INVESTIGATION OF LOWER ANCHORAGE SYSTEMS FOR CHILD RESTRAINTS IN AUSTRALIA

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ABSTRACT

Australia is considering allowing the use of lower anchorage systems for child restraints in motor vehicles. However, care needs to be taken to ensure that the mix of existing Australian child restraint systems and any proposed lower anchorage system does not pose safety risks for children. In addition, it is desirable to avoid unique requirements for an Australian lower anchorage system and hence an assessment of UNECE ISOFIX and US FMVSS LATCH requirements was undertaken.

A series of 28 frontal impact sled tests were conducted based on the Australian Standard AS/NZS 3629 child restraint dynamic test method. A further series of 15 tests were conducted in a vehicle body mounted on an impact sled with an acceleration-time history representative of a 56 km/h full frontal rigid barrier crash. Three different models of forward-facing child restraint were tested, with varying anchorage configurations including rigid ISOFIX, flexible LATCH strap and 3-point seatbelt. Top tethers were evaluated with anchorages directly behind the child restraint (0°) and offset at an angle of 20°. P3 and Hybrid III 3 year old dummies were used. Anchorage loads and safety performance of the restraint system were assessed. In tests in the vehicle body, maximum dynamic top tether loads were in the range of 7-8 kN and maximum dynamic lower anchorage loads are estimated to be in the range 13-14 kN. Tests using rigid ISOFIX anchorages generally produced lower head acceleration and forward excursion than other tested anchorage types. However, this was accompanied by increased chest deflections and neck flexion moments. These data suggest that lower anchorage systems may be acceptable in Australia, but that modifications to the UNECE and LATCH requirements may be required to ensure compatibility with existing Australian child restraint systems without a degradation of child safety.

INTRODUCTION

In Australia, the use of child restraints and top tethers has been mandatory since the 1970s. Typically, Australian passenger vehicles have been equipped with a top tether anchorage in each of three second row seating positions. When used in conjunction with a seatbelt, the top tether plays an important role in overall restraint performance by acting as an anti-rotation device.

The safety and performance of child restraint systems in Australia is regulated via requirements for the child restraint under Australian Standard AS/NZS 1754 (a mandatory consumer product safety standard under the *Trade Practices Act, 1974*) and requirements for the anchorages in the vehicle under Australian Design Rule ADR 34/01 (a legislative instrument under the *Motor Vehicle Standards Act, 1989*).

The Australian Standard AS/NZS 1754 currently requires all child restraints supplied to the Australian market to be designed to be attached to the vehicle using an adult seatbelt and top tether. This standard does not address connectors for lower anchorage systems and child restraints with ISOFIX or LATCH lower anchorage systems are currently unable to gain approval under this standard.

The Australian Design Rule ADR 34/01 currently requires each top tether anchorage to be designed to withstand a 3.4 kN static load for a period of at least 1 second. A dynamic anchorage strength test requirement may be satisfied as an alternative to this static requirement. There are currently no lower anchorage requirements in ADR 34/01.

Australia is currently considering allowing the use of child restraints equipped with lower anchorage systems. However, it is particularly important that the adoption of any proposed harmonised child restraint anchorage requirement for vehicles (including vehicle top tether anchorage strength and anchorage location requirements) does not adversely impact on the ongoing use and performance of existing Australian child restraint systems.

In this study, dynamic top tether and lower anchorage load measurements are used to assess UNECE ISOFIX (Regulation 14) and FMVSS LATCH (FMVSS 225) anchorage strength requirements, and dummy sensor measurements and head excursion results are used to evaluate the restraint performance for ISOFIX, flexible LATCH, and 3-point seatbelt child restraint systems.

METHOD

Two separate series of frontal impact sled tests were conducted using 3 different forward facing child restraint models and an instrumented 3 year old frontal impact dummy. Top tether loads, lap/sash belt loads, lower anchorage loads, head excursion, and dummy sensor output were measured and analysed for the purpose of evaluating the performance and anchorage loads of ISOFIX, flexible LATCH strap, and 3-point seatbelt child restraint systems.

One of the three tested child restraint models (Model A) was a UNECE Reg. 44 approved restraint equipped with an ISOFIX lower anchorage system. This child restraint model (Model A) is also able to be restrained using a 3-point seatbelt or a flexible LATCH strap fitted using the seatbelt mounting in the back of the restraint. The other two tested restraint models (Model B & Model C) are/were popular in the Australian market and are considered to be representative of existing (3-point seatbelt + top tether) Australian child restraint systems. Model B is able to be restrained by either a 3-point seatbelt or flexible LATCH strap using the seatbelt mounting provided at the rear of the restraint. Restraint model C is also able to be used in conjunction with either a flexible LATCH strap or 3-point seatbelt, however, for this restraint, the flexible LATCH strap / lap belt is fitted around the front base of the restraint. Restraint models A and B are both fitted with a floating or Y-shaped top tether. Model C is fitted with a single top tether strap.

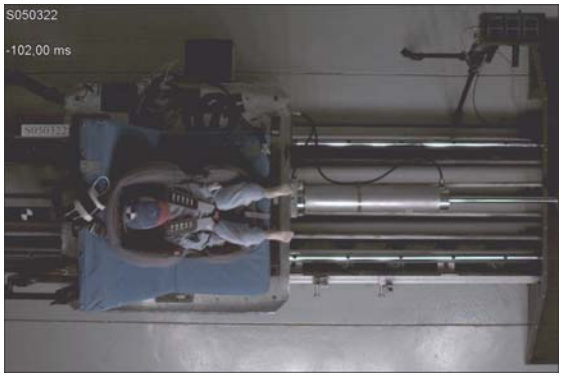

Figure 1. Sled setup (with pneumatic spring) used to certify child restraints under Australian Standard AS/NZS 1754.

The first series of 28 frontal sled tests were conducted on a sled used to certify child restraints under the existing Australian Standard AS/NZS 1754 (Child Restraint Systems for Use in Motor Vehicles) as shown in Figure 1. This sled utilises a pneumatic spring to simulate a frontal impact, and when calibrated according to the dynamic test rig requirements of the Australian Standard AS/NZS 3629.1 (Methods of Testing Child Restraints), produces a velocity change of approximately 49 km/h. Each of these sled tests were conducted using a P3 dummy fitted with tri-axial head and chest accelerometers. Load cells placed between the sled and lower anchorages were used to measure flexible LATCH and rigid ISOFIX lower anchorage loads. Top tether and seatbelt loads were measured using load cells designed to be fitted to belt webbing. The tests conducted in this series are listed in Table 1.

