. Instead more effort was directed towards those tasks involving biofidelity and injury risk testing. It should be noted that without the RibEye system the testing has the following limitations:

- The standard WorldSID-5F thorax and abdomen instrumentation option is the 2D IR-Tracc. Injury risk functions for the 2D and 1D IR-Traccs can be calculated from this data, for the lateral measurement point. No assessment of rib compression at other measurement points can be made.
- Repeat tests were proposed for some of the biofidelity and injury risk test conditions in order to provide some assessment of the repeatability of the dummy and of the RibEye measurements. These repeat tests will still be run, but can clearly only provide information on the repeatability of the dummy and the standard thorax and abdomen compression instrumentation.

By the time the decision had been taken within the project that it was unrealistic to expect to be able to use the RibEye measurement system, the initial desk-based tasks concerning the review of other RibEye installations had already been completed. These tasks are reported here for completeness. It is hoped that the information contained within those sections still serves as a useful summary of the literature and reference for future work in this area.

2 RibEye Review

2.1 Published information

A review of the literature was carried out to find published information about existing RibEye chest deflection measurement systems. This review included considering information about the implementation of RibEye in the WorldSID 50th percentile male dummy as well as in other dummies (e.g. Hybrid III frontal and SID-IIs small female side impact dummies).

Each installation of RibEye in a dummy will have some functional features which have been tailored for that dummy and are therefore installation specific. However, there are some other performance features which are intrinsic for any RibEye system of a certain type (e.g. 2D or 3D) and can be established prior to installation.

The exact measurement range available with a RibEye system will depend on the constraints of the chest cavity into which it is sited. The exact range should be measured and reported for each installation as has been done previously via the User’s Manual.

There is still a need to derive the exact RibEye system accuracy in situ. Some suggestions regarding experimental design to determine the accuracy were obtained from previous accuracy evaluations. Typically the accuracy tends to better than 1 to 2 mm, depending on which type of system is installed and the conditions under which it is evaluated.

Finally, it seems as though prove-out testing would be valuable to determine when any measurement drop-outs could occur and if the measurement range is sufficient for the end application.

Further information on the status of the RibEye literature review may be found in Appendix A.1 and A.2.

3 WorldSID 5F Testing

The following sections of the report concern the TRL test work undertaken with the WorldSID-5F. This testing was carried out to contribute to the assessment of the WorldSID-5F biofidelity and to help in the development of injury risk functions for the dummy. This work was performed whilst collaborating closely with ISO Working Group 5 and their efforts to define the biofidelity and injury risk functions for use with the WorldSID-5F.

Pendulum and sled tests were carried out at TRL with this dummy. In addition, an initial study was undertaken to check the calibration of the 2D IR-Traccs used in the dummy for measuring chest deformations. The methods used and the results derived from the ensuing tests are described in the next few sections.

3.1 Pendulum testing

This section of the report describes pendulum impactor testing to support the harmonised worldwide efforts to define the biofidelity of WorldSID-5F and to help provide dummy measurements to be used in the development of injury risk functions for the dummy.

The pendulum tests to be replicated for injury risk function development are described in ISO Technical Report 12350:2010E (ISO, 2010). The tests carried out at TRL are described below.

3.1.1 INRETS shoulder tests

INRETS conducted a series of shoulder impactor tests. In the original testing, each PMHS was seated upright, without back support. The subject was placed facing sideways in front of the impactor, upright on a table covered with two Teflon sheets and held in position by a cable attached to an electromagnet. Therefore for the dummy testing it was also suspended via an electromagnet, until just before impact, to keep the torso upright. Where an upright position with the WorldSID 5F is described, the thorax tilt sensor was positioned to read 20 degrees, approximately.

For the PMHS tests, the impactor face was centred on the glenohumeral joint. Each subject was impacted in the pure lateral direction, 15° rearward of lateral, and 15° forward of lateral. These three impact configurations were reproduced. For the WorldSID 5th in the lateral test, the impactor alignment was 17 mm anterior and 4 mm superior to the centre of the three arm mounting bolts.

The impactor speed for the oblique tests was 1.5 m/s. The pure lateral tests were conducted at the three different speeds; 1.5, 3.5 and 6 m/s.

Figure 3-1: Impactor test configuration from the lateral and oblique-lateral shoulder impacts conducted by INRETS

3.1.2 WSU shoulder tests

The Wayne State University (WSU) conducted a series of impactor tests to the shoulder. Each PMHS was seated on a plastic sheet on a wooden seat, without back support. The position of the PMHS head was maintained by light tension to webbing that was taped to the subject’s head. The webbing was attached to a ring that slid off of a hook during impact to minimize the effect on PMHS movement. For the dummy testing an electromagnet was used again to suspend the dummy prior to impact.

For the PMHS the impact face was centred on the acromion of the subject and each PMHS was impacted in the pure lateral direction. To give a similar alignment for the WorldSID-5F, the centre of impactor should be aligned 43.5 mm superior to (vertically above) the centre of the three arm mounting bolts.

The test speed for the WSU impacts was 4.5 m/s.

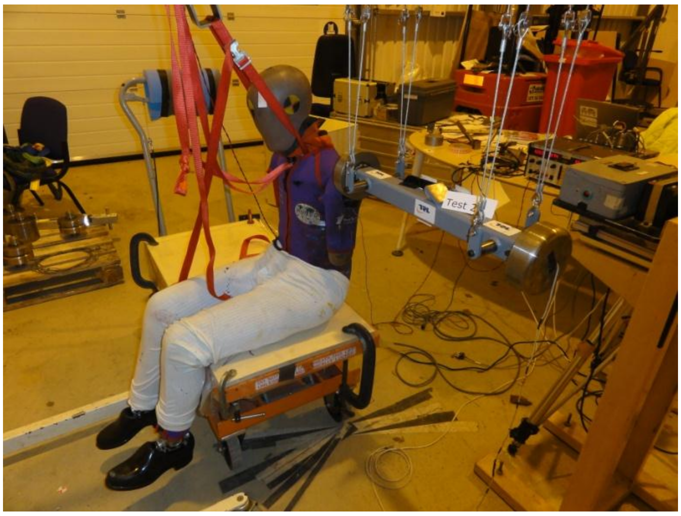


Figure 3-2: Impactor test configuration from the lateral shoulder impacts conducted by WSU

3.1.3 ISO TR 9790 Shoulder Test 1

Shoulder Test 1 in the ISO Technical Report 9790 is based on impactor tests conducted by the APR using unembalmed PMHS. Researchers of the APR subjected four PMHS to a lateral impact delivered to the shoulder. Each PMHS was seated on a horizontal hardwood surface with a vertical backrest. For the dummy tests, a sheet of ash was mounted on top of the height adjustable bench to simulate this interaction.

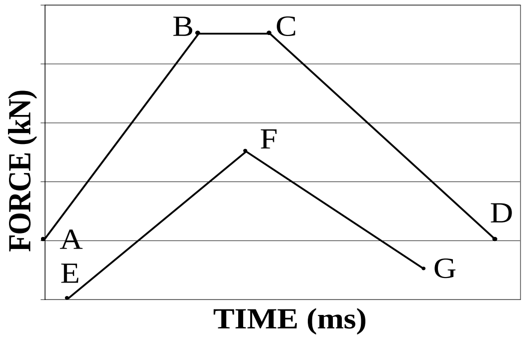
The PMHS's hands were placed on its lap and the arm on the impacted side was suspended as if supported by an armrest. For the replication, the impact was delivered laterally to the shoulder with the dummy’s half arms down by the side of the thorax. The axis of the impactor was aligned with the centre of the shoulder joint (the centre of the three arm mounting bolts). The impact velocity was 4.45 m/s.

Biomechanical response targets for the shoulder impact condition are summarised in Tables 3-1 and 3-2. These requirements were initially documented with the development of the WorldSID-5F as part of the APROSYS Project (Barnes *et al.*, 2005). They were derived in accordance with ISO TR9790 and scaled with the ratios proposed by Irwin *et al.* (2002).

Table 3-1: Biomechanical response shoulder test

Impact condition	Measurement	Units	Lower bound	Upper bound
Pendulum shoulder impact, 4.5 m/s, 14 kg	Peak shoulder deflection	mm	28	33

Table 3-2: Biomechanical response shoulder test: Response corridor

		**Pendulum shoulder impact, 4.5 m/s, 14 kg**	
		Time (ms)	**Pendulum force (kN)**
Upper boundary coordinates	A	0	1.2
	B	5	2.0
	C	21	2.0
	D	47	0.7
Lower Boundary coordinates	E	0	0
	F	11	1.2
	G	34	0.4

The ISO TR 9790 biofidelity requirements specify the use of a 14 kg pendulum impactor. However, the ISO TR 12350 specifications for these shoulder impacts in injury risk development testing require the use of a 14.7 kg pendulum. This difference arises because the biofidelity requirements are scaled down from the mid-size male to the small female whereas the injury risk tests are scaled down from a set of PMHS tests instead of the generic mid-size. As this test type was primarily identified for injury risk function development, the dummy was tested with a 14.7 kg pendulum. It is expected therefore that the force and deflection recorded in these tests are greater than would be the case if the test had been performed with the prescribed 14 kg impactor. This will influence the fit of the dummy responses with the biofidelity requirements.

3.1.4 ISO TR 9790 Thorax Test 1

Thorax Tests 1 and 2 from ISO TR 9790 are based on PMHS impactor tests conducted by the Highway Safety Research Institute (HSRI) and the Wayne State University (WSU) for the General Motors Research Laboratories (GMR), respectively.

For Thorax Test 1 tests the dummy was seated upright with its arm raised so that the side of its thorax was clear to be impacted. The dummy was again suspended from an electromagnet to maintain an upright torso posture prior to impact. The dummy was seated on a flat, horizontal, stainless steel surface. A lap belt was used to restrain the dummy, anchored to the surface on which the dummy is seated with a separation between the anchorage points of about 400 mm.

The face of the impactor was centred on the lateral aspect of the thoracic rib structure and the dummy's thorax was impacted laterally at velocities of 0.9, 4.3 and 6.1 m/s.

Regarding the vertical alignment, additional tests were carried out to investigate whether differences can be noticed between two subtly different alignments. The two options were:

1. Align the centre of the impactor with the middle of the 2nd thoracic rib

2. Align the lower border of the impactor with the lower border of the 3rd thoracic rib

These two alignment options are depicted in Figure 3-3. Here, the blue circle shows the impactor face aligned with the middle of the mid-thoracic rib (Option 1). The red circle shows the alignment where the bottom edge of the impactor face is aligned with the bottom of THORAX rib 3 (Option 2). In either case the arm did not interfere with the thoracic loading.

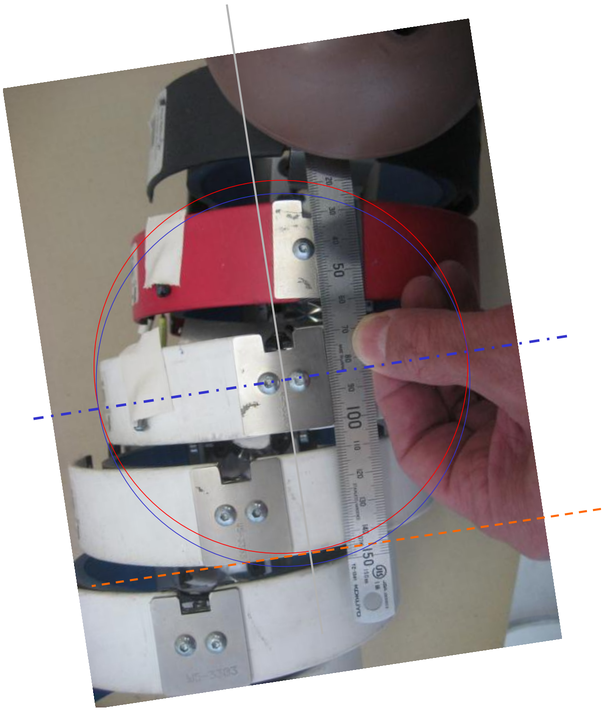


Figure 3-3: Impactor face alignment for ISO TR 9790 thoracic tests.

The biofidelity requirements from the thorax pendulum tests are again taken from the APROSYS Project (Barnes *et al.*, 2005).

**Table 3-3: Biomechanical response thorax test:
Pendulum force response corridor**

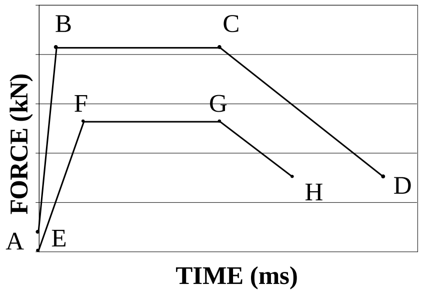
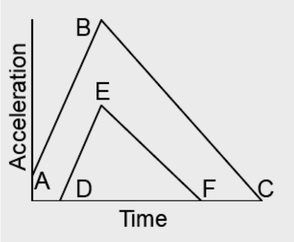
		**Pendulum thorax impact, 4.3 m/s, 14 kg**	
		Time (ms)	**Pendulum force (kN)**
Upper boundary coordinates	A	0	1.2
	B	8	2.7
	C	25	2.7
	D	37	1.5
Lower Boundary coordinates	E	0	0.0
	F	8	1.2
	G	25	1.2
	H	33	0.0

Table 3-4: Biomechanical response thorax test:
Upper thorax acceleration response corridor

		**Pendulum thorax impact, 4.3 m/s, 14 kg**	
		Time (ms)	**Upper thoracic spine acceleration (*g*)**
Upper boundary coordinates	A	0	2
	B	12	18
	C	41	0
Lower Boundary coordinates	D	5	0
	E	12	10
	F	30	0

As noted in the previous section on the shoulder test, these thorax requirements specify the use of a 14 kg pendulum impactor. However, because the results from this test type are also useful for injury risk function development, the dummy was tested with a 14.7 kg pendulum. Again, it is expected that the force and deflection recorded in these tests are greater than would be the case if the test had been performed with the prescribed 14 kg impactor.

3.1.5 WSU/GM thorax tests

The test set-up for the Wayne State University and General Motors (WSU/GM) tests is very similar to that used for the ISO (HSRI-based) tests. The dummy was seated with the torso upright. However, the surface of the height adjustable table was covered in a single sheet of PTFE.

The key difference between these and the other thorax tests, was the requirement to conduct these obliquely, 30 degrees forward of lateral. This was achieved by sitting the dummy on the bench normally, then rotating the bench through 30 degrees relative to the line of the pendulum action (so as to twist the dummy about its z-axis). The alignment then translated around the thorax so as to still be centred horizontally to strike the most lateral aspect of the thorax. The vertical alignment was the same as the previous tests, taking the approach of picking the level which would be centred with the middle of the middle thoracic rib, if it had been struck laterally.

The impact speed for this test configuration was 6 m/s. Additionally, the original tests also indicate that a test at 8.7 m/s should be carried out. This higher test speed was not possible within the facility at TRL and without the likelihood of causing damage to the dummy and its instrumentation. Therefore, alternative tests were carried out to support the scaling up of results to predict output at 8.7 m/s.

The alternative tests carried out were performed at tests speeds of 2, 3, 4, 5, 5.5 and 6 m/s. The y-displacements and resultant displacements against time for these tests are shown in Figure 3-4. The Peak y-displacement and peak resultant displacement against test speed are shown in Figure 3-5.

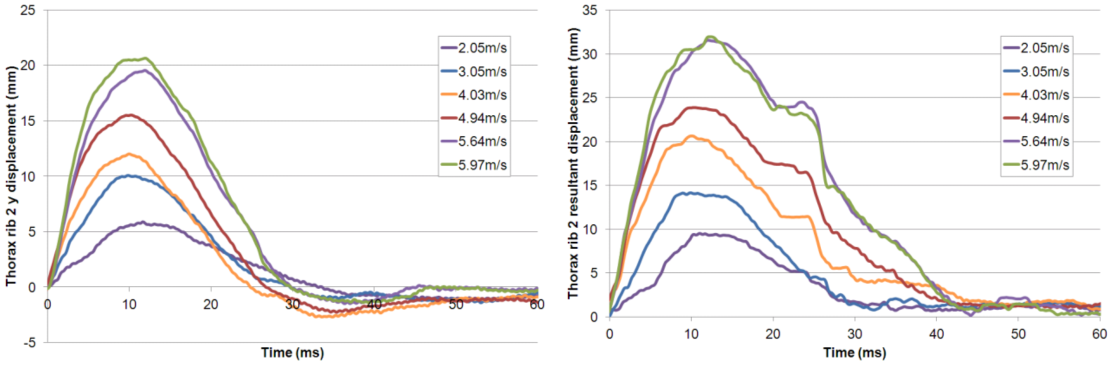


Figure 3-4: Thorax rib 2 y-displacement and resultant displacement against time in WSU/GM thorax pendulum tests at various test speeds

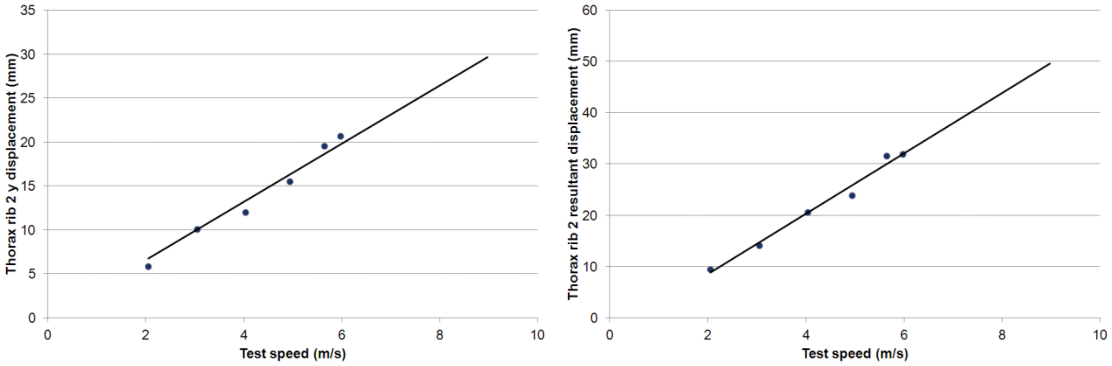


Figure 3-5: Peak y-displacement and peak resultant displacement against test speed for WSU/GM thorax pendulum tests

The results show that there are a reasonable linear correlation between test speeds and rib displacement, therefore it may be possible to use this method for extrapolation to higher test speeds.

3.1.6 UMTRI thorax tests

UMTRI conducted a series of impactor tests to the thorax of PMHS. Each PMHS was suspended in a seated position, either with the arms positioned above the shoulder and the hands above the head or with the arms down. The metal impact face had various materials affixed to it to produce different force-time histories and load distributions. Only the bare-faced impactor tests were reproduced with the WorldSID-5F.

For these tests the impact face was aligned with the mid-sternum in the vertical direction and midway between the front and the back of the subject in the fore-aft direction. For the WorldSID 5th this would correspond to a position 50 mm lower than the arm mounting bolt. The test speed was 2 m/s with a pure lateral impact direction.

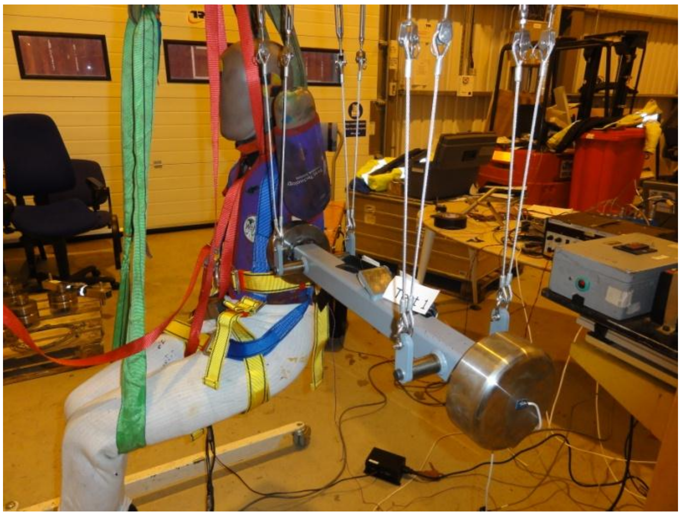


Figure 3-6: Impactor test configuration from the lateral thorax impacts as conducted by UMTRI

3.1.7 WSU/GM pelvis tests

WSU conducted a series of impactor tests to the pelvis of PMHS. Each PMHS was suspended in a standing position, with the arms positioned above the shoulder and the hands above the head. For the pelvis impacts, the impact face was centred on the greater trochanter. For the WorldSID 5th this was reproduced with the impactor aligned 9 mm forward and 29 mm inferior (downwards) to the H-point.

This test series required a test at 10m/s, however this speed cannot be reached by the TRL pendulum. Therefore a series of tests were performed at lower speeds to investigate whether the data can be extrapolated to higher speeds. The tests speeds chosen were 3, 4, 5, 6 and 7 m/s.

Figure 3-7 shows the lateral acceleration and pubic force against time, Figure 3-8 shows the lateral acceleration and pubic force against test speed, Figure 3-9 shows the left lateral acceleration and pubic force against time, and Figure 3-10 shows the Left iliac lateral force and left iliac x moment against test speed.

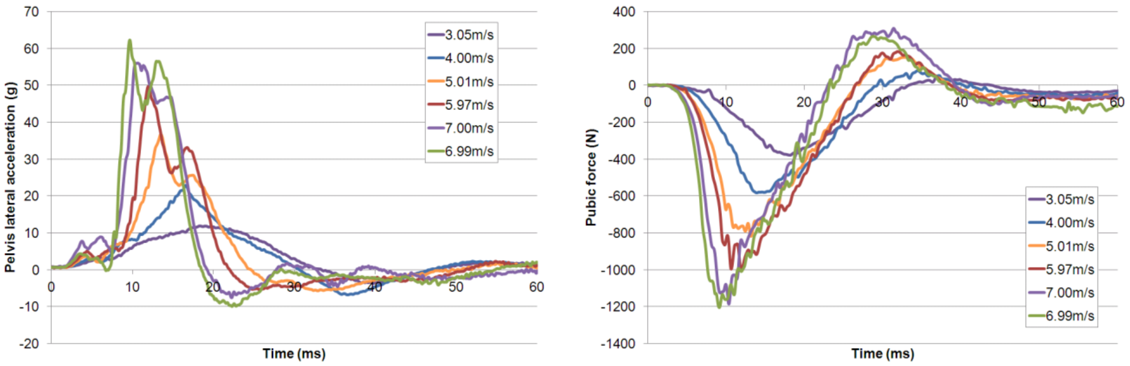


Figure 3-7: Pelvis lateral acceleration and pubic force against time for WSU/GM pelvis tests at various test speeds

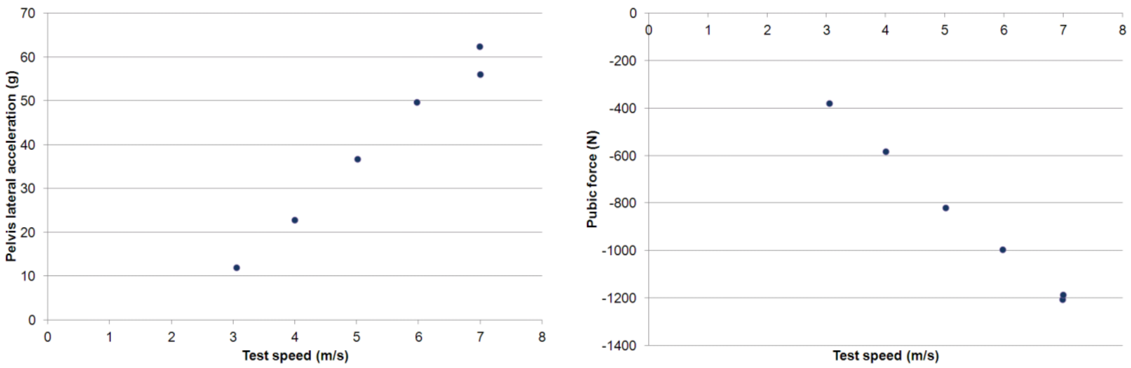


Figure 3-8: Pelvis lateral acceleration and pubic force against test speed for WSU/GM pelvis tests

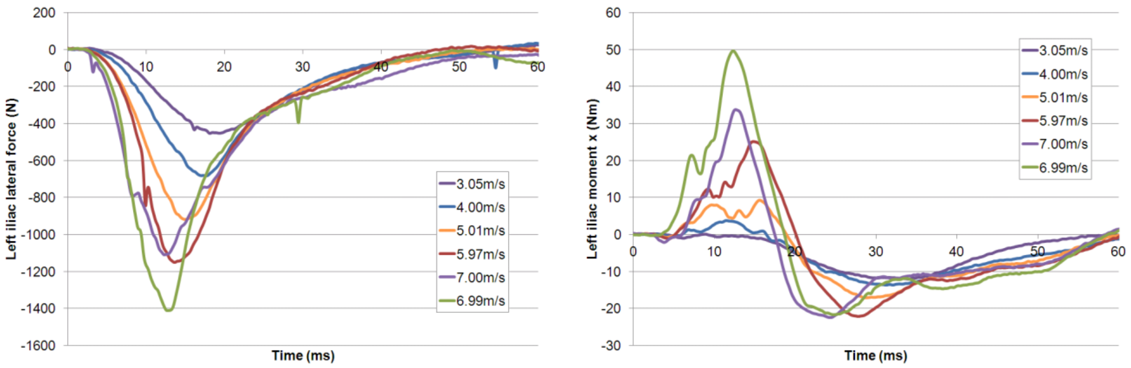


Figure 3-9: Left lateral acceleration and pubic force against time for WSU/GM pelvis tests at various test speeds

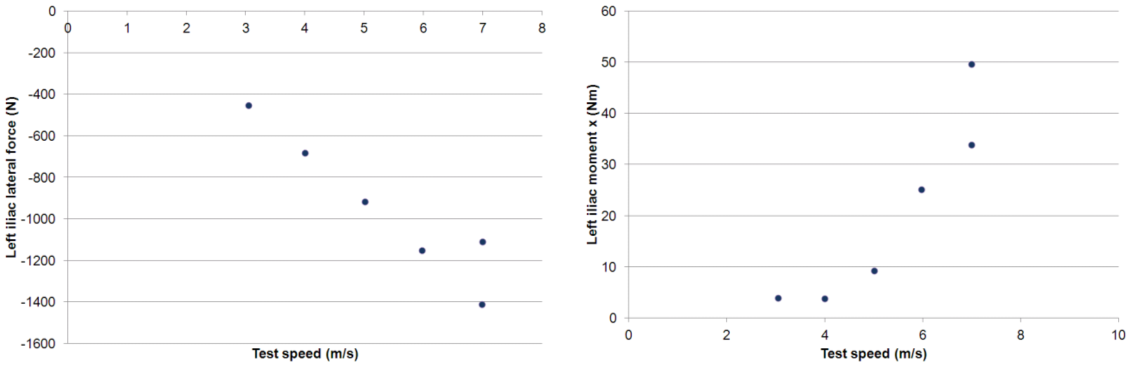


Figure 3-10: Left iliac lateral force and left iliac x moment against test speed for WSU/GM pelvis tests

The results show that there is a linear correlation, however this would not pass through the origin, and therefore at test speeds lower than 3m/s the extrapolation may not be accurate enough.

3.1.8 *Test matrix*

Based on the tests described in the sections above, a test matrix was composed. This matrix of TRL pendulum tests is shown in Table 3-5.

Table 3-5: TRL pendulum test matrix

Test number	Configuration	Impact site	Impactor	Speed	Direction
1	UMTRI	Thorax	Circular, 130 mm, 15.7 kg	2	Lateral
2	As 1				
3	UMTRI	Thorax – but with arms down	Circular, 130 mm, 15.7 kg	2	Lateral
4	As 3				
5	ISO (HSRI)	Thorax	Circular, 130 mm, 14.7 kg	0.9	Lateral
6	As 5				
7	ISO (HSRI)	Thorax – alternative alignment	Circular, 130 mm, 14.7 kg	0.9	Lateral
8	As 7				
9	ISO (HSRI)	Thorax	Circular, 130 mm, 14.7 kg	4.3	Lateral
10	As 9				
11	ISO (HSRI)	Thorax – alternative alignment	Circular, 130 mm, 14.7 kg	4.3	Lateral
12	As 11				
13	ISO (HSRI)	Thorax	Circular, 130 mm, 14.7 kg	6.1	Lateral
14	As 13				
15	ISO (HSRI)	Thorax – alternative alignment	Circular, 130 mm, 14.7 kg	6.1	Lateral
16	As 15				
17	ISO (APR)	Shoulder	Circular, 130 mm, 14.7 kg	4.5	Lateral
18	As 17				
19	WSU	Shoulder	Circular, 130 mm, 14.7 kg	4.5	Lateral
20	As 19				

21	INRETS	Shoulder	Rectangular, 70 x 114 mm, 14.7 kg	1.5	Lateral
22	As 21				
23	INRETS	Shoulder	Rectangular, 70 x 114 mm, 14.7 kg	1.5	Oblique 15° rearward
24	As 23				
25	INRETS	Shoulder	Rectangular, 70 x 114 mm, 14.7 kg	1.5	Oblique 15° forward
26	As 25				
27	INRETS	Shoulder	Rectangular, 70 x 114 mm, 14.7 kg	3.5	Lateral
28	As 27				
29	INRETS	Shoulder	Rectangular, 70 x 114 mm, 14.7 kg	6	Lateral
30	As 29				
31	WSU/GM	Thorax	Circular, 130 mm, 14.7 kg	2	Oblique 30° forward
32	WSU/GM	Thorax	Circular, 130 mm, 14.7 kg	3	Oblique 30° forward
33	WSU/GM	Thorax	Circular, 130 mm, 14.7 kg	4	Oblique 30° forward
34	WSU/GM	Thorax	Circular, 130 mm, 14.7 kg	5	Oblique 30° forward
35	WSU/GM	Thorax	Circular, 130 mm, 14.7 kg	6	Oblique 30° forward
36	WSU/GM	Thorax	Circular, 130 mm, 14.7 kg	5.5	Oblique 30° forward
37	WSU/GM	Pelvis – suspended	Circular, 145 mm, 14.7 kg	3	Lateral

38	WSU/GM	Pelvis – suspended	Circular, 145 mm, 14.7 kg	5	Lateral
39	WSU/GM	Pelvis – suspended	Circular, 145 mm, 14.7 kg	6	Lateral
40	WSU/GM	Pelvis – suspended	Circular, 145 mm, 14.7 kg	7	Lateral
41	WSU/GM	Pelvis	Circular, 145 mm, 14.7 kg	3	Lateral
42	WSU/GM	Pelvis	Circular, 145 mm, 14.7 kg	6	Lateral
43	WSU/GM	Pelvis	Circular, 145 mm, 14.7 kg	5	Lateral
44	WSU/GM	Pelvis	Circular, 145 mm, 14.7 kg	7	Lateral
45	WSU/GM	Pelvis	Circular, 145 mm, 14.7 kg	4	Lateral
46	WSU/GM	Pelvis	Circular, 145 mm, 14.7 kg	7	Lateral
47	WSU/GM	Pelvis - upgrade	Circular, 145 mm, 14.7 kg	3	Lateral
48	WSU/GM	Pelvis – upgrade	Circular, 145 mm, 14.7 kg	4	Lateral
49	WSU/GM	Pelvis - upgrade	Circular, 145 mm, 14.7 kg	5	Lateral
50	WSU/GM	Pelvis - upgrade	Circular, 145 mm, 14.7 kg	4	Lateral
51	WSU/GM	Pelvis - upgrade	Circular, 145 mm, 14.7 kg	6	Lateral

3.2 Sled testing

The objective of the sled testing phase was to test the WorldSID-5F under the conditions defined by ISO Working Group 6 for the assessment of biofidelity and in the development of injury risk functions for the dummy. This work is expected to contribute to the UNECE GRSP Informal Group evaluating the WorldSID for potential use in future regulations.

A test bench as fitted to the impact sled used in the biofidelity testing was commissioned by TRL specifically for this work.

The sled consisted of a standard trolley on which the bench seat and a load cell were mounted. The total mass of the sled was 1,400 kg.

The seat, including foot-well and foot-board, were covered with PTFE tape and the dummy's back and thighs were supported on cardboard sheets backed with PTFE tape, such that PTFE to PTFE contact was made.

3.2.1 Test types

Currently, there are three sled test conditions selected by ISO for use in the biofidelity assessment of and injury risk function development for side impact dummies. These conditions are taken from test series conducted with PMHS (post-mortem human subjects) which have been reported in the literature. The three conditions can be described by the laboratory at which the work was undertaken, and are:

- Heidelberg (University of…)
- WSU (Wayne State University)
- MCW (Medical College of Wisconsin)

The sled bench design developed for this project is capable of replicating the set-up conditions of all three test types. The following sections introduce details from the original test work and serve to highlight the similarities and differences between each.

3.2.1.1 Heidelberg

The oldest of the three test conditions is that reported by Marcus *et al.* (1983) . The sled rig used at the University of Heidelberg incorporated load cells in the wall of the sled.

The specific conditions used in the original tests were either:

- 24 km/h rigid wall
- 32 km/h rigid wall
- 40 km/h rigid wall
- 32 km/h padded wall

It was intended to recreate the rigid wall tests at both 24 km/h (6.7 m/s) and 32 km/h (8.9 m/s).

The geometry of the sled used for the testing is shown in Figure 3-11. This uses a geometry similar to that published in an EEVC review (Roberts *et al.*, 1991). The exact load plate geometry was scaled down from the original to make it more appropriate for testing with the WorldSID-5F.

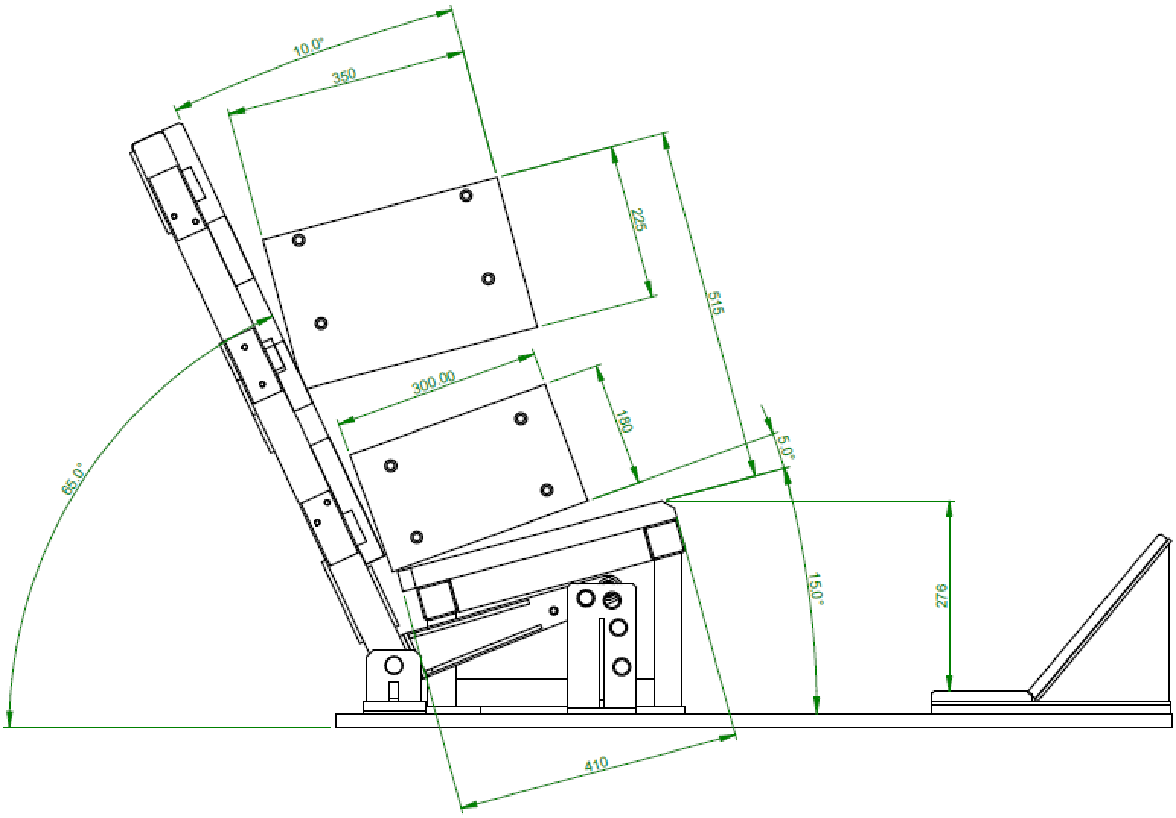


Figure 3-11: University of Heidelberg force measuring sled

The Heidelberg sled condition is used to assess the biofidelity of side impact dummies, according to ISO TR 9790 (ISO, 1999). A 6.8 m/s test is defined as Thorax Test 5 and Pelvis Test 7 in that document, whilst a 8.9 m/s test forms Pelvis Test 8.

Table 3-6: Biomechanical response thorax test

Impact condition	Measurement	Units	Lower bound	Upper bound
Thorax test, 6.8 m/s, rigid sled	Peak lateral acceleration of the upper spine	*g*	100	149
	Peak lateral acceleration of the lower spine	*g*	87	131
	Peak lateral acceleration of the impacted rib (according to the 4th rib of the adult male	*g*	78	122

Table 3-7: Biomechanical response thorax test: Response corridor

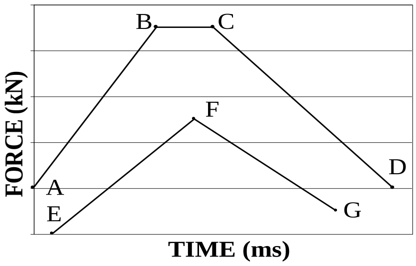
		Thorax test, 6.8 m/s, rigid sled	
		Time (ms)	Thorax plate force (kN)
Upper boundary coordinates	A	0	1.5
	B	8	12.4
	C	13	12.4
	D	41	1.8
Lower Boundary coordinates	E	11	0.0
	F	16	3.7
	G	25	0.0

Table 3-8: Biomechanical response pelvis test (7)

Impact condition	Measurement	Units	Lower bound	Upper bound
Pelvis test, 6.8 m/s, rigid sled	Peak pelvis force	kN	4.6	5.6
	Peak pelvic acceleration	*g*	78	95

Table 3-9: Biomechanical response pelvis test (8)

Impact condition	Measurement	Units	Lower bound	Upper bound
Pelvis test, 8.9 m/s, rigid sled	Peak pelvis force	kN	16.2	19.1
	Peak pelvic acceleration	*g*	119	143

3.2.1.2 Wayne State University

According to Cavanaugh *et al.* (1993), the subjects from the WSU tests were positioned on a Heidelberg-type seat fixture. The seat was mounted to a sled and accelerated up to velocities of 6.7 to 10.5 m/s. The sled was then slowed rapidly so that the subjects would continue to translate laterally on a Teflon seat into the side wall of the sled fixture.

The tests recreated at TRL were rigid wall tests with speeds of either 6.3 or 8.9 m/s.

As in the original tests, the subject sat against a two-bar seat back. The WorldSID-5F half-arms were positioned slightly anteriorly to the mid-axillary line so that they did not bridge over the thorax ribs.

Figure 3-12: WSU side impact sidewall showing beams at four levels plus knee load plate

The WSU sled condition is also used to assess the biofidelity of side impact dummies, according to ISO TR 9790. The requirements for the abdomen include assessment in a WSU 6.8 m/s and 8.9 m/s rigid wall impact. The 6.8 m/s test is defined as Thorax Test 5 and Pelvis Test 10 in that document, whilst the 8.9 m/s test forms Pelvis Test 11.

Table 3-10: Biomechanical response abdomen test (3): Response corridor

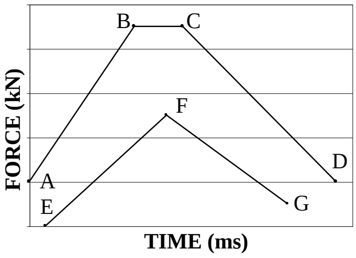
		**Abdomen impact, 6.8 m/s, rigid sled**	
		Time (ms)	**Abdomen plate force (kN)**
Upper boundary coordinates	A	0	0.4
	B	4	2.6
	C	25	2.6
	D	37	0.7
Lower Boundary coordinates	E	0	0.0
	F	15	1.5
	G	31	0.7

Table 3-11: Biomechanical response abdomen test (4): Response corridor

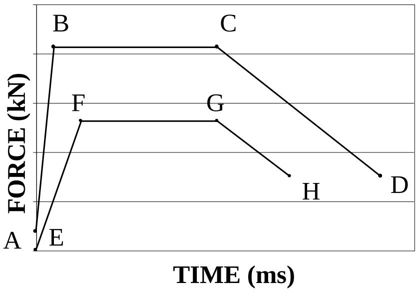
		Abdomen impact, 8.9 m/s, rigid sled	
		Time (ms)	Thorax plate force (kN)
Upper boundary coordinates	A	0	0.4
	B	2	4.0
	C	16	4.0
	D	31	1.5
Lower Boundary coordinates	E	0	0.0
	F	4	2.6
	G	16	2.6
	H	23	1.5

Table 3-12: Biomechanical response pelvis test (10)

Impact condition	Measurement	Units	Lower bound	Upper bound
Pelvis test, 6.8 m/s, rigid sled	Peak lateral pelvic acceleration	*g*	105	142

Table 3-13: Biomechanical response pelvis test (11)

Impact condition	Measurement	Units	Lower bound	Upper bound
Pelvis test, 8.9 m/s, rigid sled	Peak lateral pelvic acceleration	*g*	137	187

Table 3-14: Biomechanical response pelvis test (10): Response corridor

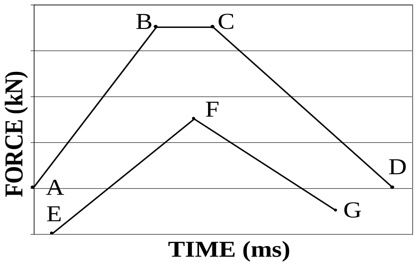
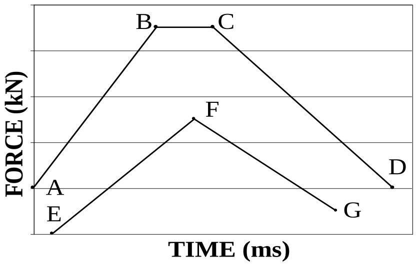
		Pelvis test, 6.8 m/s, rigid sled	
		Time (ms)	Pelvic plate force (kN)
Upper boundary coordinates	A	0	0.7
	B	8	5.4
	C	16	5.4
	D	24	2.2
Lower Boundary coordinates	E	4	0.0
	F	12	4.0
	G	24	0.0

Table 3-15: Biomechanical response pelvis test (11): Response corridor

		Pelvis test, 8.9 m/s, rigid sled	
		Time (ms)	Pelvic plate force (kN)
Upper boundary coordinates	A	0	2.9
	B	4	9.4
	C	8	9.4
	D	12	5.1
Lower Boundary coordinates	E	2	0.0
	F	6	7.2
	G	12	2.9

3.2.1.3 *Medical College, Wisconsin*

The Medical College of Wisconsin (MCW) and the NHTSA Vehicle Research and Test Centre (VRTC) performed a suite of side impact tests. According to Maltese *et al.* (2002), they were conducted at two different speeds (6.7 and 8.9 m/s), with and without impact surface padding, and using a variety of impact wall geometries. At TRL only the rigid wall tests were reproduced.

The sled apparatus was of the Heidelberg design. Test subjects were seated on the bench of the side impact sled approximately one metre from the load wall. Just after the sled achieved the prescribed velocity change, the occupant contacted the load wall. The TRL recreation of the MCW conditions incorporated the load cell wall on the sled.

The load wall for the MCW tests was divided into four sections, one each to contact the thorax, abdomen, pelvis and legs (Figure 3-13). The change in sled velocity was either 6.7 or 8.9 (± 0.3) m/s. The geometry of the load wall was also a variable. Load plates were either fixed in the same plane, or the thoracic or pelvic plate was offset, one at a time per test, toward the occupant, by 83 and 114 mm respectively. In flat wall and pelvic offset tests, the WorldSID-5F was seated with arms down, such that the arm was interposed between the thorax and load wall. In thoracic and abdominal offset tests, arms were raised to expose the thorax and abdomen directly to impact from the load wall.

Figure 3-13: MCW/VRTC side impact buck showing load plates for the thorax, abdomen, pelvis and leg

3.2.2 *Test matrix*

Based on the sled tests described above, another test matrix was composed. The matrix of TRL sled tests is shown in Table 3-16.

Table 3-16: Sled test matrix

Test number	Test type	Impact speed (m/s)	Impact wall configuration	Seat back angle (degrees)
1	WSU	5	Shoulder, thorax, abdomen, pelvis, knee - rigid	
2	WSU	6.3	"	100
3	WSU	5	"	100
4	WSU	5	"	100 – arm up
5	WSU	5.5	"	100
6	WSU	4	"	100
8	WSU	5	Pelvis offset	100
9	WSU	5	"	100
10	MCW	5	Thorax, abdomen, pelvis, leg - rigid	97
11	MCW	5	"	97
12	MCW	5.5	"	97
13	MCW	4	"	97
14	MCW	3	"	97
15	MCW	5	Pelvis offset	97
16	MCW	4	Pelvis offset	97
17	MCW	5	Thorax offset	97
18	Heidelberg	5	Thorax and pelvis plates - rigid	100
19	Heidelberg	5	"	100
20	Heidelberg	5	"	100
21	MCW	5	Abdomen plate only	90
22	MCW	5	"	90
23	MCW	5	"	90 forced pelvis-rib interaction
24	MCW	5	"	90 forced pelvis-rib interaction
25	MCW	5	"	90 cutaway pelvis flesh
26	MCW	5	"	90 cutaway pelvis flesh

4 WorldSID-5F results

4.1 WorldSID-5F shoulder impactor test results

The following table (Table 4-1) summarises the dummy data from the shoulder impactor tests, now available for use in the construction of shoulder injury related risk curves.

Table 4-1: Dummy shoulder impactor test results to be used for the construction of the injury risk curve

PMHS test condition	WorldSID-5F test number	Actual impact speed (m/s)	WorldSID-5F peak shoulder deflection (mm) (CFC_600)
APR lateral impact by 14.7 kg rigid impactor at 4.5 m/s (130 mm diameter circular impact face)	TRL Test 17	4.43	30.8
	TRL Test 18	4.46	31.3
	Mean at 4.5 m/s	4.45	31.1
WSU lateral impact by 14.7 kg rigid impactor at 4.5 m/s (130 mm diameter circular impact face)	TRL Test 19	4.43	25.9
	TRL Test 20	4.43	24.2
	Mean at 4.5 m/s	4.43	25.0
INRETS lateral impact by 14.7 kg rigid impactor at 1.5 m/s (114 mm by 70 mm rectangular impact face)	TRL Test 21	1.52	8.6
	TRL Test 22	1.51	8.8
	Mean at 1.5 m/s	1.52	8.7
INRETS 15° rearward of lateral impact by 14.7 kg rigid impactor at 1.5 m/s (114 mm by 70 mm rectangular impact face)	TRL Test 23	1.51	5.4
	TRL Test 24	1.498	6.6
	Mean at 1.5 m/s	1.50	6.0
INRETS 15° forward of lateral impact by 14.7 kg rigid impactor at 1.5 m/s (114 mm by 70 mm rectangular impact face)	TRL Test 25	1.497	8.4
	TRL Test 26b	1.53	8.3
	Mean at 1.5 m/s	1.51	8.4
INRETS lateral impact by 14.7 kg rigid impactor at 3.5 m/s (114 mm by 70 mm rectangular impact face)	TRL Test 27b	3.5	22.2
	TRL Test 28	3.52	19.8
	Mean at 3.5 m/s	3.51	21.0
INRETS lateral impact by 14.7 kg rigid impactor at 6 m/s (114 mm by 70 mm rectangular impact face)	TRL Test 29	6.08	35.9
	TRL Test 30	6.07	40.9
	Mean at 6 m/s	6.08	38.4

4.1.1 Shoulder biofidelity

As mentioned in Section 3.1.3, the ISO (APR) shoulder test is used to assess shoulder biofidelity, according to ISO TR 9790.

The requirement for peak shoulder deflection is that the value lies between 28 and 33 mm. The filtered shoulder deflections from Tests 17 and 18 give a mean peak value of 31.1 mm. This is within the required range. However, when the responses are normalised according with the ISO description, the mean peak value drops to 25.8 mm; below the lower boundary of the requirement.

The pendulum force response also suffers through the normalisation process with the filtered responses prior to normalisation lying closer to the required corridor than the normalised curves. These pendulum force results from Tests 17 and 18 are shown in Figure 4-1.

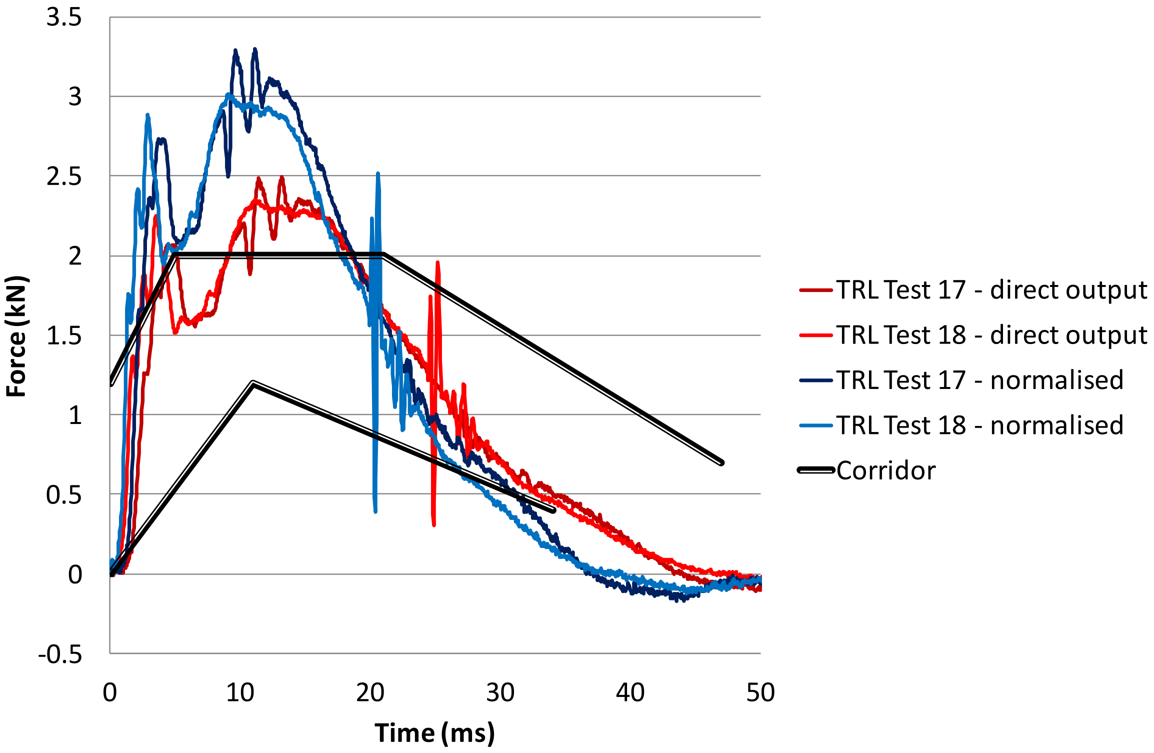


Figure 4-1: Shoulder test pendulum force response at 4.5 m/s

As noted in Section 3.1.3 these tests were performed with a pendulum that was five percent heavier than that specified for the biofidelity evaluation. The force and deflection would be expected to be lower if conducted with the correct mass of impactor. This would help to bring the pendulum force response and the normalised shoulder deflection peak values closer to the corridor. However, the scope of the change is unlikely to bring the normalised results within the corridor.