Table 1.
Test Matrix (Series 1)

Number of Tests	Restraint Model	Dummy	Top Tether Angle	Anchorage Method
3	A	P3	0	ISOFIX / Top Tether
3	A	P3	0	Flexible LATCH / Top Tether
3	A	P3	0	3 Pt Belt / Top Tether
2	B	P3	0	Flexible LATCH / Top Tether
2	B	P3	0	3 Pt Belt / Top Tether
2	C	P3	0	Flexible LATCH / Top Tether
2	C	P3	0	3 Pt Belt / Top Tether
1	A	P3	20	ISOFIX / Top Tether
1	A	P3	20	Flexible LATCH / Top Tether
1	A	P3	20	3 Pt Belt / Top Tether
1	B	P3	20	Flexible LATCH / Top Tether
1	B	P3	20	3 Pt Belt / Top Tether
1	C	P3	20	Flexible LATCH / Top Tether
1	C	P3	20	3 Pt Belt / Top Tether
2	A	P3	0	3 Pt Belt / Top Tether*
2	A	P3	n/a	ISOFIX / No Top Tether

* top tether failure

A further 15 restraint tests were conducted using the same three child restraint models and a vehicle buck constructed from a previously crash tested vehicle body (see Figure 2 and Figure 3). The vehicle model used was equipped with factory fitted lower anchorages in each outboard rear seating position. The front row seats were removed

from the vehicle and two transparent polycarbonate sheets were used to simulate the front seat back location in the mid track fore/aft position (with front seat back angle set to give an adult torso angle of 25º). The second/rear row bench seat was reinforced to allow multiple tests to be conducted. A sled and bending bar brake were then used in conjunction with this vehicle buck to simulate a 56 km/h full frontal rigid barrier crash pulse for this vehicle (see Figure 4). A P3 or HIII 3 year old dummy was used for each of the tests in this series. The P3 dummy was fitted with the same instrumentation used for the first test series. The HIII 3 year old dummy was fitted with head, chest, upper spine, lower spine, and pelvis tri-axial accelerometers, as well as an upper neck load cell, and a chest deflection rotary potentiometer. Lower anchorage loads were not measured. Webbing load cells were used to measure top tether, 3-point seatbelt, and flexible LATCH strap loads. The tests conducted in this series are listed in Table 2.

Table 2.
Test Matrix (Series 2)

Number of Tests	Restraint Model	Dummy	Top Tether Angle	Anchorage Method
1	A	P3	0	ISOFIX / Top Tether
1	A	P3	0	3 Pt Belt / Top Tether
1	A	P3	0	3 Pt Belt (P) / Top Tether
1	B	P3	0	Flexible LATCH / Top Tether
1	B	P3	0	3 Pt Belt / Top Tether
1	B	P3	0	3 Pt Belt (P) / Top Tether
1	C	P3	0	3 Pt Belt / Top Tether
1	A	P3	20	ISOFIX / Top Tether
1	A	P3	20	3 Pt Belt / Top Tether
1	A	P3	20	3 Pt Belt (P) / Top Tether
1	B	P3	20	Flexible LATCH / Top Tether
1	B	P3	20	3 Pt Belt (P) / Top Tether
1	A	HIII 3 y.o.	0	ISOFIX / Top Tether
1	A	HIII 3 y.o.	0	3 Pt Belt / Top Tether
1	A	HIII 3 y.o.	0	3 Pt Belt (P) / Top Tether

(P) – pre-tensioned

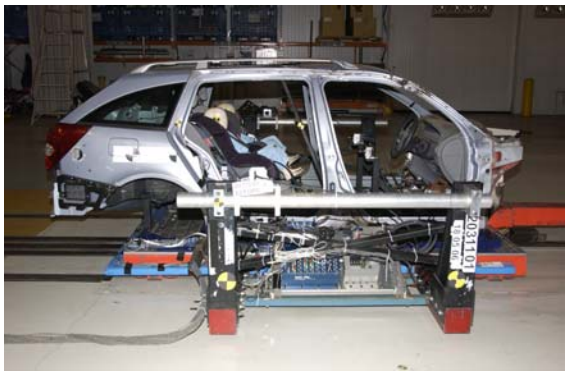

Figure 2. Vehicle body shell / buck mounted on crash sled (Series 2).

Figure 3. Test setup used in vehicle body / buck test series (Series 2).

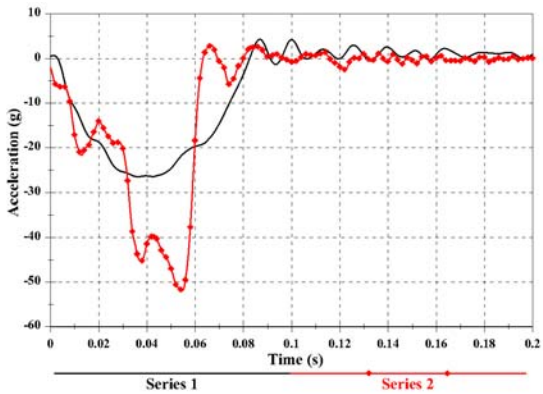

Figure 4. Typical acceleration-time history / crash pulse for each series of child restraint frontal impact tests.

Each child restraint test was conducted using, no top tether anchorage (2 sled tests only), a 0º tether anchorage, or a 20º tether anchorage (see test matrices). For the first series of tests, each 0º top tether was anchored to the sled on the seating reference plane, approximately 230 mm behind the

shoulder reference point. For the vehicle buck sled test series, each 0º tether test was conducted with the top tether attached to a child restraint anchorage located on the seating reference plane at the base of the seat back. All 20º tether tests (both series) were conducted with the tether anchored approximately 1 metre behind the shoulder reference point and 20º inboard from the seating reference plane.

For each individual test (see Table 1 and Table 2), each child restraint was tested using ISOFIX, flexible LATCH strap, or 3-point seatbelt anchorage. In the case of flexible LATCH, tests were conducted by fitting the flexible LATCH strap through/around the available seatbelt mounting. For the second test series (vehicle buck), the safety and performance of seatbelt pyrotechnic retractor pre-tensioning was also investigated.

All dummy sensor and load cell channel data were collected at a 20 kHz sampling frequency. Each data channel was then filtered using the channel frequency classes (CFC) specified in Table 3. All data plots presented in this paper are in accordance with the sign conventions specified by SAE J211-1 (Dec 2003).

High speed video images and motion analysis software were used to calculate dummy forward and lateral head excursion relative to the intersection of the seat back / bight. For the first series of tests, an off-board overhead camera view was used to calculate both forward and lateral head excursion. For the second test series, an off-board overhead camera view was used to calculate lateral head excursion, and onboard side camera views were used to calculate forward head excursion.

Table 3.
Channel Frequency Class

Data Measurement Channel	CFC (Hz)
Head acceleration x, y, and z	1000
Upper neck force x, y, and z	1000
Upper neck moment x, y, and z	600
Chest acceleration x, y, and z	180
Chest deflection x	600
Pelvis acceleration x, y, and z	1000
All top tether, seatbelt and lower anchorage loads	60

RESULTS

Dynamic Lower Anchorage Loads

Figure 5 shows the maximum lower anchorage loads obtained from the frontal sled test series conducted using the existing AS/NZS 3629.1 pulse (Series 1). For this series of tests, multiple (repeat) tests (2-3) were conducted for each 0º tether test configuration (i.e. for each unique combination of restraint model and lower anchorage method). For multiple tests, the maximum anchorage load from any one test is plotted in Figure 5 (see Appendix for all results).

The maximum total (left + right) lower anchorage load recorded during the first test series was 7.2 kN (restraint model A with ISOFIX lower anchorage and 20º top tether anchorage). In some cases, most notably the tests conducted with a 20º tether angle, the lower anchorage load was not uniformly distributed between each of the two lower anchorages. Excluding tests conducted without a top tether, the maximum dynamic load on any one anchorage (i.e. left or right anchorage) was 4 kN. For the tests conducted with a 0º top tether anchorage, the maximum total lower anchorage load was 6.3 kN. Two additional tests (not shown in Figure 5) were also conducted using restraint model A with rigid ISOFIX anchorage only (i.e. no top tether anchorage). For these additional tests, the maximum total lower anchorage load was 11 kN.

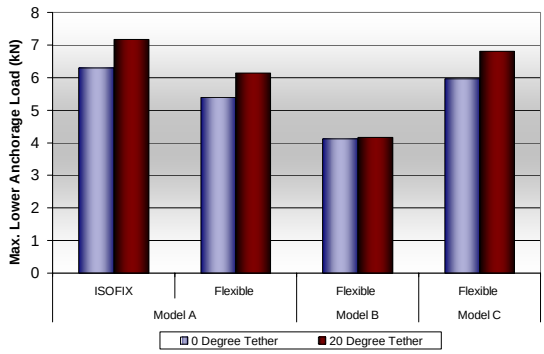

Figure 5. Maximum total lower anchorage loads (Series 1).

Rigid lower anchorage loads were not measured during the series of tests conducted using the vehicle body / buck (Series 2). For this test series, it was not physically possible or practical to use load cells (or other means) to measure lower anchorage loads. However, it is possible to use lap belt loads obtained from both series of tests, and lower anchorage loads recorded during the first test series, to estimate likely lower anchorage loads based on the proportionality of loads.

The maximum outer lap belt load (see Appendix) recorded during the vehicle buck sled test series was 5.93 kN (restraint model A with 0º tether and 3-point seatbelt mounting). For this restraint model and tether angle, the maximum outer lap belt load and maximum lower anchorage load recorded during the first series of sled tests were 2.8 kN (excluding tests conducted with top tether

modification or failure) and 6.3 kN respectively. Therefore, for the initial sled test series, the maximum total rigid lower anchorage load was approximately 2.25 times the maximum outer lap belt load (for restraint model A). Assuming a similar maximum load ratio for the vehicle buck sled test series, maximum dynamic rigid lower anchorage load is approximately 13.3 kN (i.e. 2.25 × 5.93 kN).

Dynamic Tether Anchorage Loads

Figure 6 shows the maximum top tether anchorage loads recorded during the first series of frontal sled tests. Similarly to lower anchorage loads, where multiple tether anchorage loads are available for a given test configuration, the maximum recorded anchorage load from any test is plotted (see Appendix for all results). The maximum top tether anchorage load for this series of tests was 9.4 kN (restraint model A with 3-point seatbelt and 0º top tether anchorage). In this series, 20º tether anchorage loads were generally 15-40 percent lower than the corresponding 0º tether anchorage loads. The maximum tether anchorage load recorded for the 20º tether angle was 6.5 kN.

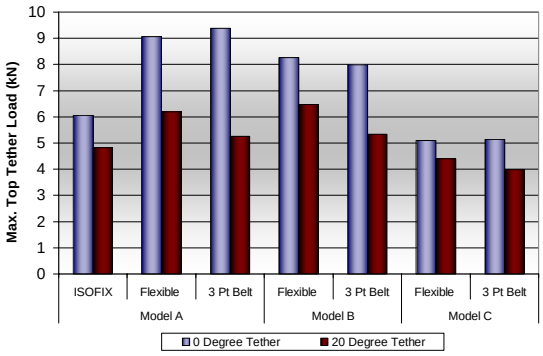

Figure 6. Maximum top tether anchorage loads (Series 1).

Figure 7 shows the maximum top tether anchorage loads recorded for each vehicle buck sled test (Series 2) conducted using a P3 dummy (see Appendix for tether anchorage loads obtained from tests conducted using HIII 3 year old dummy). The maximum top tether anchorage load measured during this test series was 7.7 kN (restraint model B with pre-tensioned 3-point seatbelt mounting and 0º tether anchorage). For the tests conducted with a 20º tether angle, the maximum top tether anchorage load was 6.9 kN.

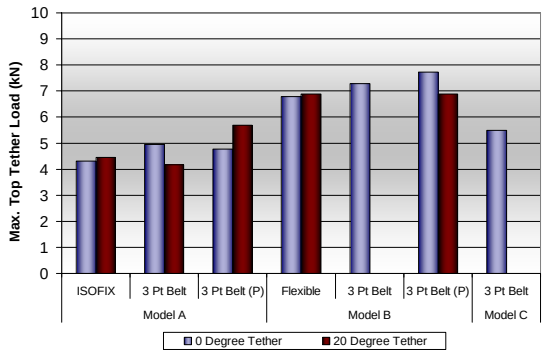

Figure 7. Maximum top tether anchorage loads (Series 2).