On the basis of these results it seems as though the shoulder of the dummy is slightly too stiff.

4.2 WorldSID-5F thorax impactor test results

The following table (Table 4-2) summarises the peak rib deflection data from the thorax impactor tests, now available for use in the construction of thorax injury related risk curves. Table 4-3 shows the equivalent data for the Viscous Criterion (V*C). The rib on which the peak deflection occurred is denoted in parentheses after the peak value. For instance, "(T3)", would indicate that the peak value was registered on the third thoracic rib.

Table 4-2: Dummy thorax impactor test deflection results to be used for the construction of the injury risk curve

PMHS test condition	WorldSID-5F test number	Actual impact speed (m/s)	WorldSID-5F peak thoracic deflection (mm) (CFC_600)			
			IR-Tracc deflection (mm)	x-axis deflection (mm)	y-axis deflection (mm)	total displacement (mm)
UMTRI lateral impact by 15.7 kg impactor at 2 m/s (130 mm diameter circular impact face) – Arm up	TRL Test 01	2.02	11.9 (T2)	4.7 (T3)	12.0 (T2)	12.0 (T2)
	TRL Test 02	2.02	10.3 (T3)	9.2 (A1)	10.5 (T3)	12.2 (T3)
	Mean at 2 m/s	2.02	11.1	6.9	11.2	12.1
UMTRI lateral impact by 15.7 kg impactor at 2 m/s (130 mm diameter circular impact face) – Arm down	TRL Test 03	2.04	6.1 (A1)	3.4 (T3)	6.1 (A1)	6.7(A1)
	TRL Test 04	2.02	5.4 (A1)	5.1 (T1)	5.4 (A1)	6.5 (T3)
	Mean at 2 m/s	2.03	5.7 (A1)	5.9	5.8 (A1)	6.6
HSRI lateral impact by 14.7 kg rigid impactor at 0.9 m/s (130 mm diameter circular impact face) – Mid-thorax alignment	TRL Test 05	0.93	5.0 (T3)	2.7 (T3)	5.0 (T3)	5.5 (T3)
	TRL Test 06	0.91	3.8 (T3)	2.9 (T1)	3.8 (T3)	4.5 (T3)
	Mean at 0.9 m/s	0.92	4.4 (T3)	2.8	4.4 (T3)	5.0 (T3)
HSRI lateral impact by 14.7 kg rigid impactor at 0.9 m/s (130 mm diameter circular impact face) – Bottom-thorax alignment	TRL Test 07	0.91	4.9 (T3)	2.8 (T3)	4.9 (T3)	5.5 (T3)
	TRL Test 08	0.91	5.0 (T3)	2.7 (T3)	5.1 (T3)	5.5 (T3)
	Mean at 0.9 m/s	0.91	5.0 (T3)	2.8 (T3)	5.0 (T3)	5.5 (T3)
HSRI lateral	TRL Test 09	4.32	24.9 (T3)	18.7 (A1)	25.5 (T3)	27.5 (T3)

impact by 14.7 kg rigid impactor at 4.3 m/s (130 mm diameter circular impact face) – Mid-thorax alignment	TRL test 10b	4.33	24.5 (T3)	16.6 (A1)	24.6 (T3)	25.0 (T3)
	Mean at 4.3 m/s	4.33	24.7 (T3)	17.6 (A1)	25.1 (T3)	26.3 (T3)
HSRI lateral impact by 14.7 kg rigid impactor at 4.3 m/s (130 mm diameter circular impact face) – Bottom-thorax alignment	TRL Test 11	4.28	26.8 (T2)	19.6 (T2)	27.5 (T2)	29.6 (T3)
	TRL Test 12	4.29	26.0 (T2)	16.2 (T3)	26.6 (T3)	27.5 (T3)
	Mean at 4.3 m/s	4.29	26.4 (T2)	17.9	27.0	28.6 (T3)
HSRI lateral impact by 14.7 kg rigid impactor at 6.1 m/s (130 mm diameter circular impact face) – Mid-thorax alignment	TRL Test 15	6.04	37.0 (T2)	22.8 (T2)	37.5 (T2)	38.1 (T2)
	TRL Test 16	6.11	36.9 (T2)	28.9 (T2)	38.4 (T2)	41.1 (T3)
	Mean at 6.1 m/s	6.08	37.0 (T2)	25.9 (T2)	37.9 (T2)	39.6
HSRI lateral impact by 14.7 kg rigid impactor at 6.1 m/s (130 mm diameter circular impact face) – Bottom-thorax alignment	TRL Test 13	6.18	33.9 (T2)	27.4 (T1)	35.6 (T1)	39.1 (T1)
	TRL Test 14	5.99	37.5 (T2)	21.7 (T2)	37.8 (T2)	38.3 (T2)
	Mean at 6.1 m/s	6.09	35.7 (T2)	24.6	36.7	38.7
WSU 30° forward of lateral impact by 14.7 kg rigid impactor at 6 m/s (130 mm diameter circular impact face)	TRL Test 35	5.97	16.7 (T2)	8.1 (A2)	21.8 (T3)	34.3 (T3)
WSU 30° forward of lateral impact by 14.7 kg rigid impactor at 8.7 m/s (130 mm diameter circular impact face)	TRL Test 31	2.05	5.5 (T2)	2.5 (A2)	5.9 (T2)	11.3 (T3)
	TRL Test 32	3.05	9.4 (T2)	4.0 (A2)	10.1 (T2)	17.0 (T3)
	TRL Test 33	4.03	10.1 (T2)	5.6 (A2)	12.0 (T2)	21.9 (T3)
	TRL Test 34	4.94	13.2 (T2)	4.9 (A2)	15.5 (T2)	25.8 (T3)
	TRL Test 36	5.64	15.3 (T3)	6.9 (A2)	20.2 (T3)	33.3 (T3)
	Extrapolation	8.7	23.4 (T2)	10.4 (A2)	28.2 (T2)	48.4 (T3)

Table 4-3: Dummy thorax impactor test V*C results to be used for the construction of the injury risk curve

PMHS test condition	**WorldSID-5F test number**	**Actual impact speed (m/s)**	**WorldSID-5F peak V*C (m/s) (CFC_180)**		
			x-axis deflection V*C (m/s)	y-axis deflection V*C (m/s)	Total displacement V*C (m/s)
UMTRI lateral impact by 15.7 kg impactor at 2 m/s (130 mm diameter circular impact face) – Arm up	TRL Test 01	2.02	0.045 (T1)	0.126 (T2)	0.13 (T2)
	TRL Test 02	2.02	0.099 (A1)	0.115 (T1)	0.129 (A1)
	Mean at 2 m/s	2.02	0.072	0.121	0.13
UMTRI lateral impact by 15.7 kg impactor at 2 m/s (130 mm diameter circular impact face) – Arm down	TRL Test 03	2.04	0.08 (T1)	0.07 (A1)	0.08 (T1)
	TRL Test 04	2.02	0.05 (T1)	0.057 (A1)	0.069 (T1)
	Mean at 2 m/s	2.03	0.065 (T1)	0.064 (A1)	0.075 (T1)
HSRI lateral impact by 14.7 kg rigid impactor at 0.9 m/s (130 mm diameter circular impact face) – Mid-thorax alignment	TRL Test 05	0.93	0.0185 (A2)	0.031 (T1)	0.035 (T1)
	TRL Test 06	0.91	0.039 (T1)	0.029 (T3)	0.04 (T1)
	Mean at 0.9 m/s	0.92	0.029	0.03	0.038 (T1)
HSRI lateral impact by 14.7 kg rigid impactor at 0.9 m/s (130 mm diameter circular impact face) – Bottom-thorax alignment	TRL Test 07	0.91	0.021 (A2)	0.032 (T3)	0.037 (T3)
	TRL Test 08	0.91	0.036 (A1)	0.037 (T2)	0.043 (T3)
	Mean at 0.9 m/s	0.91	0.029	0.035	0.04 (T3)
HSRI lateral impact by 14.7 kg rigid impactor at 4.3 m/s (130 mm diameter circular impact face) – Mid-	TRL Test 09	4.32	0.29 (A1)	0.43 (T1)	0.44 (T3)
	TRL test 10b	4.33	0.20 (T2)	0.41 (T3)	0.40 (T3)
	Mean at 4.3 m/s	4.33	0.25	0.42	0.42 (T3)

thorax alignment					
HSRI lateral impact by 14.7 kg rigid impactor at 4.3 m/s (130 mm diameter circular impact face) – Bottom-thorax alignment	TRL Test 11	4.28	0.44 (T1)	0.49 (T1)	0.54 (T1)
	TRL Test 12	4.29	0.30 (T3)	0.52 (T1)	0.51 (T1)
	Mean at 4.3 m/s	4.29	0.37 (T1)	0.51 (T1)	0.53 (T1)
HSRI lateral impact by 14.7 kg rigid impactor at 6.1 m/s (130 mm diameter circular impact face) – Mid-thorax alignment	TRL Test 15	6.04	0.58 (T2)	0.78 (T2)	0.78 (T2)
	TRL Test 16	6.11	0.52 (T2)	0.80 (T2)	0.85 (T3)
	Mean at 6.1 m/s	6.08	0.55 (T2)	0.79 (T2)	0.82
HSRI lateral impact by 14.7 kg rigid impactor at 6.1 m/s (130 mm diameter circular impact face) – Bottom-thorax alignment	TRL Test 13	6.18	0.58 (T2)	0.82 (T2)	0.83 (T2)
	TRL Test 14	5.99	0.54 (T2)	0.82 (T2)	0.82 (T2)
	Mean at 6.1 m/s	6.09	0.56 (T2)	0.82 (T2)	0.83 (T2)
WSU 30° forward of lateral impact by 14.7 kg rigid impactor at 6 m/s (130 mm diameter circular impact face)	TRL Test 35	5.97	0.74 (T2)	0.53 (T1)	1.07 (T2)
WSU 30° forward of lateral impact by 14.7 kg rigid impactor at 8.7 m/s (130 mm diameter circular impact face)	TRL Test 31	2.049	0.15 (T3)	0.044 (T2)	0.18 (T3)
	TRL Test 32	3.05	0.23 (T3)	0.11 (T1)	0.29 (T3)
	TRL Test 33	4.03	0.32 (T2)	0.14 (T3)	0.44 (T2)
	TRL Test 34	4.94	0.36 (T3)	0.23 (T1)	0.54 (T1)
	TRL Test 36	5.64	0.59 (T3)	0.34 (T1)	0.80 (T3)
	Extrapolation	8.7	0.74 (T3)	0.37 (T1)	1.01 (T3)

In both of the two preceding tables the last test condition relates to the Wayne State University impact at 8.7 m/s. This test was not carried out at TRL for two reasons:

1. The pendulum facility is unable to achieve this impact speed without adding propulsion to the impactor.
2. The WorldSID-5F showed signs of reaching the maximum sustainable impact speed soon after 6 m/s. Therefore the faster speed of 8.7 m/s was thought to involve too great a risk of dummy breakage to justify testing at that severity.

To provide results that can be applied to the 8.7 m/s test, a collection of tests at speeds lower than 6 m/s were carried out to investigate the potential for extrapolation. As described in Section 3.1.7, a straight line can be fitted to the peak deflection results with good correlation between the line and the data points. Assuming that this straight-line relationship continues above the speeds tested then the extrapolation seems reasonable. This process of extrapolation has been used to generate the results shown in the bottom row of Tables 4-2 and 4-3.

4.2.1 Thorax biofidelity

As thorax pendulum tests were carried out using the ISO TR 9790 Thorax Test 1 set-up it is possible to comment on the thorax biofidelity of the WorldSID-5F in these tests. The biofidelity requirements from these tests concern the impactor force and the upper thoracic spine acceleration. Typically, an accelerometer at the T1 position is used to give the thoracic spine acceleration. However, with this WorldSID-5F only the T4 position was available for analysis. Therefore, Figure 4-2 shows the impactor force response from these tests compared with the requirement and Figure 4-3 shows the T4 lateral acceleration plotted against the upper thoracic spine acceleration corridor.

As described in Section 3.1.4, two different alignments of the impactor were tried with this test set-up. Firstly the middle of the impactor was aligned with the middle of the mid-thoracic rib and alternatively, the lower edge of the impactor was aligned with the lower edge of the third thoracic rib. Results from these two variations in set-up are shown in the following two figures.

When considering the force responses as shown in Figure 4-2 it is clear that the dummy does not meet this requirement. The duration of the response is too short for the corridor and depending on whether the response is normalised or not the peak force is either just inside the upper corridor limit or too high, respectively.

The influence of the impactor alignment is a reduction in peak force with the bottom edge of the impactor aligned with the lower edge of the third thoracic rib. In this configuration, the pendulum was expected to be a few mm higher than with the more conventional middle of the mid-thoracic rib alignment. A slightly higher impact point may lead to a slightly lower peak force as the dummy will tend to fall away from the impactor more easily. The extent of this effect with the WorldSID-5F is sufficient to bring the impactor peak force within the limits of the biofidelity corridor.

When considering the spinal accelerations, shown in Figure 4-3, then again the duration of the dummy response is too short. Also the peak acceleration, either normalised or not, is above the upper corridor limit. With the thoracic acceleration there seems to be less influence from the impactor alignment than was the case with the pendulum forces.

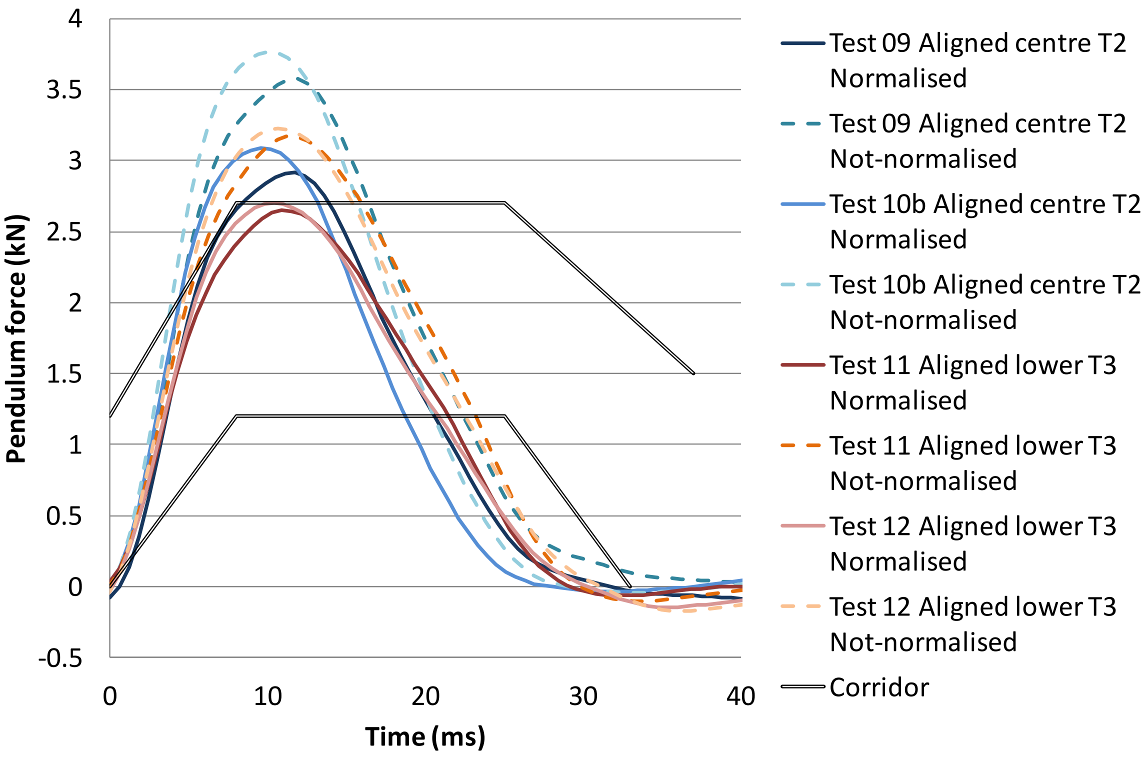


Figure 4-2: Thorax pendulum test impactor force response

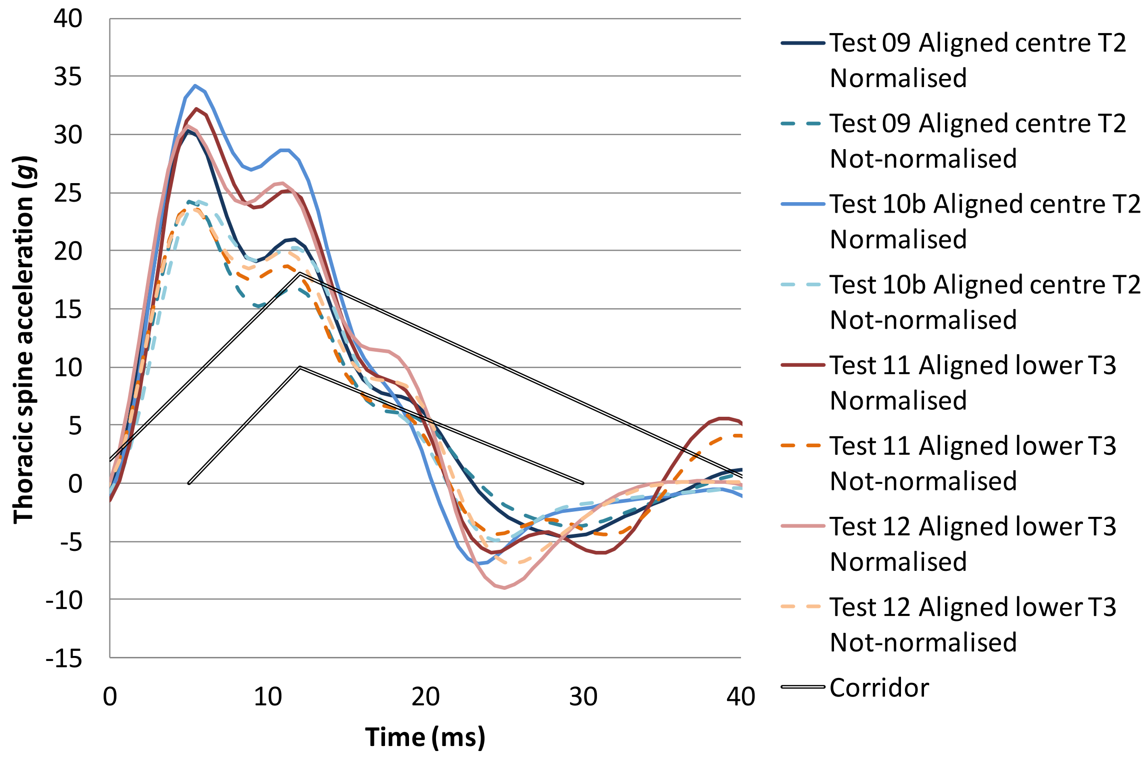


Figure 4-3: Thorax pendulum test upper thoracic spine acceleration

With these thorax biofidelity results it should be remembered that these tests were carried out with a 14.7 kg pendulum rather than the 14 kg impactor specified in the requirements. The effect of testing with a heavier pendulum would be expected to give higher peak forces and accelerations than testing with a lighter impactor. This may help bring the pendulum force responses closer to the corridor. However, the 0.7 kg difference in this test set-up would be unlikely to account for the deviation in spine acceleration response from the required corridor.

4.3 WorldSID-5F pelvis impactor test results

The pelvis impactor tests conducted at TRL were principally used to investigate the performance of the pelvis before and after modification. Additionally, the influence of conducting testing with the dummy either suspended or sitting on a flat surface was assessed. Throughout all of this work the dummy was tested in a configuration representative of the Wayne State University (General Motors) pelvis test configuration. Therefore it is hoped that some of the data will be useful in the construction of pelvis injury risk curves. For this reason the pelvis test data are summarised as for the previous, shoulder and thorax, body regions.

The following table (Table 4-4) summarises the standard dummy data from the pelvis impactor tests, now available for use in the construction of pelvis injury related risk curves. Table 4-5 shows the peak value results taken from the sacro-iliac and femoral neck load cells used in this testing. The sacro-iliac load cell was kindly loaned to TRL for the duration of the testing by Transport Canada.

Table 4-4: Dummy pelvis impactor test results to be used for the construction of the injury risk curve

PMHS test condition	WorldSID-5F test number	Actual impact speed (m/s)	WorldSID-5F peak lateral pelvis acceleration (m/s^2) (CFC_1000)	WorldSID-5F lateral pelvis acceleration, 3 ms exceedence (m/s^2) (CFC_1000)	WorldSID-5F peak pubis force (N) (CFC_1000)
WSU lateral impact by 14.7 kg rigid impactor at 6 m/s (145 mm diameter circular impact face) – suspended	TRL Test 39	5.96	57.3	35.3	1108
WSU lateral impact by 14.7 kg rigid impactor at 10 m/s (145 mm diameter circular impact face) – suspended	TRL Test 37	3.29	11.4	10.8	398
	TRL Test 38	4.95	36.8	24.2	827
	TRL Test 40	7.2	66.5	42.5	1354
	Extrapolated	10	110.9	66.9	2073

WSU lateral impact by 14.7 kg rigid impactor at 6 m/s (145 mm diameter circular impact face) – sitting, old pelvis parts	TRL Test 42	5.97	49.7	32.6	997
WSU lateral impact by 14.7 kg rigid impactor at 10 m/s (145 mm diameter circular impact face) – sitting, old pelvis parts	TRL Test 41	3.05	11.9	11.4	379
	TRL Test 45	4.0	22.9	18.3	583
	TRL Test 43	5.01	36.7	24.7	819
	TRL Test 44	7.0	62.3	44.9	1206
	TRL Test 46	6.99	56.0	45.4	1186
	Extrapolated	10	78.1	69.6	1823
WSU lateral impact by 14.7 kg rigid impactor at 6 m/s (145 mm diameter circular impact face) – sitting, new pelvis parts	TRL Test 51	5.83	40.7	32.6	953
WSU lateral impact by 14.7 kg rigid impactor at 10 m/s (145 mm diameter circular impact face) – sitting, new pelvis parts	TRL Test 47	3.05	11.7	11.3	377
	TRL Test 48	4.03	18.5	16.9	571
	TRL Test 50	4.03	19.0	17.1	567
	TRL Test 49	4.97	30.1	25.7	787
	Extrapolated	10	84.2	65.1	1834

Table 4-5: Dummy pelvis impactor test results (sacro-iliac) to be used for the construction of the injury risk curve

PMHS test condition	**WorldSID-5F test number**	**Actual impact speed (m/s)**	**WorldSID-5F peak struck-side sacro-iliac forces (N) and moments (Nm) (CFC_1000)**		**WorldSID-5F peak struck-side femoral neck forces (N) (CFC_600)**	
			y-axis force	x-axis moment	y-axis force	z-axis force
WSU lateral impact by 14.7 kg rigid impactor at 6 m/s (145 mm diameter circular impact face) – suspended	TRL Test 39	5.96	865	18.3 -10.8	2079	1151
WSU lateral impact by 14.7 kg rigid impactor at 10 m/s (145 mm diameter circular impact face) – suspended	TRL Test 37	3.29	395	3.63 -6.61	590	434
	TRL Test 38	4.95	768	9.43 -10.0	1530	897
	TRL Test 40	7.2	1001	37.8 -10.8	2677	1488
	Extrapolated	10	1471	56.9 -14.63	4211	2241
WSU lateral impact by 14.7 kg rigid impactor at 6 m/s (145 mm diameter circular impact face) – sitting, old pelvis parts	TRL Test 42	5.97	1152	25.1 -22.2	2011	1119
WSU lateral impact by 14.7 kg rigid impactor at 10 m/s (145 mm diameter circular impact face) – sitting, old pelvis parts	TRL Test 41	3.05	454	3.89 -12.1	504	459
	TRL Test 45	4.0	684	3.8 -13.7	1044	670
	TRL Test 43	5.01	917	9.24 -17.1	1537	898
	TRL Test 44	7.0	1413	49.6 -21.6	2763	1415

	TRL Test 46	6.99	1111	33.8 -22.5	2237	1384
	Extrapolated	10	1909	70.1 -31.0	4017	2115
WSU lateral impact by 14.7 kg rigid impactor at 6 m/s (145 mm diameter circular impact face) – sitting, new pelvis parts	TRL Test 51	5.83	1042	13.5 -17.7	1487	1099
WSU lateral impact by 14.7 kg rigid impactor at 10 m/s (145 mm diameter circular impact face) – sitting, new pelvis parts	TRL Test 47	3.05	421	3.59 -12.5	426	458
	TRL Test 48	4.03	646	3.90 -15.3	653	675
	TRL Test 50	4.03	640	3.40 -14.0	659	680
	TRL Test 49	4.97	929	8.47 -13.3	1273	904
	Extrapolated	10	2046	28.2 -22.7	3256	2067

As with the highest severity thorax tests the previous tables contain only extrapolated results for the 10 m/s Wayne State University test condition.

4.4 WorldSID-5F sled test results

The results from the TRL sled tests are also expected to be of value in determining injury risk functions for use with the WorldSID-5F and 2D IR-Traccs. The peak values from the dummy responses are shown in the following series of tables. The deflection measurement results are shown in Table 4-6 together with the corresponding Viscous Criterion results. Pelvis peak values are documented in Table 4-7.

In these tables there are several rows where results are expected for 6.7 or 8.9 m/s impacts. As reported earlier in this report it was intended to carry out tests at these severities. However, due to concerns over the dummy’s robustness under these conditions and the ability to provide meaningful measurements without damaging the instrumentation (i.e. reaching mechanical limits of measurement with the 2D IR-Traccs), no tests were carried out above 6.3 m/s. To provide data for impacts above 6.3 m/s extrapolation has been used, where possible.

For the shoulder deflection it appeared that a mechanical limit of about 41 mm of deflection was reached in the Wayne State University (WSU) test at 6.3 m/s. The shoulder deflection response from this sled test is shown in Figure 4-4.

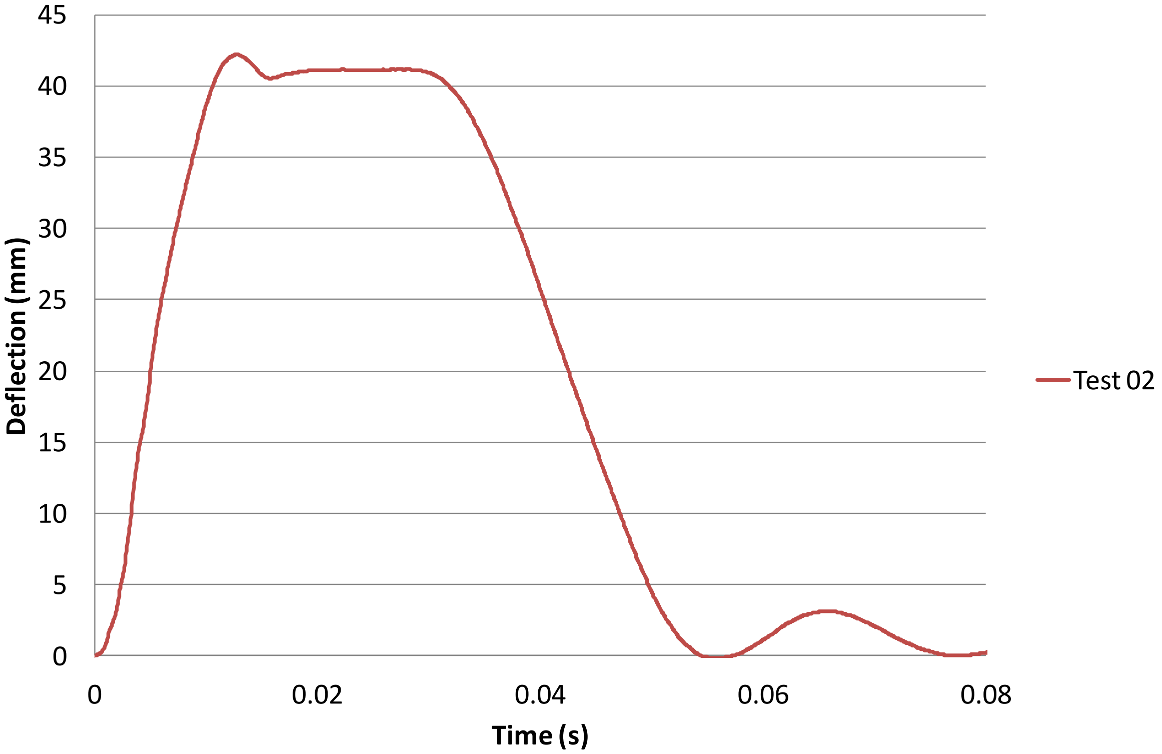


Figure 4-4: Shoulder deflection from WSU test at 6.3 m/s

The consequence of reaching a mechanical limit is that whilst the impact speed shoulder deflection relationship may be linear up to this point, a plateau would be expected in deflection values at higher speeds. This is shown in Figure 4-5 where a linear line of best fit can be imagined for test speeds between 0 and 6 m/s. Above this speed the mechanical limit, as demonstrated at 6.3 m/s, would be expected to prevent further increases in shoulder deflection values. However, it is still possible to extrapolate beyond the point even though in practice the dummy cannot measure further deflection. This extrapolation can be considered as the best estimate of what would happen if the shoulder contact preventing further deflection was avoided. It is with this idea in mind, and using the linear relationship of the best fit trendline, that extrapolated shoulder deflection values for the higher severity WSU tests were derived, as shown in Table 4-6. On this basis of the linear relationship shown in Figure 4-5 it was estimated that WSU tests at 6.7 and 8.9 m/s would produce shoulder deflection values of about 52.9 and 70.2 mm.

It should be noted that the result from the test at 6.3 m/s, where the shoulder motion was limited mechanically, was not included in the linear regression shown in Figure 4-5.

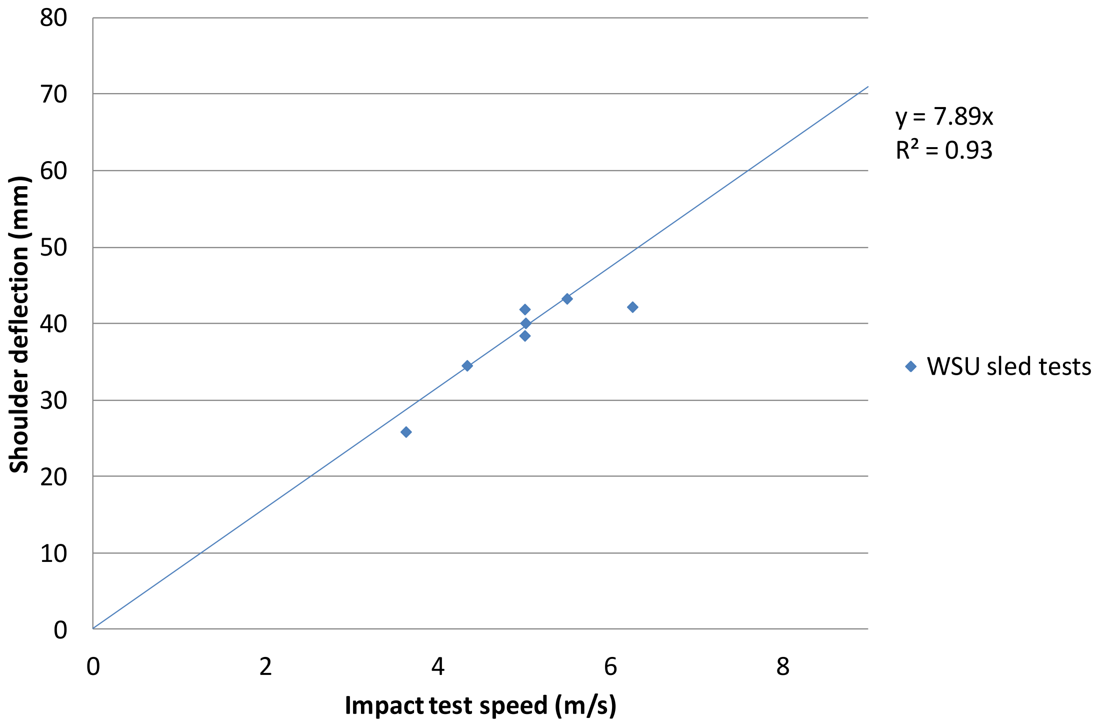


Figure 4-5: Peak shoulder deflection values from WSU sled tests at various impact speeds

When looking for potential sources of the mechanical contact preventing more than about 40 mm of shoulder deflection it became clear that contact could occur between the shoulder load cell and the lower edge of the neck bracket. The bottom of the neck bracket in the WorldSID-5F increases in width from the top of the spine box upwards. This means that when there is no vertical displacement of the shoulder rib, it could be compressed until the shoulder load cell went all the way to the spine box. However, the more vertical displacement there is of the rib, the less y-axis deformation is possible. The extreme situation is that which occurred in the WSU tests where only 40 mm of lateral deformation is possible. In this case the shoulder load cell seems to have contacted the widest part of the neck bracket.

In the Heidelberg tests, higher shoulder deflection values were recorded than in the WSU tests. It may be that differences in the force plate configurations between the WSU and Heidelberg setups allow the hard limit for shoulder deflection to be avoided during the Heidelberg tests. It is assumed that some feature of the Heidelberg tests produces less vertical displacement of the shoulder rib than was the case in the WSU tests. Hence more lateral displacement is possible with a hard contact being made with the neck bracket.

With the variety of impact speeds for the rigid, flat wall Medical College of Wisconsin (MCW) tests similar extrapolation can be set-up as for the WSU tests. A similar approach has also been used for the other configurations. However, it should be noted that not all conditions were tested at more than one impact speed. This means that the extrapolation is reliant on one real data point and forcing the line of regression to go through the origin. This is not a robust method for determining expected values at higher severities. Some confidence in a linear relationship can be taken from the behaviour shown in the flat, rigid wall tests. It would be useful to be able to demonstrate, even with another data point or two, that this relationship is maintained for different set-ups and the expected variance in the experimental results. For this reason, if these extrapolated values are critical to the injury risk functions being developed for the WorldSID-5F then efforts should be made to expand the test programme carried out for this project.

With the y-axis rib deflection measurements, the line of best fit through the peak values from the sled tests supported a negative deflection intercept value at 0 m/s. Assuming that the physical meaning of this negative intercept is not plausible, this suggests that at low speeds the relationship between peak value and impact speed changes from that observed for the range of speeds tested. This serves to illustrate the danger of assuming constant behavioural relationships beyond the spread of test conditions evaluated. In terms of the test results, this behaviour means extrapolated values cannot be provided for test conditions without more than one impact speed.

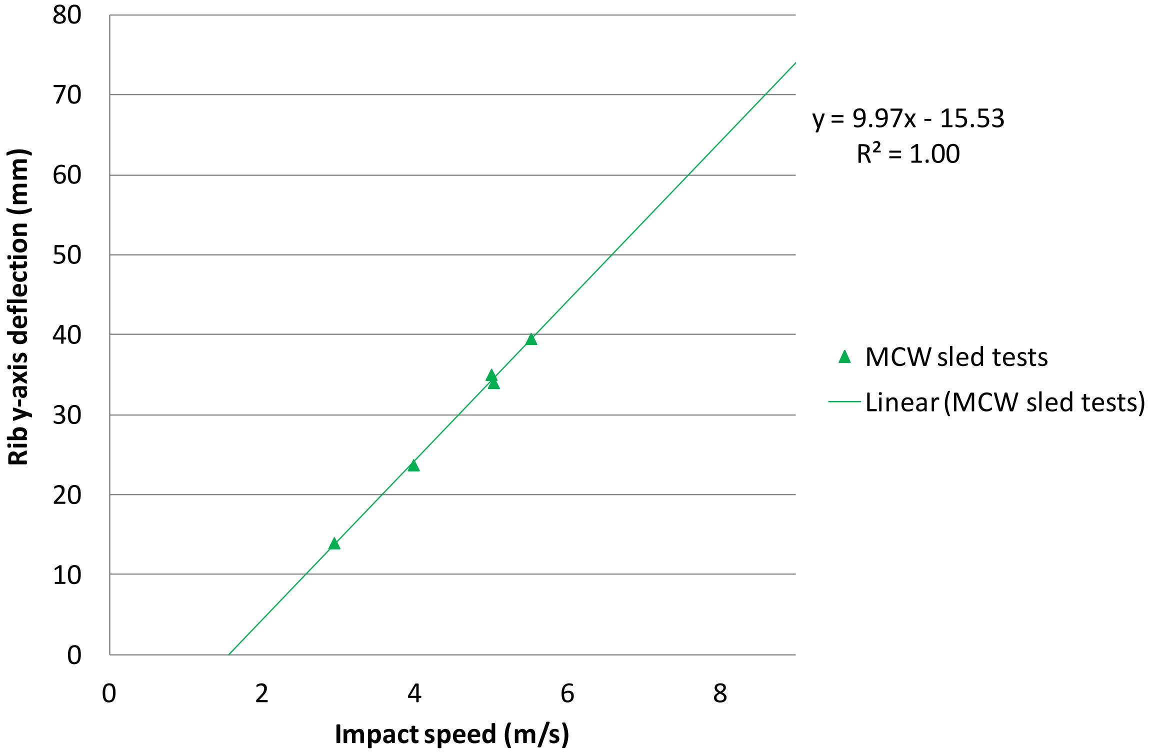


Figure 4-6: Peak y-axis chest deflection values from MCW sled tests at various impact speeds

The relationship between impact speed and x-axis Viscous Criterion (V*C) did not give a high r^2 correlation coefficient (0.42, as shown in Figure 4-7). Hence, extrapolation from these data was not appropriate. However, the MCW tests provided a much higher correlation value, $r^2 = 0.93$, though again the intercept was negative. In contrast, the left (struck) side sacro-iliac moment about the x-axis from the MCW flat wall tests did not provide a high correlation with impact speed ($r^2 = 0.05$), whereas the WSU tests provided a good correlation for this measure ($r^2 = 0.96$). Extrapolation from the WSU sled test data for y- and z-axis femoral neck forces has not been provided on the basis of a low correlation coefficient ($r^2 = 0.60$ and 0.53, respectively). This was due to an error in the set-up of the femoral neck load cell data acquisition. The error was resolved for the later sled tests, but resulted in clipping of the data from the early (WSU) tests.

The x-axis Viscous Criterion peak values shown in Figure 4-7 also illustrate a feature identified in other dummy measures as well. To investigate the sensitivity of the WorldSID-5F to initial position, the third test (TRL sled test 04) at 5 m/s in the flat, rigid wall WSU condition was carried out with the arms positioned slightly in front of the thorax. Without the arm lying immediately by the thorax, the deflection and V*C values from this test are lower than the other tests carried out at 5 m/s. This is an interesting finding with regard to the WorldSID set-up for these tests. For the extrapolation however, this test has been removed where it can be seen to affect adversely the best fit estimates.

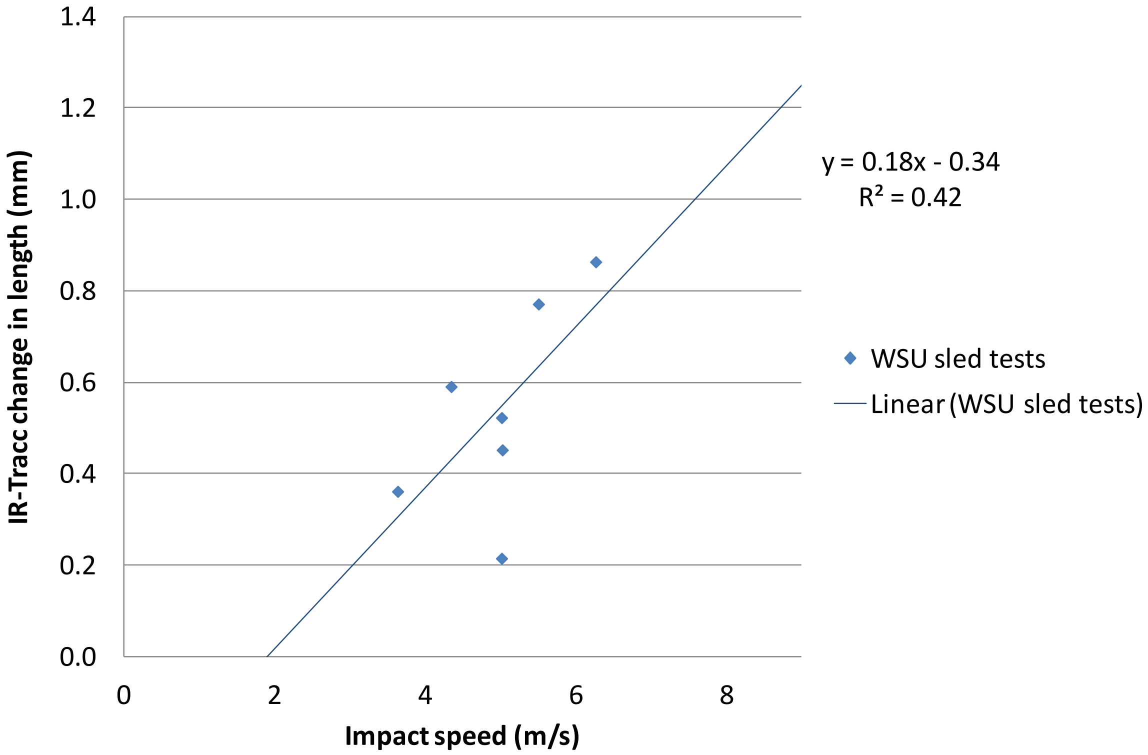


Figure 4-7: Peak x-axis Viscous Criterion values from WSU sled tests at various impact speeds

For the lower spine acceleration, the T12 dummy data were used. A resultant acceleration was calculated and the 3 ms exceedence values taken from this.

When plotting the T12 3 ms exceedence values against impact speed from the WSU rigid wall sled tests (Figure 4-8) a linear best fit trendline was again fitted to the data points. However, the arrangement of the points suggested a curve would better represent the relationship. A reasonable extrapolation of the data would be expected to show increasing acceleration with increasing impact speed. Unfortunately simply defined curves gave unrealistic extrapolated values. Therefore, based on these data a linear extrapolation to 8.9 m/s has been used.

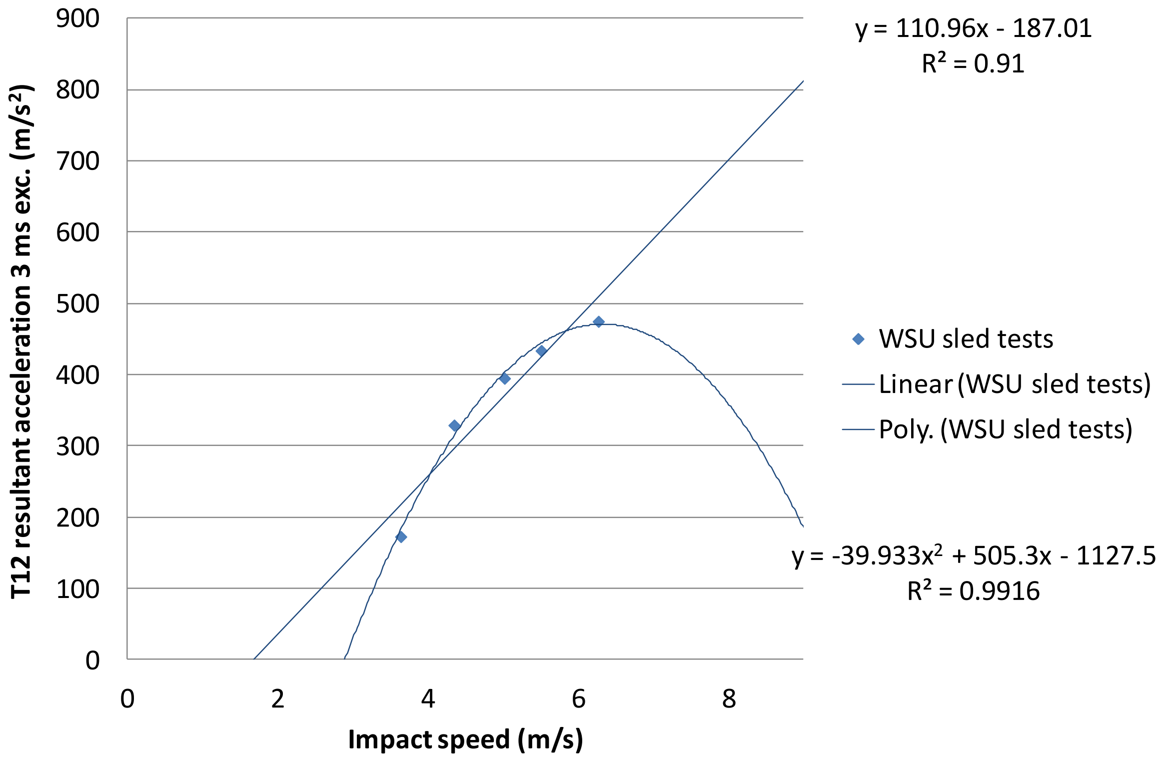


Figure 4-8: T12 3 ms exceedence values from WSU sled tests at various impact speeds

Table 4-6: WorldSID-5F sled test deflection results

PMHS test condition	WorldSID-5F test number	Actual impact speed (m/s)	Peak WorldSID-5F shoulder rib deflection (mm) (CFC_600)	Peak WorldSID-5F thorax rib deflection (mm) (CFC_600)				Peak WorldSID-5F abdomen rib deflection (mm) (CFC_600)		
				IR-Tracc deflection (mm)	x-axis deflection (mm)	y-axis deflection (mm)	Total displacement (mm)	x-axis V*C (m/s)	y-axis V*C (m/s)	Total resultant V*C (m/s)
Heidelberg rigid, flat wall test at 8.9 m/s	TRL sled test 18	5.07	50.3	33.3 (T1)	31.1 (T2)	42.0 (T1)	51.4 (T1)	0.65 (T1)	0.72 (T1)	1.30 (T1)
	TRL sled test 19	5.05	46.6	31.7 (T1)	33.8 (T2)	42.7 (T1)	54.3 (T1)	0.82 (T1)	0.87 (T1)	1.58 (T1)
	TRL sled test 20	5.05	48.0	31.3 (T1)	30.5 (T2)	39.6 (T1)	49.6 (T1)	0.63 (T1)	0.77 (T1)	1.39 (T1)
	Mean at 5 m/s	5.06	48.3	32.1 (T1)	31.8 (T2)	41.4 (T1)	51.8 (T1)	0.70 (T1)	0.79 (T1)	1.42 (T1)
	Extrapolated	8.9	(85.0)	(56.5)	(60.0)	-	-	-	-	-
WSU rigid, flat wall sled test at 6.3 m/s	TRL sled test 02	6.26	42.2	36.6 (T1)	34.9 (T1)	49.3 (T1)	59.8 (T1)	0.86 (T1)	1.15 (T1)	1.94 (T1)
WSU rigid, flat wall sled test at 8.9 m/s	TRL sled test 06	3.63	25.9	13.6 (T1)	20.1 (T1)	16.2 (T1)	25.8 (T1)	0.36 (T1)	0.17 (T1)	0.44 (T1)
	TRL sled test 07	4.34	34.5	24.6 (T1)	28.6 (T1)	13.3 (T1)	42.3 (T1)	0.59 (T1)	0.48 (T1)	0.98 (T1)

	TRL sled test 01	5.02	40.1	29.3 (T1)	26.9 (T1)	35.5 (T1)	44.4 (T1)	0.45 (T1)	0.61 (T1)	0.95 (T1)
	TRL sled test 03	5.01	41.9	29.3 (T1)	27.6 (T1)	35.8 (T1)	45.0 (T1)	0.52 (T1)	0.56 (T1)	1.05 (T1)
	TRL sled test 04	5.01	38.4	27.6 (T1)	15.7 (T1)	28.8 (T1)	31.4 (T1)	0.21 (T1)	0.36 (T1)	0.46 (T1)
	TRL sled test 05	5.5	43.3	32.4 (T1)	31.2 (T1)	42.0 (T1)	52.3 (T1)	0.77 (T1)	0.80 (T1)	1.50 (T1)
	Extrapolated	8.9	(70.2)	(50.1)	(50.4)	(81.1)	(92.8)	-	(1.96)	(3.27)
WSU rigid, pelvis offset sled test at 8.9 m/s	TRL sled test 08	5.02	37.9	24.2 (T1)	22.8 (T1)	28.0 (T1)	35.9 (T1)	0.42 (T1)	0.40 (T1)	0.77 (T1)
	TRL sled test 09	5.02	37.4	23.9 (T1)	19.0 (T1)	26.5 (T1)	32.4 (T1)	0.39 (T1)	0.38 (T1)	0.63 (T1)
	Mean at 5 m/s	5.02	37.7	24.0 (T1)	20.9 (T1)	27.3 (T1)	34.2 (T1)	0.40 (T1)	0.39 (T1)	0.70 (T1)
	Extrapolated	8.9	(66.8)	(42.6)	(37.0)	-	-	-	-	-
MCW & OSU rigid, flat wall sled test at 6.7 m/s	TRL sled test 14	2.94	26.1	11.7 (T1)	18.9 (T1)	14.0 (T1)	23.4 (T1)	0.23 (T1)	0.14 (T1)	0.35 (T1)
	TRL sled test 13	3.98	33.1	17.9 (T1)	27.9 (T1)	23.7 (T1)	36.6 (T1)	0.59 (T1)	0.33 (T1)	0.90 (T1)
	TRL sled test 10	5	41.5	25.2 (T1)	34.0 (T1)	35.0 (T1)	48.8 (T1)	0.78 (T2)	0.72 (T1)	1.37 (T2)
	TRL sled test 11	5.03	40.5	25.0 (T1)	32.8 (T1)	34.0 (T1)	47.2 (T1)	0.68 (T1)	0.64 (T1)	1.31 (T1)

	TRL sled test 12	5.52	42.5	27.6 (T1)	36.3 (T2)	39.5 (T1)	53.5 (T1)	0.96 (T3)	0.74 (T1)	1.61 (T1)
	Extrapolated	6.7	(54.4)	(32.4)	(44.7)	(51.3)	(67.6)	(1.19)	(1.06)	(2.18)
	Extrapolated	8.9	(72.3)	(43.1)	(59.4)	(73.2)	(93.1)	(1.74)	(1.61)	(3.23)
MCW & OSU rigid, thorax offset sled test at 6.7 m/s	TRL sled test 17	5.04	45.0	31.0 (T1)	31.5 (T1)	40.2 (T1)	50.9 (T1)	0.70 (T1)	0.71 (T1)	1.29 (T1)
	Extrapolated	6.7	(59.9)	(41.2)	(41.9)	-	-	-	-	-
MCW & OSU rigid, pelvis offset sled test at 6.7 m/s	TRL sled test 16	4.0	33.0	18.6 (T1)	17.3 (T1)	20.5 (T1)	26.7 (T1)	0.35 (T1)	0.24 (T1)	0.37 (T1)
	TRL sled test 15	5.03	40.1	26.7 (T1)	25.7 (T1)	31.3 (T1)	40.1 (T1)	0.44 (T1)	0.53 (T1)	0.89 (T1)
	Extrapolated	6.7	(54.2)	(33.8)	(32.2)	(48.8)	(62.0)	(0.60)	(0.98)	(1.74)