Head Excursion

High speed video images and motion analysis software were used to estimate forward and lateral head excursions. To enable evaluation of results, motion analysis techniques were consistently applied to each test conducted in each test series. However, it should be noted that different fixed camera angles / positions were used for series 1 and 2. Head excursion results obtained for series 1 and 2 are therefore unable to be directly compared (i.e. results not comparable across series), but do provide a good indication of the relative performance of each restraint model / restraint anchorage method (i.e. results can be compared within each series).

Figure 8 shows dummy forward head excursion relative to the seat back / bight intersection for the first series of sled tests. Where multiple tests were conducted for the same test configuration, average head excursions are plotted, with the full range of recorded test results indicated by vertical bars (see Appendix for all results). For restraint model A, rigid ISOFIX anchorage produced the lowest forward head excursion, and flexible LATCH anchorage produced the highest forward head excursion. For restraint models B and C, flexible LATCH and 3-point seatbelt anchorage systems produced similar forward head excursion. For this test series, multiple test results indicate good repeatability for forward head excursion. For the additional tests conducted using restraint model A, rigid lower anchorage, and no top tether anchorage (see Appendix for results), removal of the top tether increased forward head excursion by an average of approximately 130 mm (relative to restraint model A with 0º tether anchorage).

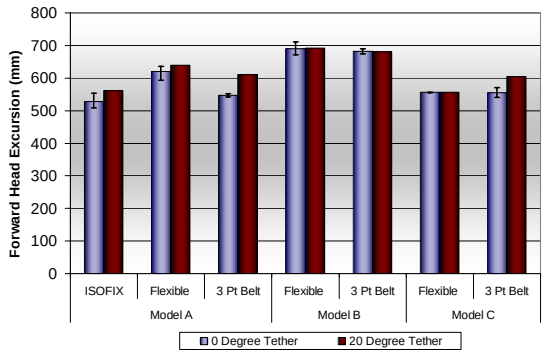

Figure 8. Forward head (centre of gravity) excursion (Series 1).

Figure 9 shows dummy forward head excursion relative to the seat back / bight intersection for each vehicle body / buck sled test conducted using a P3 dummy (see Appendix for forward head excursion results obtained from tests conducted using HIII 3 year old dummy). During some of these tests, the dummy head collided with the polycarbonate sheet / seat back (see HIC 36 results for further details). This polycarbonate sheet was used to simulate the front row seat back location for the mid track for/aft position and an adult torso angle of 25º. Therefore the seat back places an upper limit on forward head excursion. For the tests in which the dummy head collided with the seat back, this forward head excursion limit is determined by the trajectory of motion of the head / position (i.e. height) of impact. Due to the inclined angle of the polycarbonate, greater forward head excursion is possible for trajectories of motion in which the head impacts the polycarbonate closer to the base of the front seat. As a rough guide, forward head excursions of approximately 450mm resulted in head contact to the polycarbonate sheet. In this series, rigid ISOFIX anchorage produced substantially less forward head excursion than 3-point seatbelt mounting. Seatbelt pre-tensioning produced a small reduction in forward head excursion compared to no pre-tensioning.

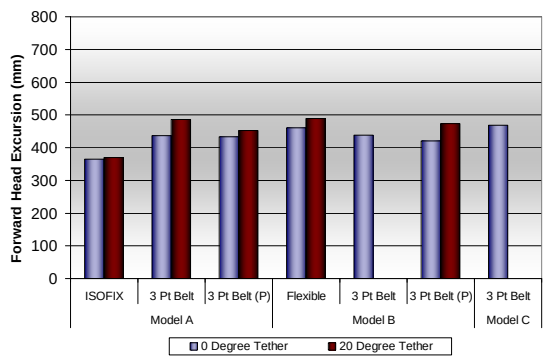

Figure 9. Forward head (centre of gravity) excursion (Series 2).

Figure 10 shows dummy lateral head excursion for the first series of sled tests. Similarly to forward head excursion, average lateral head excursions are plotted, with vertical bars used to indicate the range of results obtained from multiple / repeat tests (see Appendix for all results). Lateral head excursions were influenced more by top tether configuration, than by lower anchorage method. For each restraint model / lower anchorage method, lateral head excursions were greatest for the test conducted with a 20º tether angle. The lateral head excursion estimates obtained from this series of tests do not exhibit the repeatability observed for forward head excursion (i.e. lateral head excursion results appear to be less repeatable / subject to greater variability).

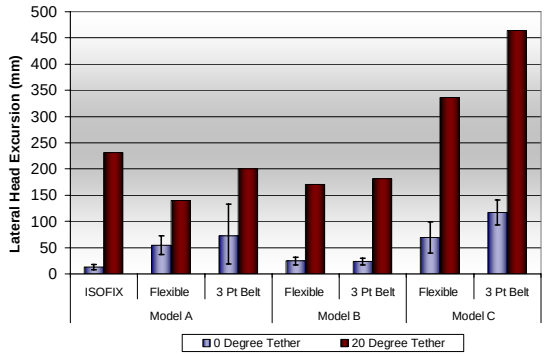

Figure 10. Lateral head (centre of gravity) excursion (Series 1).

Figure 11 shows dummy lateral head excursion for each vehicle body / buck sled test conducted using a P3 dummy (see Appendix for HIII 3 year old lateral head excursion results). Like the first test series, lateral head excursions were influenced more by tether angle, than by lower anchorage method. With the exception of restraint model A with ISOFIX lower anchorage, lateral head excursions were substantially greater for tests conducted with a 20º tether anchorage.

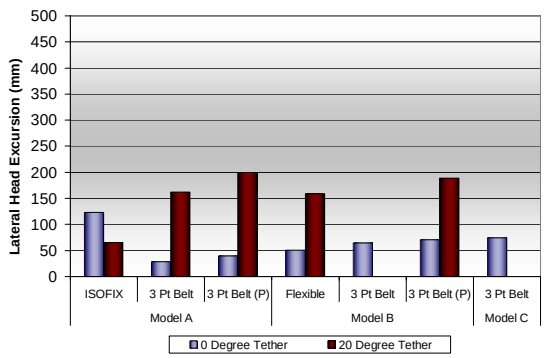

Figure 11. Lateral head (centre of gravity) excursion (Series 2).

P3 Dummy Sensor Data

A P3 dummy was used for each test conducted in Series 1, and for all but three of the tests conducted in Series 2. In this section, where multiple tests have been conducted for a single test configuration, averages are plotted and vertical bars are again used to indicate the range of recorded results.

During the first test series, dummy head to knee / buckle collisions were observed for some tests (see Appendix for test specific details). These collisions were not necessarily repeatable for multiple tests (i.e. each 0º tether configuration). Furthermore, during the second test series, the presence of a front row seat back was observed to greatly diminish the likelihood of head to knee / buckle collisions. Therefore, for some test configurations, the occurrence of head collisions is likely to have artificially increased both the average and range of 3 ms head acceleration / HIC 36 results.

Figure 12 and Figure 13 show 3 ms head acceleration and HIC 36 for the first series of sled tests. The 3 ms head acceleration and HIC 36 results obtained for restraint model A, indicate similar levels of head injury risk for rigid ISOFIX and 3-point seatbelt anchorage methods. In most cases, results obtained for flexible LATCH anchorage indicate a head injury risk approximately equal to or greater than that of 3-point seatbelt mounting. There were however, some test configurations for which flexible LATCH anchorage exhibited HIC 36 results superior to 3-point seatbelt mounting (restraint models B and C with 20º tether anchorage). Head acceleration and HIC 36 results obtained from two additional tests conducted with rigid lower anchorage only (see Appendix for results); indicate an increased head injury risk for no top tether anchorage compared to tests conducted using top tethers.

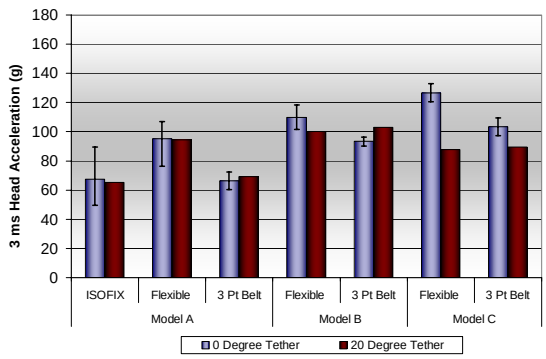

Figure 12. 3 ms head acceleration (Series 1).

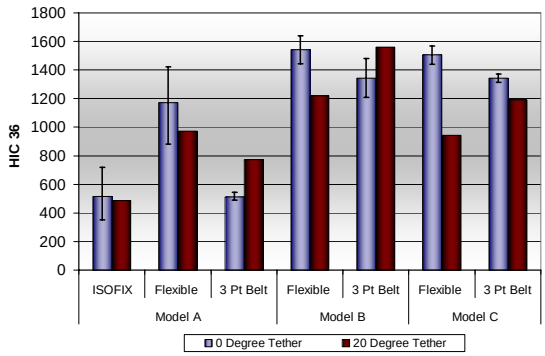

Figure 13. HIC 36 (Series 1).

During the vehicle buck sled test series, all but one of the HIC results greater than 2500 occurred as a consequence of the head striking the polycarbonate front row seat back simulation. It is important to note that the energy absorbing properties of an upholstered seat back are quite different to a transparent polycarbonate sheet. Consequently, the 3 ms head acceleration and HIC 36 results obtained from tests involving head to polycarbonate collisions provide an indicative rather than truly representative measure of head injury risk.

Figure 14 and Figure 15 show 3 ms head acceleration and HIC 36 for each vehicle buck sled test conducted using a P3 dummy. The 3 ms head acceleration and HIC 36 results obtained for restraint model A, indicate a lower head injury risk for rigid ISOFIX anchorage than for either form of 3-point seatbelt mounting. In this series, flexible LATCH anchorage was only tested using restraint model B. For this restraint model and 0º tether anchorage, flexible LATCH anchorage produced slightly lower 3 ms head acceleration and HIC 36 than 3-point seatbelt mounting. For some restraint test configurations, seatbelt pre-tensioning was effective in reducing forward head excursion by just enough to prevent the dummy head from colliding with the polycarbonate sheet / front row seat back (eg. restraint model A with 20º top tether anchorage). For these test configurations, seatbelt pre-tensioning produced a substantial reduction in both 3 ms head acceleration and HIC 36. However, for restraint model A with 0º top tether anchorage, there were no head collisions with the polycarbonate seat back, and 3 ms head acceleration and HIC 36 were similar for 3-point seatbelt mounting with and without pre-tensioning. The effect of seatbelt pre-tensioning is most pronounced when the reduction in forward head excursion due to pre-tensioning is such that head contact to the polycarbonate sheet that would otherwise occur is prevented.

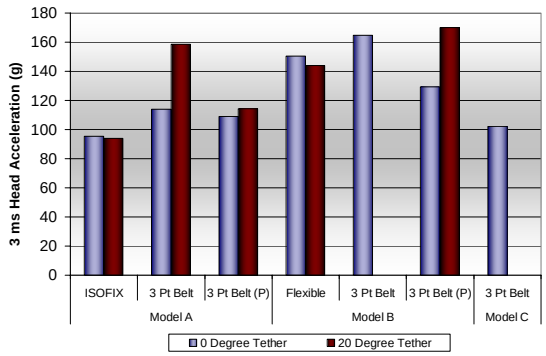

Figure 14. 3 ms head acceleration (Series 2).

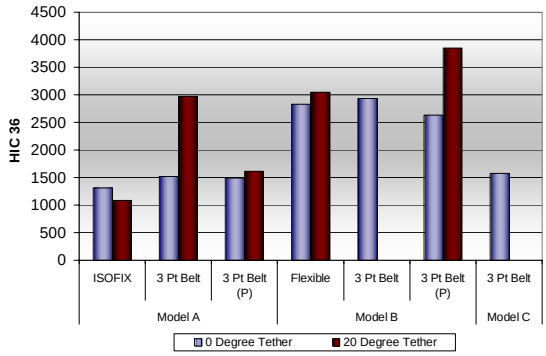

Figure 15. HIC 36 (Series 2).

Figure 16 shows maximum resultant chest acceleration for the first sled test series. For each child restraint model tested; rigid ISOFIX, flexible lower anchorage, and 3-point seatbelt mounting all produced similar maximum resultant chest accelerations.