Table 4-7: WorldSID-5F sled test pelvis results

PMHS test condition	WorldSID-5F test number	Actual impact speed (m/s)	WorldSID-5F lower spine acceleration, 3 ms exceedence (m/s^2) (CFC_180)	WorldSID-5F peak lateral pelvis acceleration (m/s2) (CFC_1000)	WorldSID-5F lateral pelvis acceleration, 3 ms exceedence (m/s^2) (CFC_1000)	WorldSID-5F peak pubis force (N) (CFC_1000)	WorldSID-5F peak struck-side sacro-iliac forces (N) and moments (Nm) (CFC_1000)		WorldSID-5F peak struck-side femoral neck forces (N) (CFC_1000)	
							y-axis force	x-axis moment	y-axis force	z-axis force
Heidelberg rigid, flat wall test at 8.9 m/s	TRL sled test 18	5.07	343	700	597	1,074	1,028	28	1,898	1,064
	TRL sled test 19	5.05	380	700	579	1,079	1,188	31	2,048	1,015
	TRL sled test 20	5.05	411	708	562	1,197	1,294	25	2,270	1,033
	Mean at 5 m/s	5.06	378	703	579	1,117	1,170	31	2,072	1,037
	Extrapolated	8.9	-	-	-	-	-	-	-	-
WSU rigid, flat wall sled test at 6.3 m/s	TRL sled test 02	6.26	476	1,043	538	1,178	1,396	47	> 1,338‡	> 493‡
WSU rigid, flat wall sled test at 8.9 m/s	TRL sled test 06	3.63	174	122	117	178	124	16	80	174
	TRL sled test 07	4.34	330	513	427	634	1036	24	> 1,257‡	> 486‡
	TRL sled test 01	5.02	†	†	†	708	776	30	> 1,141‡	> 477‡

	TRL sled test 03	5.01	396	538	520	637	723	35	> 1,153‡	> 492‡
	TRL sled test 04	5.01	322	540	461	723	971	20	> 1,330‡	> 498‡
	TRL sled test 05	5.5	435	822	625	1,036	1194	34	> 1,331‡	> 492‡
	Extrapolated	8.9	(801)	(1,928)	(1,492)	(2,189)	(2,526)	(75)	-	-
WSU rigid, pelvis offset sled test at 8.9 m/s	TRL sled test 08	5.02	393	535	461	1,108	1,650	22	> 1,334‡	> 497‡
	TRL sled test 09	5.02	376	552	464	1,054	1,361	30	2,475	1,278
	Mean at 5 m/s	5.02	385	544	462	1,081	1,506	26	2,475	1,278
	Extrapolated	8.9	-	-	-	-	-	-	-	-
MCW & OSU rigid, flat wall sled test at 6.7 m/s	TRL sled test 14	2.94	137	171	149	332	88	18	349	280
	TRL sled test 13	3.98	239	395	339	540	443	19	1,330	728
	TRL sled test 10	5	387	606	474	727	746	24	1,310	637
	TRL sled test 11	5.03	381	540	478	792	869	16	1,530	887
	TRL sled test 12	5.52	447	601	465	783	968	14	1,541	728
	Extrapolated	6.7	(588)	(846)	(673)	(1,049)	(1,382)	-	(2,160)	(1,048)

	Extrapolated	8.9	(858)	(1,229)	(965)	(1,462)	(2,140)	-	(3,105)	(1,491)
MCW & OSU rigid, thorax offset sled test at 6.7 m/s	TRL sled test 17	5.04	362	296	224	339	76	52	215	516
	Extrapolated	6.7	(481)	-	-	-	-	-	-	-
MCW & OSU rigid, pelvis offset sled test at 6.7 m/s	TRL sled test 16	4.0	343	397	303	738	1,014	13	1,392	725
	TRL sled test 15	5.03	425	615	486	1,098	1,349	35	2,403	1092
	Extrapolated	6.7	(560)	(969)	(782)	(1,681)	(1,893)	(70)	(4,042)	(1,688)

† Data lost due to partial download after test.

‡ Data artificially clipped due to error in acquisition set-up

4.4.1 Thorax biofidelity

As noted in Section 3.2.1.1, the Heidelberg testing is used within ISO TR 9790 to assess both thorax and pelvis biofidelity. A 6.8 m/s test is required for Thorax Test 5. In the sled test programme carried out at TRL, impacts above 6.3 m/s were not carried out because of concerns over dummy breakages. Heidelberg tests were only performed at 5 m/s.

With regard to the biofidelity assessment, it is expected that the test at 5 m/s can provide some useful information. The thorax plate force response, with and without normalisation, is shown in Figure 4-9.

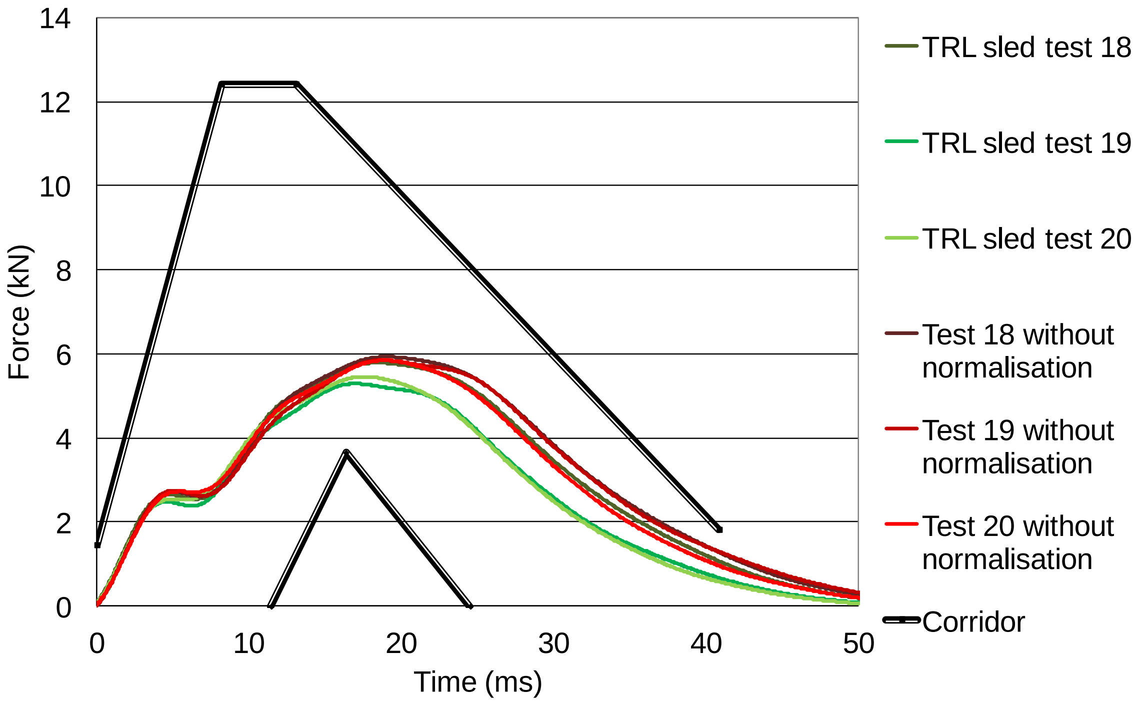


Figure 4-9: Heidelberg thorax plate response (5 m/s rigid plate tests, corridor for 6.8 m/s response requirement)

It is clear from Figure 4-9 that at the reduced impact speed of 5 m/s, the WorldSID-5F meets the thorax plate force response corridor. It is expected that the response at the correct biofidelity test speed of 6.8 m/s could also remain within the corridor limits. However, it would be much closer to the upper corridor boundary.

Within the thorax biofidelity assessment there are also specifications for the desired subject accelerations. Spine accelerations are intended to be matched with requirements for the upper and lower spine. With the WorldSID-5F, accelerations from T4 and T12 have been used for this purpose. There is also a target for the peak lateral acceleration from the impacted rib. In this case the peak lateral acceleration values from Thorax ribs two and three are reported. These results are shown in Table 4-8. A 100 Hz Finite Impulse Response filter was used to process the dummy acceleration signals prior to the peak value being taken. They have also been normalised using the ratio derived from the effective and standard mass estimates (R_a = 1.02 to 1.11).

Table 4-8: Heidelberg thorax acceleration response (6.8 m/s rigid plate test)

Measurement	Units	Lower bound	Upper bound	WorldSID-5F response (mean from three 5 m/s tests)
Peak lateral acceleration of the upper spine	*g*	100	149	41
Peak lateral acceleration of the lower spine	*g*	87	131	43
Peak lateral acceleration of the impacted rib (according to the 4th rib of the adult male	*g*	78	122	122 (Thorax rib 2) 124 (Thorax rib 3)

The acceleration results show that the peak spine acceleration is too low for the ISO target boundaries; whereas, the rib acceleration is just on the limit, though only if the higher acceleration value from Thorax rib 3 is dismissed. Again, it should be remembered that this test was conducted at 5 m/s and not the 6.8 m/s expected for use with these requirements. It should be expected that the acceleration values would increase when tested at a higher speed. This would move the spine accelerations closer to the targets whilst probably not achieving the required shift to produce values within the limits. Any increase in the rib acceleration would take it beyond the upper boundary limit. In essence it seems as though the rib acceleration is too high, whereas the spine acceleration of the WorldSID-5F is too low. This behaviour may be a consequence of the large spine box in the small female WorldSID which, apparently, had to be kept at the same size as the spine box in the 50th percentile dummy to house the data acquisition modules. The consequence of this is that proportionally more mass is located in the spine of the WorldSID-5F than in the larger 50M or would be expected in a human.

4.4.2 *Abdomen biofidelity*

The only abdomen biofidelity requirements set for the tests carried out at TRL were for the Wayne State University sled tests. As already noted in Section 3.2.1.2, requirements are available for both 6.8 and 8.9 m/s rigid wall tests. However, the WorldSID-5F was only tested at speeds up to 6.3 m/s.

To give some indication of how the dummy response scales with impact speed a variety of test speeds up to the peak of 6.3 m/s were used. The abdomen results from these tests are plotted against the 6.8 m/s corridor in Figure 4-10.

The force measured at the abdomen load plate increases with increasing impact speed. When tested at 6.3 m/s it had already exceeded the upper boundary of the biofidelity corridor. This indicates that the abdomen of the dummy is too stiff for the required response.

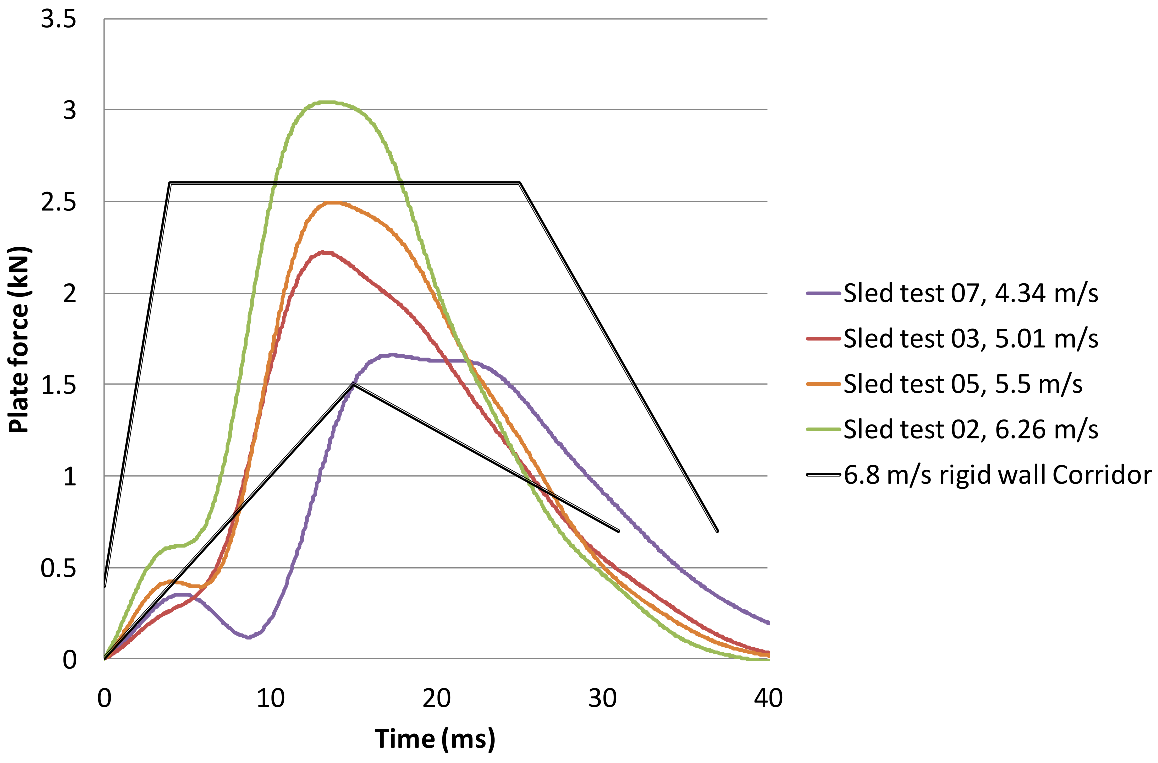


Figure 4-10: Wayne State University abdomen plate response (6.8 m/s rigid plate test requirement)

4.4.3 Pelvis biofidelity

The Heidelberg sled tests are also used in the evaluation of the pelvis biofidelity of side impact test dummies. The mean response from the three Heidelberg sled tests (at 5 m/s) is shown in the following results. Again, it must be noted that the target impact speed for the flat, rigid wall Heidelberg tests is either 6.8 or 8.9 m/s. As such, the test severity used to produce these results is substantially lower than expected for comparison with the biofidelity requirements. For this reason only the 6.8 m/s requirements are shown below.

In Table 4-9 the WorldSID-5F pelvis responses are shown together with the requirements for a 6.8 m/s rigid wall Heidelberg impact. The WorldSID-5F results were filtered and normalised in accordance with processes defined in ISO TR 9790 (ISO, 1999).

Table 4-9: Heidelberg pelvis acceleration response (6.8 m/s rigid plate test)

Measurement	**Units**	**Lower bound**	**Upper bound**	**WorldSID-5F response (mean from three 5 m/s tests)**
Peak pelvis plate force	kN	4.6	5.6	9.9
Peak pelvic acceleration	*g*	78	95	44

Based on these results it can be seen that the pelvis acceleration is slightly too low for the required levels when tested at a lower severity. This would improve as the impact speed is increased towards the necessary level. However, the Pelvis plate force is already above the upper limit. This will move further from the requirements at a higher severity.

It was noted that at 5 m/s there was contact between the lower pelvis iliac wing and the sacro-iliac load cell and cable cover. However, there was no contact recorded between the upper central pelvis iliac wing and the lumbar spine mounting plate. The positions of the contact switches used to determine this are described later in Section 6.4.

For the Wayne State University (WSU) tests, pelvis response requirements are also given for both 6.8 m/s and 8.9 m/s rigid wall impacts. As tests with the WorldSID-5F were not carried out above 6.3 m/s only the lower severity requirements are considered below.

The peak pelvis lateral acceleration requirement is shown in Table 4-10, together with the response from the WorldSID-5F test at 6.3 m/s. The pelvis acceleration from the WorldSID-5F was filtered with a FIR 100 filter and normalised using the ratios of effective mass and standard length based on erect seating height (multiply acceleration by 1.20).

The result from Table 4-10 indicates that the peak lateral pelvis acceleration is within the boundaries of the desired response. It is also likely that this could still be met even when the impact speed is increased by nine percent.

Table 4-10: Wayne State University pelvis acceleration response (6.8 m/s rigid plate test)

Measurement	Units	Lower bound	Upper bound	WorldSID-5F response (from 6.3 m/s test)
Peak lateral pelvis acceleration	*g*	105	142	118

The other part of the WSU pelvis biofidelity requirement concerns the pelvis plate force. The dummy responses from the range of impact speeds tested are shown against the biofidelity corridor in Figure 4-11.

From Figure 4-11 it can be seen that when an impact speed of 6.3 m/s is reached, the pelvis response has a peak already above the upper limit of the corridor. In agreement with the Heidelberg pelvis evaluation this suggests that the WorldSID-5F behaviour puts more force through the pelvis than is expected based on the biofidelity requirements.

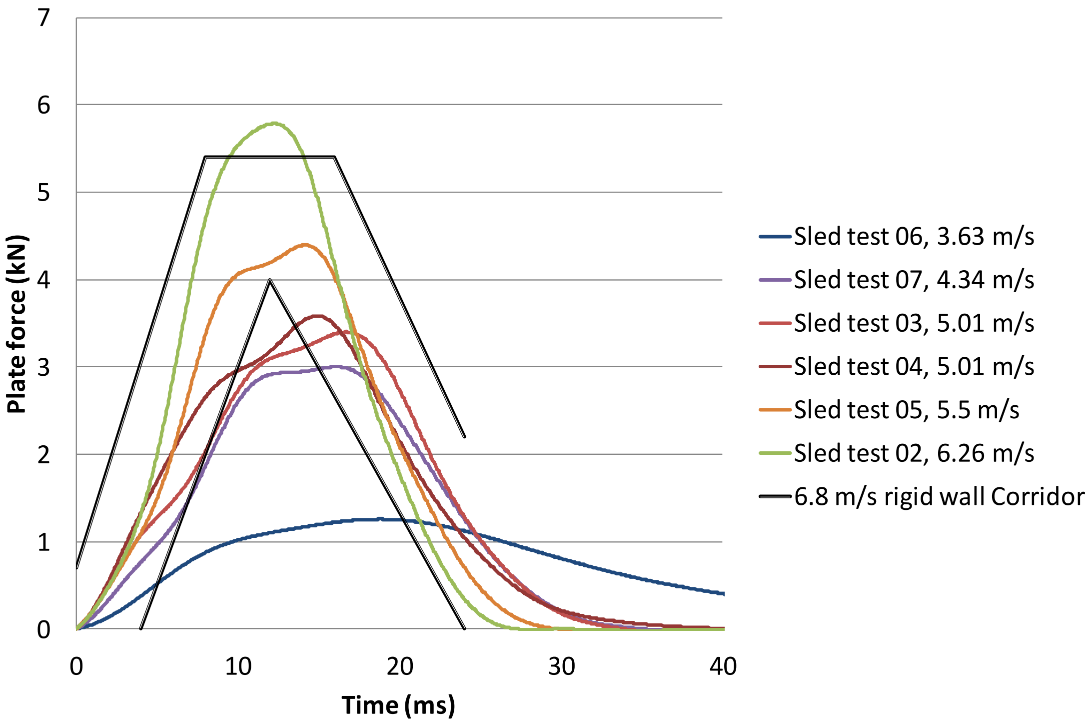


Figure 4-11: Wayne State University pelvis plate response (6.8 m/s rigid plate test requirement)

4.5 IR-Tracc orientation

Prior to any testing with the dummy, it was thought important to disassemble the thorax and investigate the orientation and calibration of the chest deflection measuring 2D IR-Traccs. This was in response to concerns raised at a WorldSID Technical Evaluation Group meeting, that a twist in the rod of the IR-Tracc could affect the transmission/receipt of the optical signal. The implication of this would be that after calibration of the IR-Traccs out of the dummy, installation may inadvertently rotate the rod. IR-Traccs do not give a linear response therefore it is important that the measured output can be correlated with a known rod length. If the measurement was sensitive to the exact orientation of the IR-Tracc ends then the original calibration would be invalidated.

The explanation given for such sensitivity to rod orientation is that some versions of the IR-Tracc design incorporate a diffraction grating between the emitter and receiver. Prior to the TRL testing, it was not clear whether this design feature was present on the 2D IR-Traccs installed in the specific WorldSID-5F available for testing.

To check that the calibration of the 2D IR-Traccs was correct the lateral ends of the rods were moved to known positions relative to the base and the displacement from a known starting point compared with the expected position. To enable such a calibration check of the IR-Traccs, a jig is required to hold the base of the unit and allow movement of the lateral end (as in the dummy). Such a jig had been used by NHTSA previously, therefore this was replicated for this work. An assembly drawing of the jig, including an outline of an IR-Tracc is shown in Figure 4-12. In this figure, item 1 is the base plate to which the IR-Tracc is mounted. The baseplate has a shallow cut-out for housing the base of the

IR-Tracc. It also has a series of 'through' holes drilled at specific locations and able to take a dowel as fitted to the bottom of the block shown as Item 2 in the figure. This block serves to keep the IR-Tracc level from the base to the end of the rod and provide the linkage between ball joint at the end of the IR-Tracc and location with the drilled holes in the baseplate.

To test the 2D IR-Traccs it was necessary to keep them connected to the dummy DAS. This meant keeping them close to the dummy whilst trying not to exert strain on the cabling. Once free from the rib and spine box, the base of the IR-Tracc was mounted firmly to the jig. The other end of the unit, with the ball joint used for mounting to the lateral part of the rib, was screwed to the movable block of the jig. The data outputs were then recorded at each step, using the real-time data monitoring mode, whilst the block was moved through the range of positions allowed in the jig. Once a full set of positions had been checked, the IR-Tracc was then twisted/untwisted by 180 degrees and the analysis was repeated.

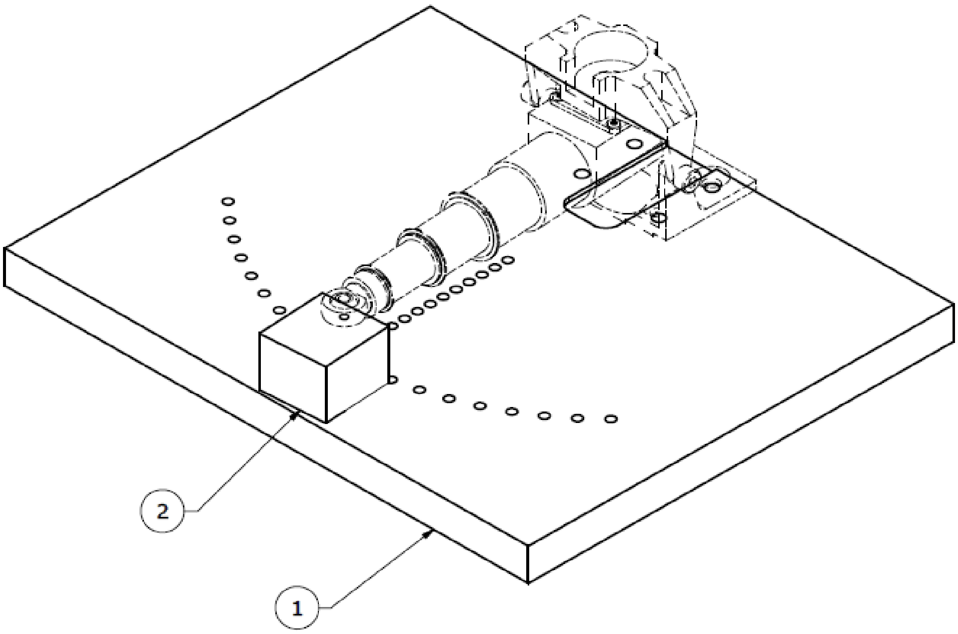


Figure 4-12: Assembly drawing of the jig used in checking the 2D IR-Tracc calibration

As may be expected, the potentiometer mounted at the base of the IR-Tracc did not appear to be affected by the orientation of the IR-Tracc rod. Therefore, the investigation focussed primarily on the y-axis (straight line) measurements provided by extending and shortening the IR-Tracc itself.

For the purposes of consistent analysis a point towards (but not at) full extension of the IR-Tracc was defined as the origin. For the majority of the IR-Traccs the point designated as A14 in the drawing package was used for this purpose. Upon shortening the IR-Tracc from this position, a smaller y-axis length would be expected, varying with about 5 mm between the holes.

From the 2D IR-Tracc evaluations, the y-axis output consistently underestimated the displacement of the rod end. This underestimate increased towards the extreme of the measurement range. The worst result obtained from the whole investigation was from THORAX rib 1 where the difference in known and measured output over the 65 mm was 4.3 mm (6.6 %).

The underestimate error did seem to be affected by the orientation of the IR-Tracc rod; however, the effect was not as large as expected based on the concerns raised previously. The change in error with a ± 180 degree twist varied between 0.1 and 1.3 mm (mean = 0.5 mm). Therefore the additional error could be in the region of around 2 % over the expected measurement range in the dummy.

It should be noted that the length of the wire running from the base to the end of the IR-Tracc was short enough that not all combinations of ± 180, ± 360 degrees could be evaluated. In many orientations the wire would pull tight and restrict the available measurement range.

Also of importance was the fact that no clear orientation could be identified as the best position before testing was undertaken. In many cases two options were very similar in output.

On the basis that the differences between two orientations separated by 180 degrees were typically small, could not be readily identified without testing and that the wire tension could limit measurement range; it is recommended that the IR-Tracc be installed in an orientation which minimises strain on the wiring. This seems to be the most important feature in obtaining accurate measurements through a suitable range.

4.5.1 Summary of IR-Tracc orientation investigation

In summary it does not appear that the 2D IR-Traccs fitted in the WorldSID-5F tested at TRL were not susceptible to the same affect from rod orientation seen in other cases. Small differences in the measurement accuracy were observed with the addition of twists to the IR-Tracc rod. However, in the most part these twists had the more important effect of limiting the available measurement range before tension was exerted on the wiring. For this reason it is suggested that the optimal orientation for IR-Tracc installation (without going to the trouble of testing every option) would be to choose that with the least potential for strain on the wire running from the base to the rib attachment end.

Furthermore there seems to be an increased risk of damage to the IR-Tracc with the wire leaving the end of the rod exiting form the superior side (See Section 5.1 on robustness). The orientations where this would be the case should be avoided. As such the orientation of the IR-Tracc should be chosen so that the wire leaves the lateral end of the rod via the inferior side and with the minimum possible twists along the rod.

As a point of interest, with a live feed from the data acquisition system it was clear that small rotations of the IR-Tracc rod appeared to influence the output. Based on the other results, it is expected that this was not a result of the rotation itself. Instead it seems that any bending moment applied to the IR-Tracc could cause more (or maybe less) of the signal to be lost from the transmission. For this reason it seems important, whenever possible, to check that IR-Traccs are free from bends and the telescoping rods are free-sliding over one another. If an IR-Tracc has become damaged in any way these results suggest that the measurement outputs will be affected and the calibration will no longer be accurate.

4.6 Pelvis interaction

Concerns had been raised in the WorldSID-5F Technical Evaluation Group over a non-instrumented load path in the pelvis. Apparently, contact can occur between the pelvis bone and the metal pelvis insert (which provides the mounting for the pelvis instrumentation and spine attachment). To detect contact, and the duration of that contact, a solution has been demonstrated where self-adhesive conductive foil is wrapped around the appropriate part of the pelvic bone to make a contact switch with the pelvis insert. A similar approach was taken at TRL to detect such a contact.

In the initial preparation of the dummy pelvis before testing, the pelvis bone mouldings (pelvis iliac wings) were inspected for indentation or scratch marks where contact may have occurred in previous testing with the dummy. Two areas were noted as having contact marks. These were correlated with the likely impact area on the metal pelvis insert and lumbar spine assembly. These areas were:

- The lower pelvis iliac wing with the sacro-iliac load cell and lumbar load cell cable cover
- The upper central pelvis iliac wing with the lumbar spine mounting plate

These are shown in Figure 4-13.

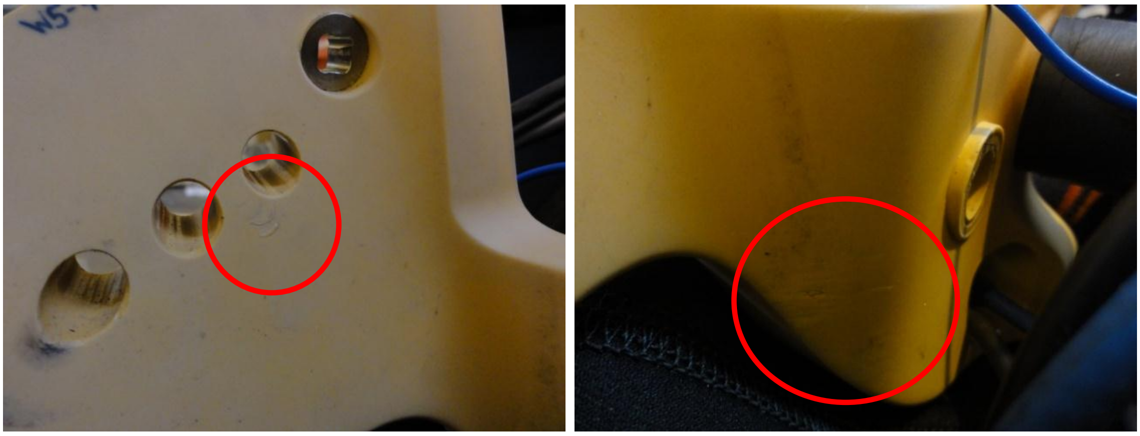


Figure 4-13: Contact marks on pelvis bone from previous testing

These areas and the corresponding area of the lumbar and sacro-iliac structure were fitted with the contact switches. The contact switches are shown in Figure 4-14.

Figure 4-14: Contact switches fitted to pelvis bone moulding and corresponding impacts points on the pelvis iliac and lumbar structures

A series of pendulum tests to impact the pelvis was used to evaluate the severity of test at which the contact occurs. The dummy was seated on a metal bench and impacted with a 14.7kg 145mm circular faced pendulum. The test speed was increased in increments of 1m/s from 3m/s to 7m/s.

Humanetics provided modified parts with smaller volumes in critical areas to evaluate whether this improved the situation. Comparisons of the original parts (left) modified parts (right) are shown in Figure 4-15.

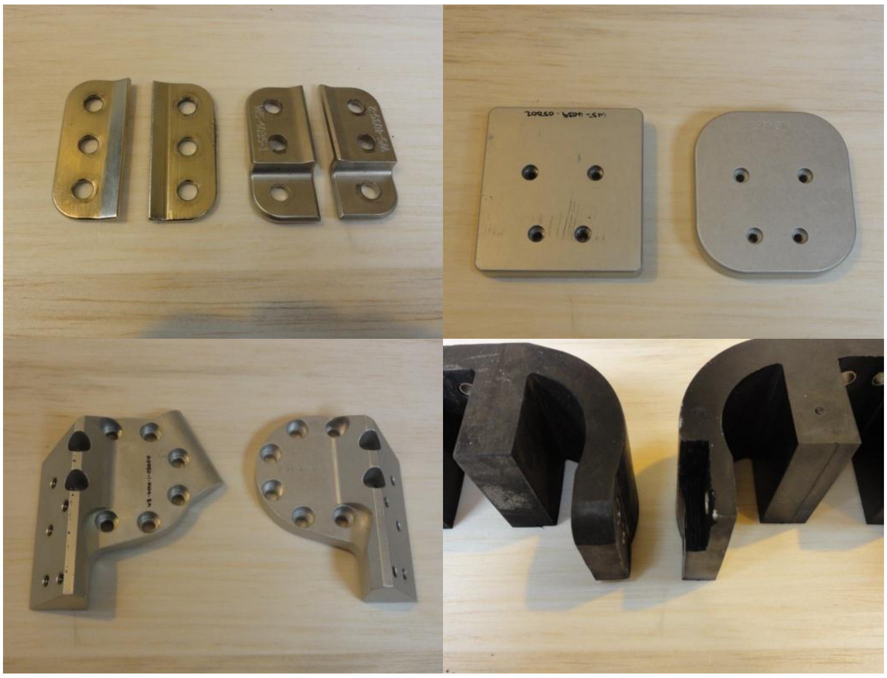


Figure 4-15: Original and modified sacro-iliac and lumbar parts

The modified parts were fitted to the dummy and the testing series was repeated. The results of the contact switches are shown in Table 4-11.

Table 4-11: Results of pendulum testing with original and modified pelvis-iliac and lumbar spine components

Test speed (m/s)	Original parts				Modified parts			
	Upper contact	Duration (ms)	Lower contact	Duration (ms)	Upper contact	Duration (ms)	Lower contact	Duration (ms)
3	No	-	-	-	No	-	No	-
4	No	-	Yes	8	No	-	No	-
5	Yes	7	Yes	10	No	-	Yes	5
6	Yes	10	Yes	13	Yes	3	Yes	2
7	Yes	10	Yes	14	-	-	-	-

NB. Test speed for 6m/s modified parts test was 5.83m/s.

The results show that there is contact at the lower part of the pelvis bone with the sacro-iliac load cell from 4m/s and upwards. The results show that there is contact with the upper part of the pelvis bone and lumbar spine mounting plate from 5m/s and upwards. These results improve with the modified parts to 5m/s and 6m/s respectively. However this improvement would not be enough to remove contact at the higher speed tests, as required for the ISO TR 12350 (ISO, 2010) test series for developing injury risk functions.

4.7 Pelvis-rib interaction

In previous tests with the 50th percentile WorldSID it had been noted that it may be possible to accidently seat the dummy with either:

- The lower abdomen rib on the flat upper face of the anterior pelvis flesh
- The anterior pelvis flesh pushed behind or “tucked under” the lower abdomen rib

In order to investigate the effect of this and a possible solution to the problem, additional tests were performed with the WorldSID-5F dummy. These tests enabled responses from the dummy, when seated correctly, to be compared with those from the dummy when seated with the anterior pelvis flesh pushed behind the lower abdomen rib. In order to push the anterior pelvis flesh under the lower abdomen rib, the dummy had to be leaned forward on the seat, the pelvis flesh tucked under the rib, and then the dummy leaned back into position.

The tests performed were sled tests at 5m/s with just the MCW abdomen plate and load cells on the impact face. Each test was repeated.

The dummy pelvis when seated normally and when tucked under the rib are shown in Figure 4-16.

Figure 4-16: Standard dummy setup (left) and dummy setup with pelvis-rib interaction (right)

The lower abdomen rib rotation and change in length in IR-Tracc are shown in Figure 4-17. The resultant displacement is shown in Figure 4-18.

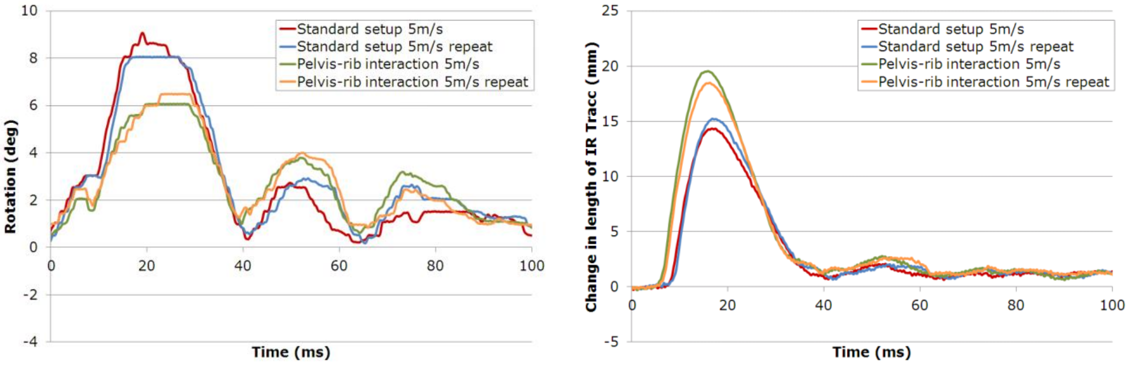


Figure 4-17: Lower abdomen rotation and change in length of IR-Tracc for standard dummy setup and setup with pelvis-rib interaction

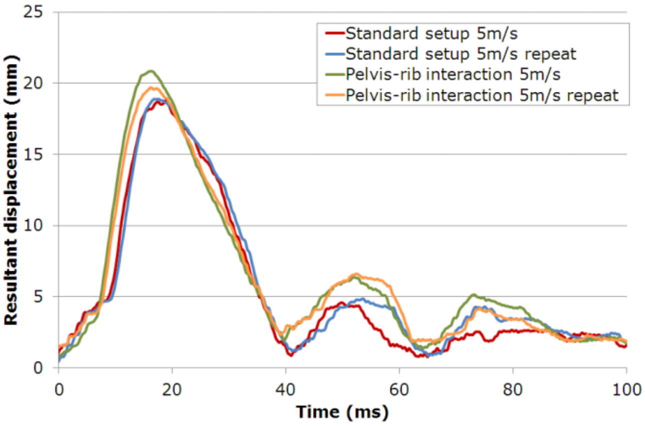


Figure 4-18: Lower abdomen resultant displacement for standard dummy setup and setup with pelvis-rib interaction

Figure 4-17 shows that in the test with forced pelvis-rib interaction (with the pelvis flesh deliberately pushed under the abdominal rib) there is less rotation, but greater change in IR-Tracc length than in the standard test. Figure 4-18 shows that this results in a slightly greater resultant displacement for the test with pelvis-rib interaction.

In order to reduce the possibility of accidently seating the dummy with the pelvis flesh interacting with the lower abdomen rib, modifications were made by TRL to the anterior pelvis flesh. Parts of the flesh were cut away to reduce the volume of the flesh in this region. The profile of the anterior surface was not affected by the removal of the foam behind it, although the stiffness of this part of the pelvis flesh would be reduced. Figure 4-19 shows the flesh before and after the modification. Figure 4-20 also shows the flesh after modification.

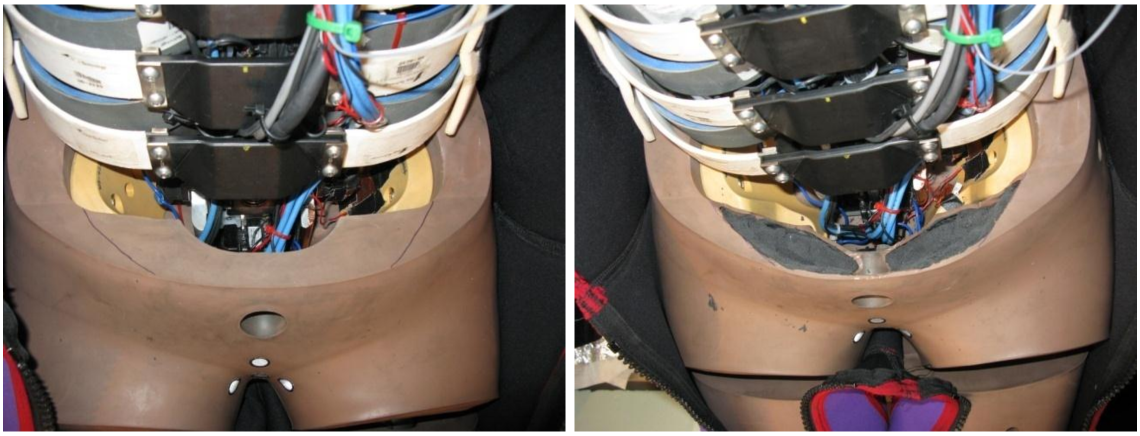


Figure 4-19: Anterior pelvis flesh before (left) and after (right) modification

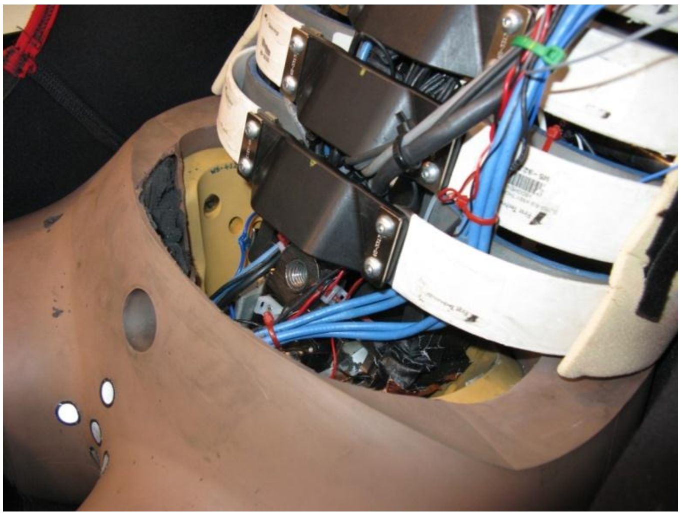


Figure 4-20: Anterior pelvis flesh after modification

With the modified pelvis flesh it was now not possible for the anterior pelvis flesh to be pushed inside the lower abdominal rib and stay there when seated for a test. Two sled tests were performed with the modified pelvis flesh. The lower abdomen rotation and change in length in IR-Tracc are shown in Figure 4-21. The lower abdomen resultant displacement is shown in Figure 4-22.

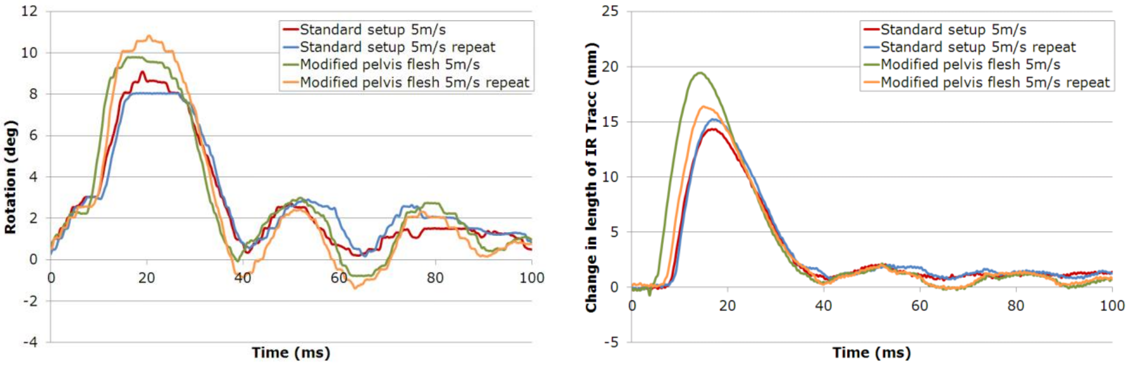


Figure 4-21: Lower abdomen rotation and change in length of IR-Tracc for standard dummy setup and modified pelvis

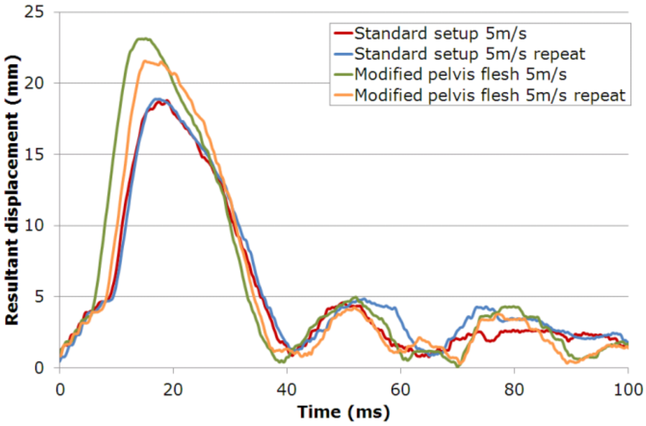


Figure 4-22: Lower abdomen rib resultant displacement for standard dummy setup and modified pelvis

Figure 4-21 shows that both the lower abdomen rib rotation and change in length in IR-Tracc are greater in the test with the modified pelvis. This results in a greater resultant displacement as shown in Figure 4-22.

The abdominal load plate forces are shown in Figure 4-23. The time axis has been set to zero at the last time the response crosses zero force, prior to the peak loading. The results from the force plate show that the forced pelvis-rib interaction tests have a higher peak force than the standard set-up. This indicates that the pelvis-rib interaction is making the abdomen of the dummy stiffer. With the pelvis flesh modification, the force response falls somewhere between the previous two test options.

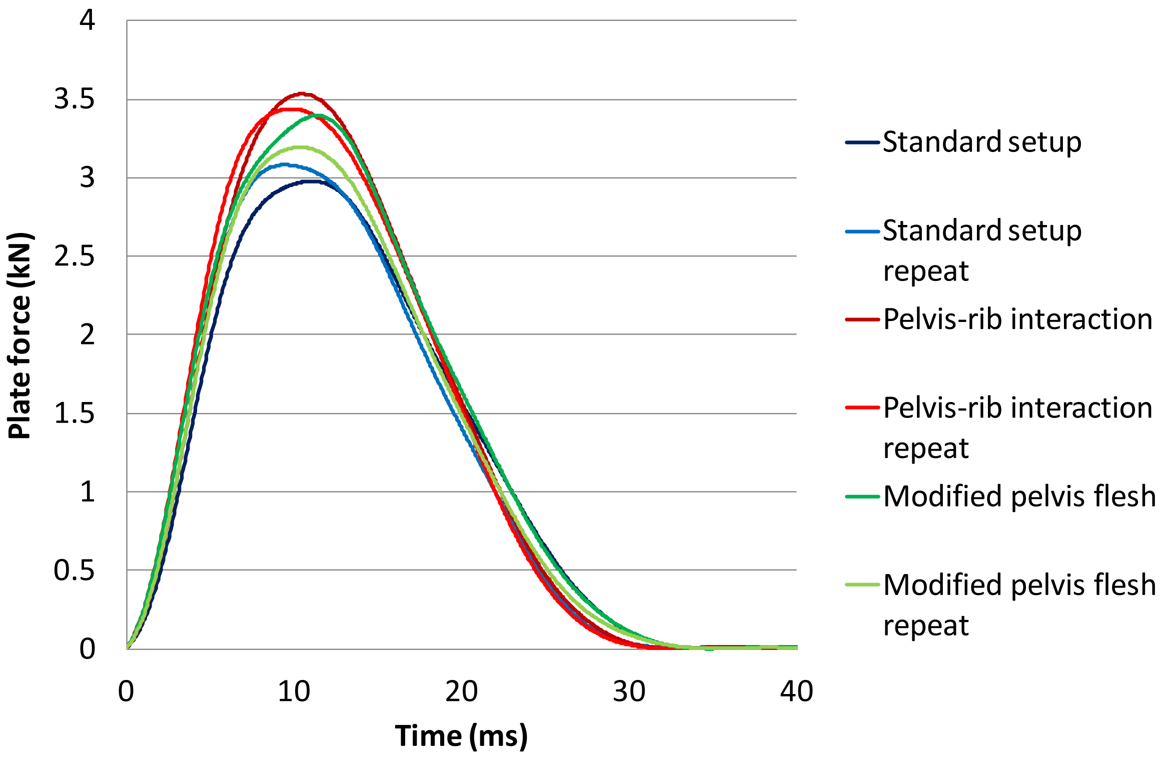


Figure 4-23: Abdomen load plate forces from pelvis-rib interaction tests

5 Robustness and handling

As the WorldSID-5F is a relatively new dummy, in terms of level of use and testing experience, there may be interest in handling, use and robustness issues. For this reason the issues identified during the TRL tests are documented below.

Firstly, it is important to note that the dummy was used in 26 sled tests and 60 pendulum impacts. Throughout this test programme the dummy functioned well.

5.1 Robustness

The following detailed robustness issues were noted:

- On arrival at TRL the lifting bracket for use with the dummy was fitted. However, the thread for the top mounting bolt had been stripped. For this reason the lifting bracket could not be used. As the dummy should only be lifted via this bracket formal interpretation of this requirement would have meant that no testing could have been completed. It is not clear how this damage had been caused, although it is known that it can be difficult to attach the lifting bracket if the dummy is sitting with a particularly flexed or extended lumbar spine.
- Between two of the pendulum tests communication was lost with one of the TDAS G5 in-dummy data acquisition modules. To the rear of the dummy the status lights indicated a fault, whilst the other module was operating correctly still. Suspecting that the fault might be caused by loss of power to the module the dummy’s suit was unzipped and cables tracked beneath the sternum parts. It was discovered that the connector into the in-dummy mini-distributor was loose. This connector is held in place by a retaining bar. It was observed that with only a couple of connectors being used, it is possible to install the bar with one end much less well engaged than the other. This puts uneven support on the back of the connectors and in this particular case had allowed one to come loose.
- During the sled tests a similar fault occurred, as described in the previous bullet point. However, on inspection the connector was not loose. Thinking that there may be some benefit in identifying the communication issue, the positions of the connectors from the G5 modules to the mini-distributor were swapped. This did not help in reinitiating communications with the G5. However, when the connectors were restored to their original places the fault was cured. It is not known which part of this process resolved the problem. It could have been that the act of swapping the connector released some cable strain hence easing a break in a cable or connector. However, it is suspected that the more probable action was to remove power supply from the G5, letting it reset itself.
- In one of the pendulum tests it was noticed that the lowest abdominal IR-Tracc became noisy after the impact. When the dummy was inspected it was observed that the wiring from the IR-Tracc had been trapped under one of the superior ribs. Evidently that upper rib had rolled forward during the impact trapping the wire and had not returned to a neutral position after the test. When the wires were released the signal quality from that IR-Tracc improved again. An additional cable-tie was used behind the dummy’s sternum parts to prevent this from happening again.

- Coincidently, during the sled tests the signal from the lower abdominal IR-Tracc again became noisy following a test. However, in this instance the wires from the IR-Tracc were not trapped. On disassembly it was discovered that contact with the upper abdominal rib had damaged the wire running from the base to the tip of the IR-Tracc. Closer inspection revealed a break in the cable. Attempts were made to repair this break but to no avail. The risk of this contact occurring for all ribs leads to the suggestion that the IR-Traccs should be orientated so as to force this fragile wire away from the superior rib.
- During both the pendulum and sled testing unexpected results were seen with the rotation of the IR-Tracc in the 2nd thorax rib. On multiple tests the rotation of the rib on the rebound phase would stop for approximately 5ms and then rapidly return to the expected path of rotation. After the rib was disassembled and reassembled the issue was not seen again. This issue may be solved by single rib calibration or certification. This issue is discussed further in Appendix B.

5.2 Handling

As a result of the robustness issues and wanting to investigate the benefit of new pelvis designs, much time was spent working on the dummy and assembly/disassembly. Based on these experiences it has become clear that some comments are warranted regarding the ease of using the WorldSID-5F.

1. The pelvis was disassembled and reassembled four times during the testing programme. This is an extremely time-consuming job. There appears to be no easy way of sliding the pelvic bone back into the pelvis flesh. As a result it is very easy to put a lot of strain onto the cables running between the upper body of the dummy and the pelvis. It seems unrealistic to expect a dummy technician to do this on a routine basis. Consideration should be given to making this task easier for the sake of protecting instrumentation and easing the process for the technician.
2. It is not clear why the cabling running from the data acquisition modules in the upper body of the dummy to the pelvis and legs cannot be split where the dummy is split. This seems as though it would be an extremely useful design feature to mitigate the risk of instrumentation damage when working on the dummy whilst being separated top to bottom. At the very least sufficient cable lengths should be supplied to allow a reasonable distance between the two dummy portions.
3. It is very difficult to attach the bolts that hold the femoral heads into the acetabula of the pelvic bone with the full complement of instrumentation in the dummy pelvis.

6 Summary and discussion

6.1 Biofidelity

The biofidelity of the WorldSID-5F shoulder was evaluated in pendulum tests. The results show that the shoulder of the dummy is slightly too stiff.