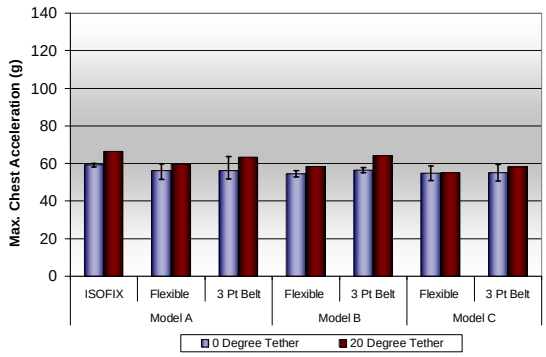

Figure 16. Maximum chest acceleration (Series 1).

Figure 17 shows maximum resultant chest acceleration for each vehicle buck sled test conducted with a P3 dummy. For this series of tests, there was no clearly identifiable and consistent correlation between maximum resultant chest acceleration and lower anchorage method. Peak resultant chest accelerations varied depending on a range of factors, including the restraint design and the top tether anchorage location / angle. The lowest maximum chest acceleration occurred for restraint model A with rigid ISOFIX lower anchorage and 20º top tether anchorage.

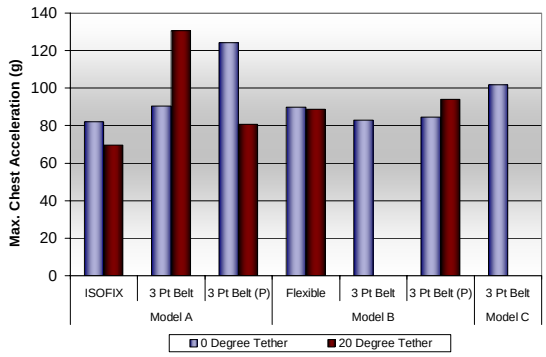

Figure 17. Maximum chest acceleration (Series 2).

HIII 3 Year Old Sensor Data

The current Australian Standard AS/NZS 3629.1 (Methods of Testing Child Restraints) specifies P series dummies for the dynamic testing of child restraints. Each child restraint must retain the appropriate P series dummy without any separation of load carrying parts. Vehicle anchorage strength requirements should ensure that vehicle top tether anchorages are able to withstand loads at least equal to those to which child restraints are certified. For this reason, a P3 dummy was used for each frontal sled test conducted using the AS/NZS 3629.1 pulse.

To enable comparison of test results, a P3 dummy was also used in the majority of tests conducted in the vehicle buck sled test series. However, a major limitation of the P series dummies is their lack of instrumentation – the P3 dummy is equipped with head and chest accelerometers only. In contrast, the HIII 3 year old dummy is equipped with head, neck, chest, upper spine, lower spine, and pelvis instrumentation. Consequently, the HIII 3 year old dummy is able to be used to identify potential injury risks not measured by the P3 dummy. For this reason, three restraint tests were conducted using restraint model A and an instrumented HIII 3 year old dummy. Each of these HIII 3 year old tests was conducted with a 0º tether anchorage and rigid ISOFIX, 3-point seatbelt, or pre-tensioned 3-point seatbelt mounting.

Figures 18 to 25 show dummy sensor output for each restraint test conducted using a HIII 3 year old dummy. Table 4 lists 3 ms head acceleration, HIC 36, and head excursion results for each test. Each restraint anchorage method produced similar resultant chest acceleration (values slightly higher for ISOFIX), neck tension, and neck shear results. In contrast, head excursion, head acceleration / HIC 36, upper neck moment, chest deflection, and

pelvis acceleration results were substantially affected by restraint anchorage method.

Similarly to the vehicle buck sled tests conducted with a P3 dummy, rigid ISOFIX anchorage produced substantially less forward head excursion than either form of 3-point seatbelt mounting. When 3-point seatbelt mounting was used the dummy head collided with the polycarbonate sheet / front row seat back, producing a local head acceleration maximum (see Figure 18, t ≈ 0.079 seconds). For this restraint model and tether angle, seatbelt pre-tensioning reduced forward head excursion by enough to prevent the dummy head from colliding with the polycarbonate sheet.

Table 4.
Summary of Head Injury Predictors
(HIII 3 year old)

Anchorage Method	3 ms Head Accel. (g)	HIC 36	Max. Forward Head Excursion (mm)	Max. Lateral Head Excursion (mm)
ISOFIX / Top Tether	103.40	1578	376	33
3 Pt Belt / Top Tether	132.90	1853	467	150
3 Pt Belt (P) / Top Tether	95.32	1673	431	73

(P) – pre-tensioned

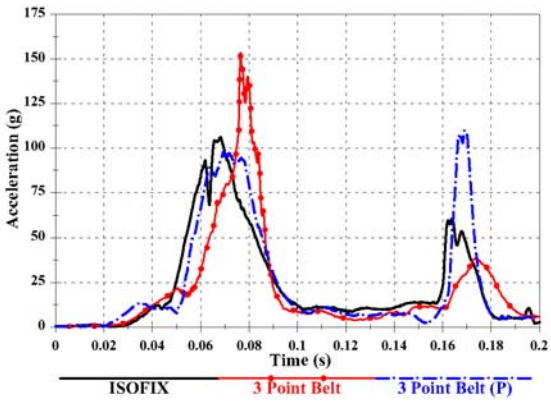

Figure 18. Resultant head acceleration (HIII 3 year old – Series 2).

Each restraint anchorage method produced similar peak upper neck tension and peak upper neck shear load results. Rigid ISOFIX and pre-tensioned 3-point seatbelt anchorage methods both produced significantly longer upper neck tensile load duration (above 1 kN) than 3-point seatbelt mounting.

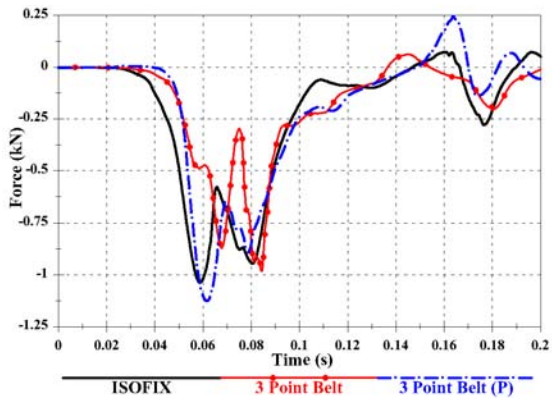

Figure 19. Upper neck shear load (Fx) (HIII 3 year old – Series 2).

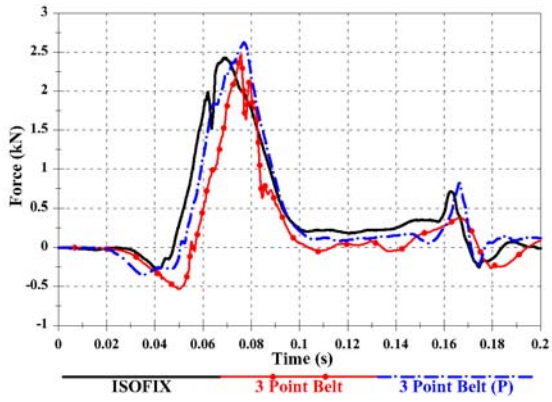

Figure 20. Upper neck tension (Fz) (HIII 3 year old – Series 2).

Peak upper neck moments about the x-axis in the dummy coordinate system (Mx) varied depending on the restraint anchorage method used. The largest of these peak upper neck moments (19.5 Nm – see Figure 21) was produced by 3-point seatbelt mounting. For rigid ISOFIX anchorage, the peak upper neck moment about the x-axis was 6.1 Nm. As a result, 3-point seatbelt mounting exhibited more visible head rotation about the x-axis (ear tilts towards shoulder), than rigid ISOFIX anchorage.

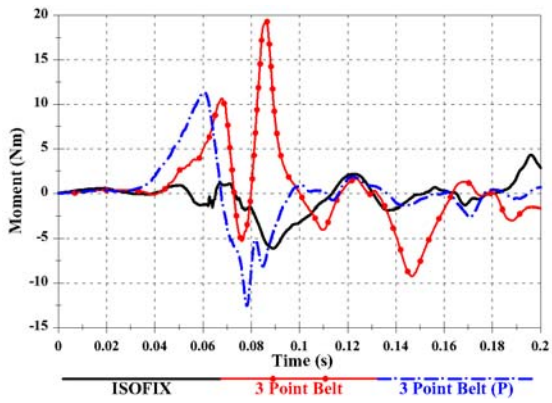

Figure 21. Upper neck moment (Mx) (HIII 3 year old – Series 2).

Rigid ISOFIX and pre-tensioned 3-point seatbelt anchorage methods produced substantially higher neck flexion / extension moments than 3-point seatbelt mounting. For rigid ISOFIX, 3-point seatbelt, and pre-tensioned 3-point seatbelt anchorage, the peak upper neck flexion moments were 29.8 Nm, 13.8 Nm, and 35.5 Nm respectively. For each of these anchorage methods, the corresponding peak upper neck extension moments were 24.8 Nm, 9.3 Nm, and 20.4 Nm (see Figure 22).

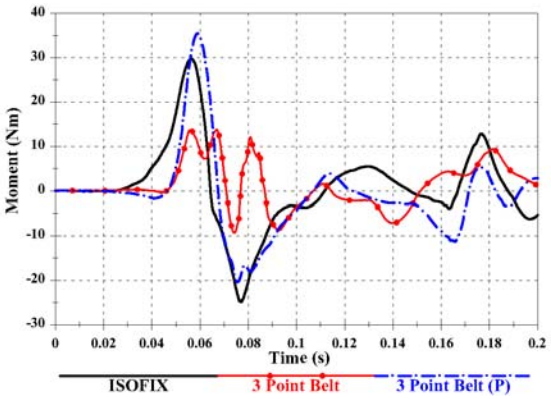

Figure 22. Upper neck moment (My) (HIII 3 year old – Series 2).

Maximum resultant chest acceleration was similar for each 3-point seatbelt anchorage method tested. Rigid ISOFIX anchorage produced slightly higher maximum resultant chest acceleration. There were also differences in the relative timing of maximum chest acceleration. For the rigid ISOFIX and pre-tensioned 3-point seatbelt anchorage modes, maximum chest acceleration occurred approximately 15-20 ms before maximum head acceleration. For 3-point seatbelt mounting, maximum head and chest acceleration occurred at approximately the same time.

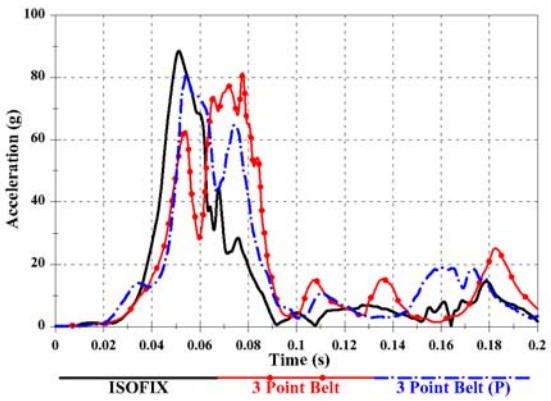

Figure 23. Resultant chest acceleration (HIII 3 year old – Series 2).

The onset, duration, and magnitude of chest deflection varied depending on the restraint anchorage method used. Rigid ISOFIX and pre-tensioned 3-point seatbelt mounting both produced substantially more chest deflection than 3-point seatbelt mounting. For rigid ISOFIX, 3-point seatbelt, and pre-tensioned 3-point seatbelt anchorage, the peak chest deflections were 17.5 mm, 16 mm, and 8.2 mm respectively. For rigid ISOFIX anchorage, the chest deflection response also indicated an earlier onset and longer duration of chest loading (see Figure 24).

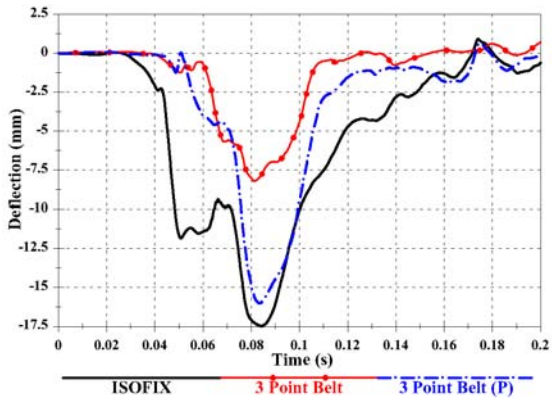

Figure 24. Chest deflection (HIII 3 year old – Series 2).

Peak resultant pelvis accelerations were substantially greater for 3-point seatbelt mounting, than for rigid ISOFIX anchorage (see Figure 25). Pelvis acceleration values were not obtained for the test using pre-tensioned 3-point seatbelt attachment. When 3-point seatbelt mounting was used, the base of the child restraint moved forward before the lap portion of the 3-point seatbelt began to carry substantial load. This delay in the onset of lap belt load, led to a higher and later occurrence of peak resultant pelvis acceleration (relative to rigid ISOFIX anchorage).