The dummy thorax was evaluated in both pendulum tests and the Heidelberg sled tests. The dummy thorax is also too stiff. The pendulum test results were of too short a duration to fit within the response corridor and whilst the Heidelberg plate responses fitted within the corridor, that result would be marginal if tested at the correct speed.

The Wayne State University (WSU) tests provided an evaluation of the abdomen biofidelity. This was also found to be too stiff; exceeding the upper limit of the abdominal plate force response.

Finally, based on the force plate responses from both the Heidelberg and WSU sled tests, the WorldSID-5F pelvis also seems to be too stiff. The responses exceed the biofidelity requirements even at lower test speeds than defined in the biofidelity test specification.

Of interest may be that the WSU pelvis plate response is closer to the corridor at 6.3 m/s than the Heidelberg plate force was at 5 m/s. This may indicate slightly conflicting design guidance from these two tests. However, the main issue of the pelvis being too stiff is clear.

In all cases the dummy responses have been compared against the requirements after having been normalised according to the ISO TR 9790 process. If it was to be decided by ISO that the dummy response should be compared with the requirements before normalisation instead, then this could be done. In some cases, where clarity of results allows for showing two response options, the pre-normalised results are already shown above. The normalisation has a substantial effect on the results and it is therefore important to define exactly which results are considered most relevant for the international research community. The authors have tried to accommodate those discussions and ease of use for the data generated within this test work, wherever possible.

It is not clear whether the previously published WorldSID-5F Revision 1 biofidelity (Eggers *et al.*, 2009) included normalised responses throughout. If not, it may be that the overall biofidelity rating could be different. Assuming that the same responses are being compared, then these results are unlikely to produce a substantial change in the overall biofidelity rating which was 7.6 ‘Good’ using the ISO rating system. Note that this was shown to be an improvement over other side impact dummies when reported for the WorldSID-50M (EEVC WG12, 2009).

6.1.1 Impactor alignment

Two options for impactor alignment were investigated during the ISO TR 9790 Thorax Test 1 testing. One option aligned the middle of the impactor with the middle of the mid-thoracic rib. The other option aligned the bottom edge of the impactor with the lowest edge of Thorax rib 3. This second option positions the impactor a few millimetres above the first option. The differences in results attributed to the varying set-up for these two options can be seen in the figures presented in Section 4.2.1. It was observed that the alignment options produced little difference in the spine acceleration response but a substantial difference in the pendulum force.

It is not known how precise the impactor alignment was in the original PMHS tests used to define this test. Some variation in relative impact height would be expected from subject to subject. The sensitivity of the dummy to this set-up feature is clear. For this reason it is suggested that the design requirement based on ISO TR 9790 should be for the dummy response to be in the middle of the corridor. This would remove the possibility to make use of the impact alignment sensitivity to 'improve' the dummy biofidelity. That is, the potential for test results with one alignment to be outside of the corridor whilst another alignment would give results just inside the corridor.

Perhaps, of equal important are comments on the ease of set-up. With the dummy fully suited, alignment with the lower edge of the third thoracic rib is easier than trying to pick out the middle of the second thoracic rib. Understanding this and the sensitivity of the dummy to small changes in impact alignment, it is suggested that the standard alignment for these tests with the WorldSID dummies should be changed to the lower edge of the thorax ribs. Alternatively solutions could be prepared where the dummy can be tested without a suit. For instance, representative thorax foam and jacket parts could be supplied to fix to the impactor surface allowing the dummy to be tested without those coverings.

6.2 Injury risk functions

Peak values taken from the TRL testing have been documented in the relevant sections above.

Data from the test work have been made available to the ISO Working Group 5. These data will form the basis of ongoing efforts by that group to develop risk functions for the WorldSID-5F.

All target test severities for matched PMHS tests to be used in the injury risk function development could not be achieved with the WorldSID-5F due to concerns over its durability. In particular, it was expected that the high severities required for some tests would lead to:

1. The 2D IR-Traccs rotating forwards in the dummy to reach their mechanical limit. The consequence of which would be the potential to bend the IR-Tracc rods, which would preclude them from offering accurate measurements in the future (i.e. they would need replacing).
2. Contact of the shoulder load cell with the neck bracket. This was not expected to break the dummy but is a behaviour which is not biofidelic and needs to be avoided.
3. Contact between the iliac wing and either the lumbar spine mounting or the sacro-iliac load cell. Again this is a non-biofidelic and uninstrumented load path through the pelvis.

To avoid these issues with the dummy one possible approach is to extrapolate dummy measurements from tests at lower speeds. To enable such extrapolation certain test conditions were performed at a range of low impact speeds. This was in an effort to generate the dummy measurement with speed relationships required for extrapolation to higher speeds. With such information extrapolation would be possible if the WorldSID Technical Evaluation Group wanted to adopt that approach.

As noted in Section 4.2, to demonstrate the potential for this approach, extrapolation of lower speed impact test results was used to generate the data in the last row of Tables 4-2 and 4-3. The justification for the extrapolation of the thorax results is described in that section and the linear relationship between peak deflection and impact speed is shown in Section 3.1.5.

Extrapolation to predict the response in higher severity tests may not be recommended. In this case it is reliant upon the assumption that any relationship established empirically will continue at higher speeds. This will not be the case if there is a non-linear change in the rib stiffness, for example. However, to demonstrate whether or not the behaviour continues in a linear manner it would be necessary to extend the range of severities already tested.

One method of testing the validity of the extrapolated values would be to fit the dummy with an alternative measurement system which can accommodate more chest compression. One could imagine an optical system being used to determine rib displacement if a rib was tested in isolation. This would allow testing to be conducted at higher severities without the risk of damaging the instrumentation. Therefore the linear relationship assumed in the extrapolation could be examined beyond the current maximum speed. To provide information on rib displacements from high severity full body tests it is likely that an advanced instrumentation system will be necessary; as was originally planned to be used within this project.

6.2.1 Shoulder deflection

Discussion within the WorldSID Technical Evaluation Groups and Informal Groups has drawn attention to the fact that the shoulder designs of the WorldSID-5F and WorldSID-50M are different. The WorldSID-50M has the load cell mounted on the outside of the shoulder rib whilst in the WorldSID-5F it is inside the rib (The WorldSID-5F load cell structural replacement can be seen in Figure 6-1). This design difference is not desirable for a family of dummies. Therefore it is expected that some redesign of the shoulder area will be required for one or both of these dummies.

Additionally it is hoped that any redesign will help to prevent the load cell to neck bracket contact, as suspected in causing the mechanical limit to shoulder deflection seen in the WSU tests. This contact will occur when lateral displacement of the shoulder rib is accompanied by vertical motion as well. In the work to develop injury risk functions for shoulder deflection it is this limit on the range of motion which prevents reliable measurements being obtained from tests of the severity prescribed in ISO TR 12350.

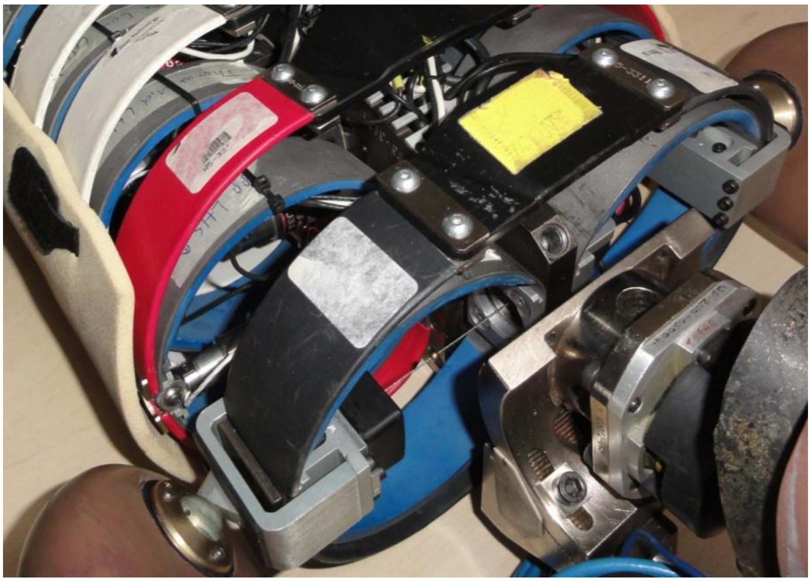


Figure 6-1: Image of WorldSID-5F showing shoulder load cell structural replacement and deflection measuring string potentiometer mounting

If the redesign of the load cell could affect the performance of the shoulder, then it is suggested that further testing will be needed with the revised dummy to confirm its biofidelity (whether it is the same, or more importantly, if improvements are made) and develop appropriate injury risk functions. However, if the design change simply shrinks the size of the load cell and string potentiometer mounting, then it may be that the extrapolated deflection values provided within this report could be used. Noting the general issues with extrapolation beyond the bounds of empirical measurements, the values provided may be of sufficient accuracy to give results comparable with usual confidence limits for injury risk estimates. This should be considered further when the exact design changes (if any) to be implemented with the dummy are known.

6.2.2 Arm interaction

It was found in the WSU tests that the position of the arm had a substantial influence on the dummy measurements. This means that to obtain results which are consistent from test-to-test, care should be taken to ensure a repeatable set-up. The position of the arm should be defined to reproduce as closely as possible the position of the PMHS arm in the original tests.

6.3 IR-Tracc orientation

Limited influence was observed on the basis of the IR-Tracc orientation. However, these are out-weighed by durability and functional requirements for how the IR-Traccs should be installed. Recommendations on how to arrange the IR-Traccs are documented above.

6.4 Pelvis interaction

A concern had been raised from other groups evaluating the WorldSID dummies, that the abdomen behaviour of the dummy was influenced through interaction with the pelvis flesh. In particular, there was a further concern that, in certain set-ups, there was a possibility for the pelvis flesh to become caught under the lowest abdominal rib.

With the WorldSID-5F it was very hard to force the pelvis flesh under the lower abdomen rib. It is the authors belief that is unlikely to occur in normal use of the dummy and that if it does it should be quite obvious with only a quick visual check. However, the pelvis interaction with the lowest abdominal rib was investigated in the TRL sled testing.

With the pelvis flesh forced under the abdomen rib different rib displacements were obtained compared with the normal seated position of the dummy. Therefore, the situation of the rib sitting on top of that flesh part should be avoided in tests with this dummy.

Following this result, the pelvis flesh was modified (cut away) to see if the potential for this interaction could be prevented and whether pelvis interaction affected the normal dummy response. The results with the modified flesh were different again from forced interaction or conventional position. This indicates that even in the normal position the pelvis flesh does indeed influence the motion of the lowest abdominal rib. Greater rib displacement was measured with the modified pelvis. With the modified pelvis it was also no longer possible to keep the flesh in a position stuck under the abdominal ribs.

The pelvis of the dummy was modified by hand (it was cut with a sharp knife), giving a rough shape without a continuous rubber skin. Based on results from this testing Humanetics are investigating the need for a new pelvis flesh mould.

These results were discussed at the Technical Evaluation Group meeting in March 2012. Similar tests with the WorldSID-50M are being conducted in the US. It was decided that these should be finished and the data reviewed before any final decision is made on modifications to the shape of the anterior pelvis flesh. Consideration should also be given to the interaction between the lap belt and the pelvis. Based on the shape of the modified pelvis tested at TRL, reasonable belt retention should still be fine for the WorldSID-5F in a standard vehicle seat and belt configuration. It may be more of a problem for the 50M because this has a lower anterior pelvis flesh.

6.5 Pelvis contact

Contact switches were used to assess when the pelvis bone contacted hard components in the sacro-iliac region. Prototype parts were fitted to the dummy and further evaluations made to see if the parts mitigated or removed the potential for contact. The updated parts did show an improvement but further design modifications are required to prevent such contacts from arising in standard biofidelity tests. Even more improvement would be required if contact is to be avoided in the higher speed tests as specified in ISO TR 12350 for the development of injury risk functions. To avoid contacts in the injury risk tests, one solution would be to prepare a special one-off narrower sacro-iliac load cell. This might avoid having to make overly extensive and expensive modifications to the normal dummy. However, depending on the design solutions possible it may be best to evaluate the exact dummy to be used in later applications throughout the injury risk development process.

7 Conclusions

- A broad programme of tests has been carried out at TRL with the WorldSID-5F
    - This included 26 sled tests and 51 pendulum impacts
- The WorldSID-5F generally performed as expected
    - The dummy biofidelity was shown to be outside of the ISO requirements in a number of areas. However, this performance has been demonstrated previously with the Revision 1 release of the dummy and may still represent a 'good' rating compared with other side impact dummies.
    - Test-to-test use of the dummy is straight forward and no significant issues occurred with the data acquisition system, etc.
- Durability is a problem when trying to achieve test severities needed for the development of injury risk functions
    - Sled tests were limited to impact speeds less than required for the higher severity biofidelity tests
    - Whilst the highest severity injury risk tests may be outside the range of normal reasonable use of the dummy, there is still the need to provide dummy measurements in equivalent tests in order to generate robust injury risk functions
    - Without dummy measurements from high severity tests it may be difficult to generate robust injury risk functions for this dummy
    - Dummy design changes which seem to be necessary to be able to perform these tests are:
        - Improved displacement and angle range of motion for the 2D IR-Traccs
        - Removal of the contact potential between the shoulder load cell and the neck bracket
        - Greater space for iliac wing bending without contact occurring with the sacro-iliac load cell or lumbar spine mounting in the pelvis
- In accordance with the Customer's wishes, results from this test work have already been presented to the WorldSID Informal Group (IG)
    - Test data have also been offered to the ISO WG5
- On the basis of discussions within the Technical Evaluation Group (TEG) meeting, Humanetics has proposed to revise the dummy. The revisions will be based on this test work and similar findings from other groups participating in the TEG
- A new design release will need further checks of biofidelity
    - The updated dummy may offer the possibility to test at higher severities without risk of damage. This should facilitate the development of better injury risk functions.

References

Barnes, A., Been, B., Bermond, F., Bortenschlager, K., Caire, Y., Carroll, J., Compigne, S., Hynd, D. and Martinez, L. (2005). *APROSYS WorldSID 5th Female Requirements.* Aprosys 6th Framework EC Project AP-SP52-0007-D1. APROSYS Project TIP3-CT-2004-506503.

Been, B., Waagmeester, K., Trosseille, X., Carroll, J. and Hynd, D. (2009). WorldSID small female two-dimensional chest deflection sensors and sensitivity to oblique impact. *21st International Technical Conference on the Enhanced Safety of Vehicles, 15-18 June, 2009, Stuttgart, Germany.* 09-0418: US Department of Transportation, National Highway Traffic Safety Administration.

Belcher, T., Terrell, M. and Tylko, S. (2011). An assessment of WorldSID 50th percentile male injury responses to oblique and perpendicular pole side impacts. *22nd Enhanced Safety of Vehicles Conference (ESV), 13-16 June 2011, Washington, D.C., U.S.A.* Washington, D.C., U.S.A.: U.S. Department of Transportation, National Highway Traffic Safety Administration (NHTSA).

Boxboro Systems (2007). *User's Manual: RibEye multi-point deflection measurement system 2-axis version for 50th male Hybrid III ATD.* Boxboro Systems, LLC.

Boxboro Systems (2009). *Hardware user's manual: RibEye multi-point deflection measurement system 3-axis version for the WorldSID 50th ATD.* Boxboro Systems LLC.

Boxboro Systems (2011). *Hardware user's manual: RibEye multi-point deflection measurement system 3-axis version for the WorldSID 50th ATD.* Boxboro Systems LLC.

Cavanaugh, J., Zhu, Y., Huang, Y. and King, A. (1993). *Injury and response of the thorax in side impact cadaveric tests.* 37th Stapp Car Crash Conference, 8-10 November, 1993, San Antonio, Texas, USA: Society of Automotive Engineers, Warrendale, PA, USA, pp.199-221.

Edwards, M., Hynd, D., Cuerden, R., Thompson, A., Carroll, J. and Broughton, J. (2010). *Side Impact Safety.* Published Project Report PPR501. Crowthorne: TRL.

EEVC WG12 (2009). *Status of WorldSID 50th percentile male side impact dummy.* Report to the EEVC Steering Committee EEVC WG12 Report Doc547. European Enhanced Vehicle-safety Committee (EEVC) Working Group 12. EEVC

Eggers, A., Schnottale, B., Been, B., Waagmeester, K., Hynd, D., Carroll, J. and Martinez, L. (2009). Biofidelity of the WorldSID small female revision 1 dummy. *21st International Technical Conference on the Enhanced Safety of Vehicles, 15-18 June, 2009, Stuttgart, Germany.* US Department of Transportation, National Highway Traffic Safety Administration.

Hynd, D., Carroll, J., Been, B. and Payne, A. (2004). *Evaluation of the shoulder, thorax and abdomen of the WorldSID pre-production side impact dummy.* IMechE Vehicle Safety Conference, 14-15 December, 2004, Westminster, London, UK: Institution of Mechanical Engineers.

Irwin, A. L., Mertz, H. J., Elhagediab, A. M. and Moss, S. (2002). *Guidelines for assessing the biofidelity of side impact dummies of various sizes and ages.* Stapp car crash journal, 46 (2002). Proceedings of the 46th Stapp car crash conference, 11-13 November 2002, Pointe Verdra Beach, Florida, U.S.A.: Warrendale, PA, U.S.A., Society of Automotive Engineers, Inc. (SAE).

ISO (1999). *ISO TR 9790: Road vehicles - anthropomorphic side impact dummy - lateral response requirements to assess the biofidelity of the dummy.* ISO.

ISO (2010). *ISO/TR 12350:2010 Road vehicles - injury risk curves to evaluate occupant protection in side impact.* ISO/TR 12350:2010. ISO.

Jensen, J., Berliner, J., Bunn, B., Pietsch, H., Handman, D., Salloum, M., Charlebois, D. and Tylko, S. (2009). Evaluation of an alternative thorax deflection device in the SID-IIs ATD. *21st International Technical Conference on the Enhanced Safety of Vehicles, 15-18 June, 2009, Stuttgart, Germany.* 09-0437: US Department of Transportation, National Highway Traffic Safety Administration.

Maltese, M., Eppinger, R., Rhule, H., Donnelly, B., Pintar, F. and Yoganandan, N. (2002). Response corridors of human surrogates in lateral impacts. *46th Stapp Car Crash Conference, 11-13 November, 2002, Ponte Vedra Beach, Florida, USA.* 2002-22-0017: Society of Automotive Engineers, Warrendale, PA, USA, pp.321-351.

Marcus, J., Morgan, R., Eppinger, R., Kallieris, D., Mattern, R. and Schmidt, G. (1983). *Human response to and injury from lateral impact.* 27th Stapp Car Crash Conference, 17th to 19th October, 1983, San Diego, California, USA: Society of Automotive Engineers, Warrendale, PA, USA, pp.419-432.

Roberts, A. K., Lowne, R. W., Beusenberg, M. and Cesari, D. (1991). *Test procedures for defining biofidelity targets for lateral impact test dummies.* Proceedings of the 13th international technical conference on Experimental Safety Vehicles (ESV), 4-7 November 1991, Paris, France, Washington, D.C., U.S.A.: US Department of Transportation, National Highway Traffic Safety Administration (NHTSA), pp.956-967.

Tylko, S., Charlebois, D. and Bussières, A. (2007). Comparison of the kinematic and thoracic response of the 5th percentile Hybrid III in 40, 48 and 56 km/h rigid barrier tests. *20th International Technical Conference on the Enhanced Safety of Vehicles, 18-21 June, 2007, Lyon, France.* 07-0506: US Department of Transportation, National Highway Traffic Safety Administration.

Yoganandan, N., Pintar, F. and Rinaldi, J. (2009). *Evaluation of the RibEye deflection measurement system in the 50th percentile Hybrid III dummy - final report.* DOT HS 811 102. Milwaukee, WI: Medical College of Wisconsin. National Highway Traffic Safety Administration (NHTSA), U. D. o. T.

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- Humanetics who provided the WorldSID-5F dummy for the test work
    - They were extremely understanding (and encouraging) through discussions about the need to irreversibly modify the pelvis flesh
    - Updated pelvis parts were also rushed through production. These were critical to the investigation of potential solutions for the pelvis contact issues
- Transport Canada who lent to TRL the very rare sacro-iliac loadcell

Appendix A Evaluation of RibEye (literature review)

A.1 RibEye performance

The performance of a measurement system in a dummy will be considered primarily regarding the end use for the dummy, so the performance in full-scale regulatory or consumer crash tests. However, there are many different aspects to this performance which can be controlled, or at least monitored. For instance, the measurement device should be calibrated under tightly-controlled and known conditions before fitting to the dummy, then standard installation-ready performance can be certified. At this stage there will be a known accuracy and measurement range of the system, independent of its application. Once installed in a dummy, installation-specific performance may be slightly different. This is usually determined on the basis of laboratory or component-level testing. Finally whole body calibration testing of the dummy and full-scale performance can be evaluated.

Before adoption of a new measurement system for ‘end use’ it is important to understand the performance at each of the stages described above. The following sections of the report document what is known about the RibEye optical measurement system in each case.

It should be noted that the RibEye system will be tailored to the dummy in which it is being implemented. Therefore whilst basic functional specifications may remain similar for each dummy system, most aspects of performance will be installation specific, to some extent.

A.1.1 Calibration and certification

In the RibEye User’s manual for the WorldSID 50th percentile male dummy (Boxboro Systems, 2009), it states:

> “To check the calibration of the RibEye, the LEDs were moved in increments of 5 mm through the dummy’s x-y plane at center-LED z offsets of 0 mm, ± 10 mm, ± 15 mm, ± 20 mm, and ± 25 mm.”

The calibration report would then show plots for x-y plane measurements for each rib at each of these z-axis offsets. The accuracy of the system could be judged by the difference between the measured x-y position and the known position at which the measurement was taken.

In the RibEye User’s Manual for the Hybrid III 50th percentile dummy (Boxboro Systems, 2007) it specifies that the RibEye controller continuously adjusts how hard it drives the LEDs to get a good signal from the sensors. Also, the calibration curves to process the LED data are specific to the rib (z-axis location) and side (y-axis location) to which the LED is mounted. For this reason the rib to which each LED should be fitted is specified.

A.2 Accuracy of RibEye as a measurement instrument

For the RibEye installation in a WorldSID 50th percentile female, Boxboro Systems (Boxboro Systems, 2011) make the following statement regarding measurement accuracy:

> "The maximum error for the Y and Z data is less than 1 mm, and the maximum X error is less than 2 mm"

This statement relates to measurements within a measurement range. This range is depicted in Figures A-1 and A-2.

It should be kept in mind that these show a maximum measurement range for the particular RibEye system. The initial LED positions used with the dummy will fall within this range. Therefore, the measurable compression may be quite different from the total range of the system.

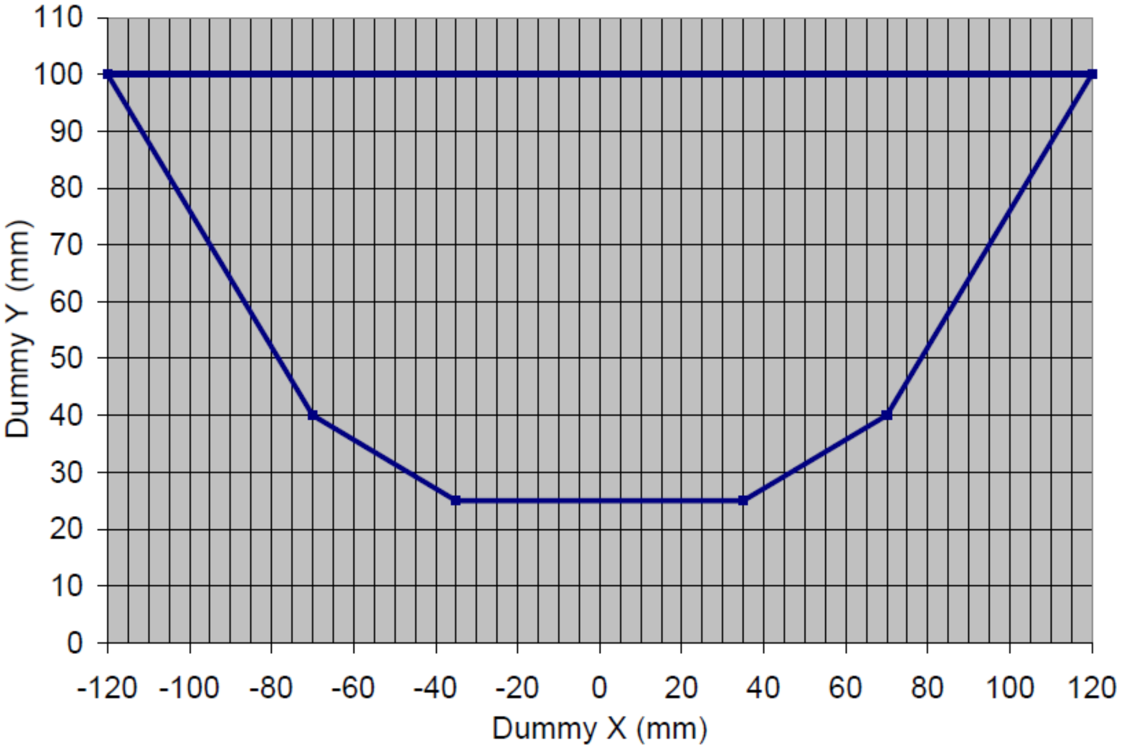

Figure A-1: RibEye measurement range for the WorldSID 50th percentile dummy 3-axis installation in the X-Y plane (Boxboro Systems, 2011)

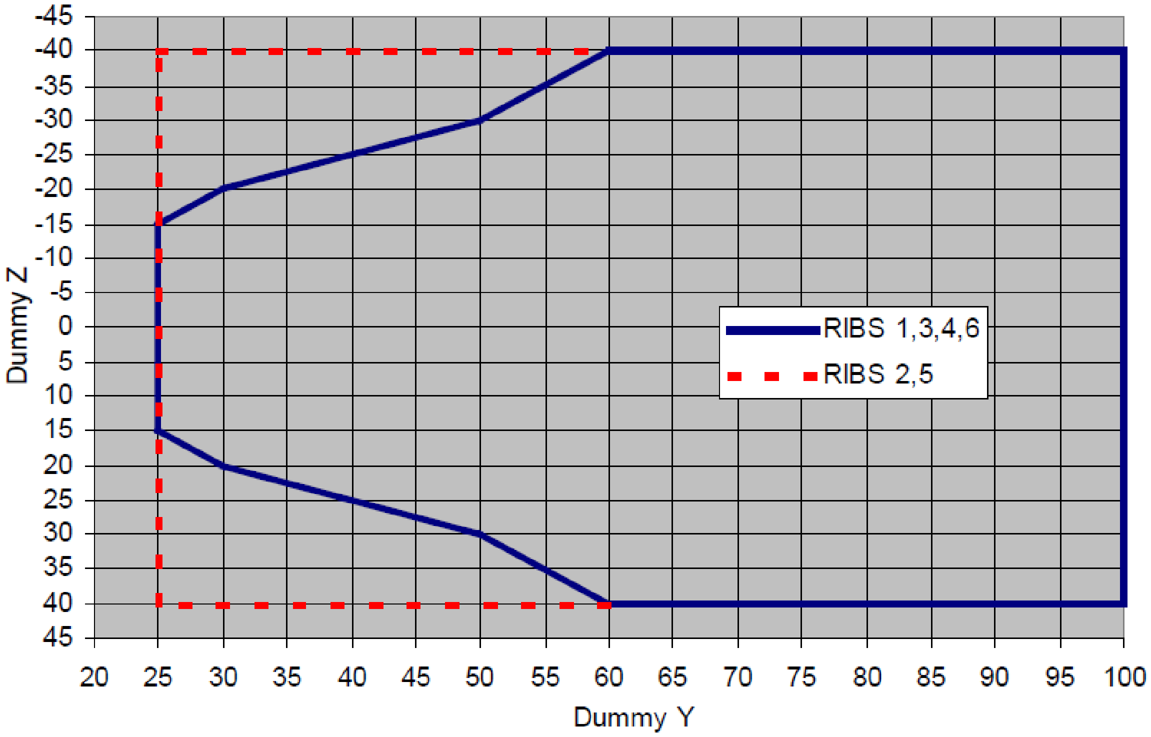

Figure A-2: RibEye measurement range for the WorldSID 50th percentile dummy 3-axis installation in the Y-Z plane (Boxboro Systems, 2011)

When comparing the User's manuals for the 2-axis and 3-axis RibEye systems available for installation in a Hybrid III 50th percentile dummy it can be noted that the accuracy is better with the 3 axis system. In that case, the measurement accuracy for all LEDs for all axes is guaranteed to be better than 1 mm. Whereas with the 2 axis system, the accuracy can be within 2 mm depending on the z (non-measured) axis deflection of the rib.

A.2.1 Comparison with alternative measurement systems

It has been shown previously that the single point, single axis IR-Tracc (Infra-Red – Telescoping Rod for Assessment Chest Compression), fitted as standard in the WorldSID, is not able to measure rib loading under oblique loading conditions correctly (Hynd *et al.*, 2004). Tests with an isolated WorldSID rib have shown that the measured rib compression markedly underestimates the actual compression in oblique loading conditions. Also, it does not provide any information to quantify the extent and effects of any oblique loading.

To address this limitation, the WorldSID 5F (5th percentile female WorldSID) was developed with a two-dimensional IR-Tracc compression measurement system. This consists of a conventional IR-Tracc but with a potentiometer at its base to enable displacement of the measurement point to be calculated in the transverse (x-y) plane. Through assessment within the EC APROSYS Project, Been *et al.* (2009) found that the 2D IR-Tracc was useful in understanding phenomena taking place under various lateral oblique loading conditions that could not have been understood with a conventional 1D compression sensor. "The calculated lateral displacement Y offered a simple and straightforward parameter to improve the sensitivity to oblique impacts, as compared to the current single axis deflection sensor."

The RibEye facilitates calculation of the same measurements as the 2D IR-Tracc, or indeed a 1D system. Therefore, it offers equivalent compression assessment abilities to the IR-Traccs. In addition, the use of RibEye also provides the potential to assess compression at more than one point for each rib.

A.2.2 Measurement range

In order for the RibEye system to track optically the position of the LED markers, then there must be sufficient light received, from each marker, by the sensors (Yoganandan *et al.*, 2009). If the light intensity drops below a critical threshold, then the signal for that marker will drop-out. LED signal drop-out may occur either because the rib bending directs the LED light beam away from the sensor(s) or because the light beam is obstructed by another component of the dummy. Drop-out can also occur if an LED moves too far, beyond the measurement range, as was shown for the WorldSID example above. In this case it may be the angle of the LED with respect to the sensor or obstruction from the edge of the sensor itself which eventually causes the drop-out, rather than just the RibEye providing measurements of an accuracy below the levels specified in the User's manual.

When set-up for use in the 50th percentile male Hybrid III dummy, the RibEye system allowed over 70 mm of chest deflection in the x-axis before measurement drop-out occurred (Yoganandan *et al.*, 2009). This result was achieved using the LED markers positioned 9 cm from the centreline (mid-sagittal line) of the dummy thorax. However, about 65 mm could be achieved with the markers mounted on the sternum of the Hybrid III, which is more than the U.S. injury assessment reference value of 63 mm. This performance of the system was assessed using table-top indentor tests, with either a round or rectangular loading plate. It was found to be independent of loading rate.

It should be noted that the minimum measurement distance from the sensor varies with each installation. In the latest version of the WorldSID installation, the minimum y-axis measurement is about 25 mm. In the equivalent 3-axis installation for the Hybrid III it is 40 mm in the x-axis. However, what also needs to be taken into account is that the initial LED position with respect to the sensor will also be different in these dummies. This starting distance is not described precisely in the manuals and would be expected to vary according to which particular rib is being measured and the condition (e.g. if there is any permanent offset) of that rib.

A.2.3 Performance in component and laboratory testing

The RibEye evaluation reported by Jensen *et al.* (2009) was intended to assess the accuracy of the system in different loading conditions. The study used linear impactor tests of a thorax component, a series of drop tower tests of the instrumentation itself, and then full-scale, whole dummy vehicle crash tests.

Ten linear impactor tests (at 4.9 m/s) were conducted by Jensen et al. to compare the response of the RibEye system in the SID-IIs dummy with the responses from rib accelerometers and high speed video analysis. The direction of impact was intended to generate y axis loading only. Comparative testing with the original deflection measurement instrumentation was not conducted. Instead, each rib acceleration response was double integrated to provide a rib deflection estimate.

Jensen *et al.* identified inaccuracies in the LED placement at all locations. This had caused improper calibration of the RibEye system. More importantly, Jensen *et al.* had attempted to fix the spine box of the SID-IIs to a rigid mount for the testing. This mounting was observed to move during the impact, thereby giving errors in the accelerometer and film analysis data.

A series of drop tower tests was used to compare RibEye measurements with linear potentiometers. The test fixture allowed orientations where either one axis or multiple axes of the RibEye system were aligned with the direction of loading.

The first drop tower test showed good correlation between the RibEye system, the linear potentiometers, and the image analysis. The difference between the maxima measured at the front potentiometers was 0.04 mm. At the rear potentiometer this difference was 0.6 mm, though it was reported that this difference in accuracy may have been because of vibrations or tilting of the upper plate during the impact. The discrepancy in results at the rear position was greater at faster impact speeds (up to 10 m/s, giving a difference of 1.4 mm to 1.6 mm).

A second series of drop tests was used by Jensen *et al.* to investigate the potential for oblique loading to create measurement inaccuracies. The RibEye sensors were tilted 10 degrees about the x-axis and 20 degrees about the z-axis, and three tests were conducted at 5 m/s. Jensen *et al.* observed that the RibEye measurements (after being converted so that the coordinate system was equivalent to the potentiometer measurements) in the x- and y-axis were less than 1 mm (where zero would be expected). They therefore reported that the RibEye measurements were accurate in multiple axes.

The accuracy of the RibEye measurement system installed in a Hybrid III 50th percentile male dummy was investigated by Yoganandan *et al.* (2009). There were four sub series of quasi-static tests within this assessment.

Firstly, Yoganandan *et al.* considered the accuracy of the RibEye measurements when the markers were attached to the sternum of the dummy. The accuracy comparisons were made against a marker on the indenter used to compress the chest over the sternum and the conventional Hybrid III chest compression potentiometer which was used in about half of the tests. As the bib material over the sternum was included in the test, under the indentor, it was expected that the RibEye measurements would match the internal chest potentiometer and not necessarily the indentor displacement. As it turned out, the RibEye measurements of 25 to 68 mm were within 3.3 to 2.4 mm (11.5 to 3.7 %) of the indenter displacement and -0.1 to 0.7 mm (-0.5 to 1.8 %) of the chest/sternum potentiometer, meeting expectations.

In a second set-up, an LED was mounted at the anterior-medial rib margin of the right fourth rib. In tests to a ½ inch compression with a small circular indenter, this marker gave deflection measurements which were smaller than the indenter displacement (by 0.78 to -0.84 mm; 6.1 to -6.5 %), but comparable with previous results. However, the real concern was whether this accuracy could be maintained with some z-axis displacement as well. To test this, the marker was offset vertically from its first position by 1.5 cm (in the z-axis). This led to a greater discrepancy (2.8 to 3.7 mm; 15.1 to

18.4 %) between the RibEye measurement and the indenter displacement than with the zero offset configuration. This additional discrepancy was attributed to the z-axis offset. It seems that for the condition where the marker is offset from the point of localised loading the error in the measurement can exceed the stipulated accuracy range. Furthermore in 1 inch deflection tests, there were also problems with drop-out of the RibEye measurements.

To simulate offset tests, Yoganandan *et al.* rotated the dummy chest about the z-axis by 13 degrees. The small circular indenter was again used to load the thorax directly over an LED attached to the right fourth rib 8 cm from the sternum midline. The deflections measured with the LED were lower than the indenter displacements by -0.7 to -1.5 mm (-1.9 to -9.4 %).

Finally, Yoganandan *et al.* used the RibEye system to measure the displacement of the indenter directly, by fitting an extension and LED to the indenter. Tests were run at 0.08 to 0.25 m/s (12 to 60 mm deflections). In this set-up the RibEye gave reasonable outputs describing the vertical indenter path, from -1.92 to 0.49 mm (-3.75 to 2.24 %) of the indenter measurements. In the description of the testing and associated diagrams and figures, it seems as though the marker on the indentor extension is within the thorax cavity in the region that the LEDs would be expected to cover throughout a normal impact. The precise z-axis offset is not clear, but assuming that it is within 12.5 mm of the original LED position, then the level of accuracy is outside of the 1 mm accuracy specified in the User’s manual for the two-axis version of RibEye for use in the Hybrid III (Boxboro Systems, 2007).

Yoganandan *et al.* also performed dynamic pendulum impactor component level tests with the Hybrid III dummy. For these tests, the RibEye was installed with the LEDs 9 cm from the mid-sternum line. The RibEye was able to capture x- and y-axis displacement information from both frontal and 25 degree oblique impacts. However, drop-out occurred for three of twelve LEDs in the highest speed test (conducted at 6.6 m/s).

A series of pendulum tests was used by Edwards *et al.* (2010) to evaluate the RibEye fitted in a WorldSID 50M (50th percentile WorldSID) with respect to the existing 1-D and 2-D IR-Tracc measurement systems available for the WorldSID dummies. As mentioned above, the differences between the RibEye and 2-D systems are that the RibEye measures vertical displacements as well as lateral and fore-aft, and the deflections are assessed at three different positions around the rib.

Edwards *et al.* again identified the limitations of using a single-axis measurement system with the WorldSID dummy, noting an underestimate of the lateral deflection even in purely lateral impacts.

However, in the pendulum tests, little benefit was expected based on the additional sensing of z-axis displacements over 2D deformations, and this was the case. With regard to the additional measurement positions, the forward of lateral LED position often provided a larger lateral (y-axis) displacement measurement than the middle position. This was not true when considering the resultant deflection data instead of the lateral measurement, unless the loading was particularly oblique (greater than about 30 degrees) or offset (by about 50 mm). Edwards *et al.* noted that, “Only with particularly concentrated loading would it be expected that the rearward of lateral LED position would measure greater rib deflection values than the forward of lateral and middle LED positions.”

A.2.4 Performance in full-scale car crash tests

The RibEye when installed in the 5th percentile female Hybrid III dummy was evaluated by Tylko *et al.* (2007). The dummy was used in full-scale frontal rigid barrier tests carried out at speeds of 40, 48, and 56 km/h. The performance comparisons were made between the original Hybrid III potentiometer and a multipoint measurement system consisting of four IR-TRACCs, called THUMPER.

In this instance, the 12 sensors used with the RibEye were located on each rib at approximately 60 mm from the centreline of the sternum.

The majority of the testing by Tylko *et al.* made use of the small female dummy in the rear seats, where it was subjected to belt-only loading. However, two further tests were conducted with the dummy in the driver's position with a belt and airbag restraint system.

Tylko *et al.* reported that, "The RibEye system was able to consistently characterize the asymmetrical deformations of the chest for the belted loading conditions". Also, "The system was able to track the belt position at peak load rather well". They concluded that the RibEye system, "will greatly facilitate the characterization of the chest response" and "could prove useful in delimiting belt routing on the chest".

Yoganandan *et al.* (2009) also commented after a full-scale test with the Hybrid III 50th that, "the optics-based deflection measurement device appears to capture asymmetric loading and motions of the chest in real-world simulations".

Paired full-scale vehicle crash tests were used by Jensen *et al.* to compare chest deflection measurements obtained with the RibEye with those obtained with linear potentiometers. The sample of tests included 10 paired tests. As a result of the tests, Jensen *et al.* found the RibEye deflection measurements to correlate well with those from linear potentiometers.

A full-scale side impact barrier test was performed by Edwards *et al.* (2010). This test was between an AE-MDB v3.10 MDB bullet vehicle and a Volkswagen Golf target vehicle at 60 km/h and used a WorldSID 50M driver with the RibEye chest compression measurement system. Based on calculation of equivalent 1-D and 2-D measurements, Edwards et al. noted that,

> "The RibEye deflection measurement system provided additional information about the rib deflection compared to the 2D IR-Tracc. The vertical component of the RibEye measurement indicated that the thorax and abdomen ribs deflected upwards by approximately 10 mm during the test, although the significance of this in terms of injury risk is not known."

Edwards *et al.* observed substantial upward deflection of the shoulder rib during the test. This high vertical deflection, together with high deflections in the other two axes as well, corresponded with the shoulder front and middle LEDs moving out of sensor range during the test and therefore dropping out. This drop-out was considered by Edwards *et al.* to constitute an issue with the range of the RibEye system. "It is important that the instrumentation can measure the full range of applied compression, at least to an agreed level". They suggested that the range needs to be sufficiently large to measure shoulder compression correctly in a test of this severity.

Subsequently, Belcher *et al.* (2011) used this 50th percentile WorldSID equipped with the RibEye in six vehicle-to-pole side impact tests. Their study investigated the level of obliquity that could be expected in pole impacts with changes in the specific alignment and angle of the resulting vehicle intrusion. Belcher *et al.* (2011) reported that the RibEye measurement system was a very useful tool for the purposes of their study. According to Belcher *et al.* the RibEye system was able to detect differences in airbag loading from the upper thorax to the lower abdomen. It "provided important information about the multi-dimensional nature of the rib responses." Belcher *et al.* also commented that, "Although this [the RibEye] system provides a lot of data, computational methods can be developed and used to aid and expedite the data analysis."

A.2.5 Limitations of RibEye

Based on the testing by Tylko *et al.* (2007), those authors noted that, "Interference with the potentiometer resulted in data loss during initial trials" (presumably this occurred due to occlusion of the markers for measurement by the sensors). Similar findings due to obscuration of the LEDs by the chest potentiometer were also found by Yoganandan *et al.* in their Hybrid III 50th percentile tests. However, Tylko *et al.* managed to resolve this problem with slight adjustment of the sensors. Further data loss was observed in the more severe test conditions because the abdominal insert moved upwards blocking the 'line of sight' from the sensors to the markers. This drew Tylko *et al.* to comment that, "interference due to obstruction does not appear to be a problem unless belt intrusion and abdominal insert displacement occurs". Of course, this will be a dummy-specific comment concerning the Hybrid III regarding the potential for the abdominal insert to move upwards into the RibEye measurement field.

According to Jensen *et al.* (2009), previous testing with the RibEye had indicated that ambient lighting may interfere with the RibEye measurements. This would be a problem for a crash test dummy because the filming of crash tests with high speed cameras usually requires concomitant use of bright lighting throughout the area of interest. Jensen *et al.* state that alternative clothing for the dummy was available at the time of publication. Unfortunately for their component testing a suit could not be incorporated into the procedure. For this reason they suggest that further analysis of the suitability of the clothing may be necessary. With this suggestion in mind, Edwards *et al.* (2010) came across no such issues when testing the WorldSID RibEye system in a standard full scale test set-up.

Jensen *et al.* were not able to complete a full durability analysis within their study of the RibEye system. However, from their series of tests they identified no durability issues. In contrast, during the full-scale paired tests, the linear potentiometers did exhibit some damage.

When using the WorldSID installation of RibEye, Edwards *et al.* (2010) noted durability issues with the communication box (mounted on the non-struck side of the dummy's spine box) and also with the cabling to this box. These durability issues were passed onto Boxboro Systems for improvement.

Edwards *et al.* also reported that additional measurement range was necessary for the WorldSID shoulder rib displacement in order to prevent the LED markers going out of range in full-scale tests.

Another issue raised by Edwards *et al.* was regarding the cleanliness of the RibEye sensors,

> “When troubleshooting the RibEye system it was observed that the sensors had clearly visible dust on them. It was also observed that it would be easy to get fingerprints on the sensors or LEDs when working on the system, e.g. connecting and disconnecting the LEDs from the sensors. It is recommended that more information is provided on how dust or dirt may affect the accuracy of RibEye compression measurements.” (Edwards *et al.*, 2010)

A.2.6 Discussion of RibEye performance and recommendations for testing

To determine the performance of the RibEye as a standalone unit, it seems as though the calibration rig described by Boxboro Systems, Inc. would be an appropriate tool. If there are any modifications to the sensors or LEDs in the RibEye to be installed in a WorldSID 5th percentile dummy, then it is suggested that basic performance (measurement range and accuracy) are evaluated on such a rig.

The measurement range within the WorldSID 5F could be deduced by detaching one of the LEDS and moving it throughout the torso cavity, whilst trying to track it with the sensors. This approach would not provide any information regarding the accuracy of the system, as the exact position of the LED at anytime would not be known. However, it should be possible to track the edges of the measurement range. It may be that the expected measurement range is provided with the dummy. If this information is not available, or if independent validation is required, then there would be merit in checking this.

As noted in Section A.2.3, there have been many studies looking at the accuracy of the RibEye measurement system, in various dummies, in laboratory (component or desk top) test conditions. The findings from these studies are often associated with severe limitations and may not be directly relevant to the performance of the system in the WorldSID 5F. Therefore, some laboratory study of accuracy may still be necessary. Learning from the previous studies, some constraints on experimental design become clear. Therefore, this testing would need to involve:

- The spine box of the dummy mounted rigidly to a laboratory fixture
- Three-dimensional tracking of the same point with RibEye and another system
- Removal of all dummy parts which may interfere with this tracking
- Load applied to the dummy in a number of oblique directions

Finally, the measurement potential for the RibEye in usual, but reasonably severe, conditions should be determined to investigate the potential for drop-outs, etc. This could be considered through component or full-scale testing, but needs to represent conditions of end-use.

Appendix B Thorax rib 2 rotation issue

When analysing the results from the pendulum and sled testing, it was observed that in some of the tests the rotation of the thorax rib 2 against time did not follow the expected path. Figure B-1 shows the rotation of thorax rib 2 against time for a series of consecutive pendulum tests. The area of note is circled.

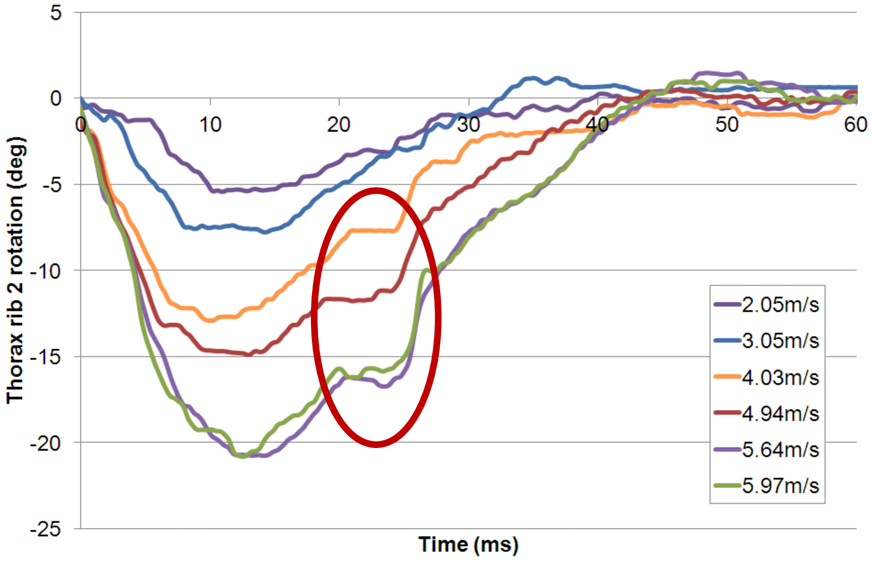

Figure B-1: Thorax rib 2 rotation against time for pendulum tests

The figure shows that the on the rebound phase of rotation, the rib stops for approximately 5ms at around 20ms from initial impact. The rib then rapidly rotates back to the initial expected path of rotation. This result was not seen in any other rib. The change in length of IR-Tracc did not show any significant issues (Figure B-2).

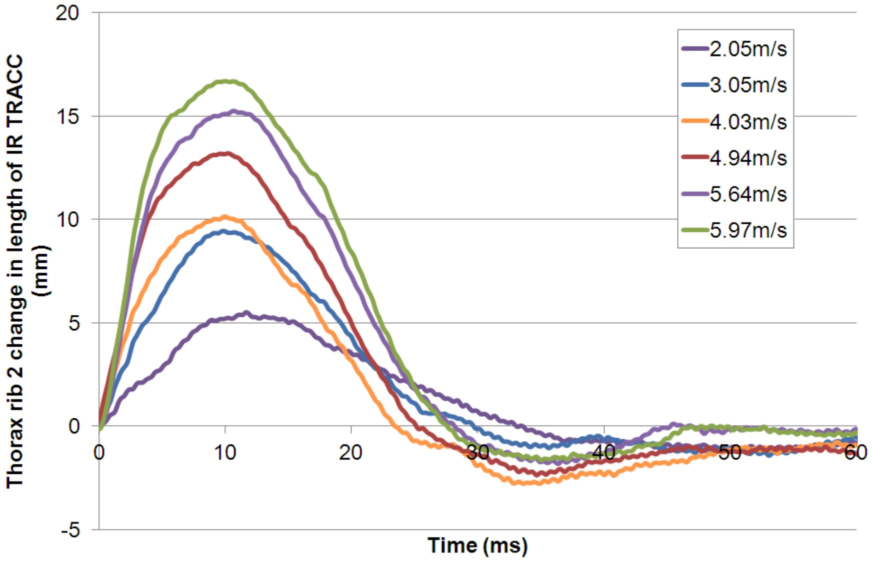

Figure B-2: Change in length of IR-Tracc agaisnt time for pendulum tests

In the sled testing the same result was seen when the rib was significantly loaded. This is seen in test 17 (Figure B-3). Between tests 17 and 18, all of the ribs were disassembled to investigate a different issue, and then reassembled. Tests 18 and 19 showed that the response of the rib now followed the expected path.

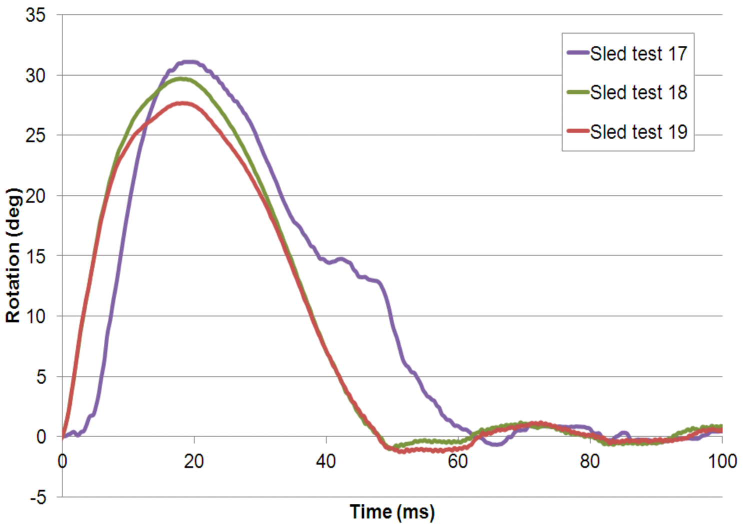

Figure B-3: Thorax rib 2 rotation against time for sled tests 17, 18 and 19

The ribs had been assembled and disassembled both times according to the instructions and in the same manner. As the IR-Tracc produced expected results after reassembly, this indicates that the issue may have occurred in the assembly of the rib components prior to the pendulum testing. As it is not possible to observe if there is an issue with this until a test has been performed, it may be useful to perform single rib calibration on each rib when it has been fully assembled.