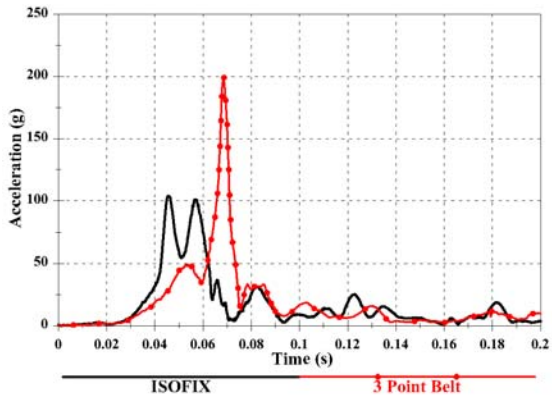

Figure 25. Resultant pelvis acceleration (HIII 3 year old – Series 2).

DISCUSSION

Australian Design Rule (ADR) 34/01 currently requires each child restraint top tether anchorage to be able to withstand a minimum static test load of 3.4 kN. The Department of Transport and Regional Services is not aware of any cases of failure in the field of top tether anchorages complying with ADR 34/01.

The results presented in this paper show a maximum dynamic top tether load of 9.4 kN for a restraint attached using 3-point seatbelt and subjected to the AS/NZS 3629.1 test pulse. Tests of restraints mounted in the vehicle body shell using 3-point seatbelt recorded a maximum dynamic top tether load of 7.7 kN. Maximum dynamic top tether loads for restraints mounted using rigid ISOFIX were around 6 kN. These results indicate that the use of lower anchorage systems to mount child restraints does not impose increased loading on top tether anchorages compared with the loads imposed by the mounting of child restraints using 3-point seatbelts.

The application of static or dynamic load imposes different stress states on anchorages. A static load of the same magnitude as a peak dynamic load is a more severe load condition than the transient dynamic load. Due to the longer duration of loading, a static load may cause greater deformation than a transient load of greater magnitude acting only for short duration. This would suggest that in order to withstand a 9.4 kN dynamic load, a top tether anchorage may need to withstand a static load somewhat less than this value. The 3.4 kN static load requirement of ADR 34/01 is significantly lower than the 9.4 kN maximum recorded dynamic load and there is a risk that an anchorage designed to withstand the 3.4 kN static load may not be able to withstand the 9.4 kN dynamic load. However, there is no field data to suggest that the ADR requirement is inadequate. This may be because the AS/NZS 3629.1 test is a more severe condition than observed in the field. This contention is supported by top tether loads recorded in the vehicle body shell that were lower than those in the AS/NZS 3629.1 tests. It is also important to note that the 3.4 kN static test load is a minimum load that must be withstood. Vehicle manufacturers are likely to design top tether anchorages to pass this requirement by a significant margin, such that the static failure load is significantly higher than 3.4 kN.

The maximum dynamic load on the lower anchorages recorded during tests of child restraints with a top tether connected and subjected to the AS/NZS 3629.1 pulse was 7.2 kN. Tests conducted using rigid ISOFIX without a top tether connected recorded a maximum dynamic lower anchorage load of 11 kN. For tests conducted in the vehicle body shell, maximum dynamic lower anchorage loads have been estimated to be 13.3 kN.
Both UNECE Regulation 14 and US Federal Motor Vehicle Safety Standard (FMVSS) 225 specify the testing of child restraint anchorages by application of static force through a fixture loading only the lower anchorages. UNECE Reg 14 requires an 8 kN static test load; FMVSS 225 requires 11 kN static test load. In addition, there is a requirement to use a fixture to test the strength of the lower anchorages and top tether anchorage simultaneously – UNECE Reg 14 requires an 8 kN static test load; FMVSS 225 requires 15 kN.

The maximum dynamic load on the lower anchorages in the tests reported in this paper has been estimated to be 13.3 kN. It is not straightforward to determine the static test load that would need to be used to ensure that anchorages are capable of withstanding this peak dynamic load. One possible approach could be to use the experience gained from existing ADR 34/01 requirements to find a ratio of static to dynamic loads that may be appropriate. This approach would suggest that either the UNECE static load requirement (8kN) or the FMVSS static load requirement (11 kN) may be sufficient to address the 13.3 kN maximum dynamic load. However, one further step of research will be required to confirm the static load requirements for lower anchorages.

The geometry of the UNECE and FMVSS fixture used to simultaneously load the lower anchorages and top tether anchorage is such that roughly half of the applied load is distributed to the top tether anchorage. A static force of 8 kN applied to the fixture would result in approximately 4 kN static load applied to the top tether anchorage. This compares favourably with the 3.4 kN requirement currently in ADR 34/01. There is however, a difference in the duration of the UNECE Reg 14 and ADR 34/01 static test loads. UNECE Reg 14 requires the load to be sustained for at least 0.2 seconds, whereas ADR 34/01 specifies 1 second.

In terms of restraint performance and dummy injury measures from the tests reported in this paper, flexible LATCH strap does not seem to offer any significant benefits when compared with 3-point seatbelts. Indeed, it could be argued that some of the injury measures for restraints mounted using flexible LATCH straps indicate a higher risk of injury than for 3-point seatbelts. However, the LATCH strap routing path was the same as that used for 3-point seatbelt and was not optimised for a flexible strap to be attached to the lower anchorages. Such optimisation may improve the

performance of restraints attached using the flexible LATCH strap.

Attachment of restraints using rigid ISOFIX shows a reduced risk of injury for many of the dummy injury assessment measures, but with a relative increase in risk for neck injury and chest deflection when using a Hybrid III 3 year old dummy. However, these relative increases in injury risk for rigid ISOFIX attachment were similar to those observed for attachment using 3-point seatbelt with pyrotechnic retractor pre-tensioning. Hence, it could be argued that rigid ISOFIX attachment would not present any increased safety risk compared with systems that would currently be allowed in the Australian market.

The current Australian Standard AS/NZS 1754 for child restraints for use in motor vehicles does not specify injury assessment reference values for dummies when testing forward facing child restraints.

Appropriate injury criteria and injury assessment reference values for children are the subject of ongoing international research and debate. Scaling techniques have been applied to adult injury risk functions in an attempt to estimate injury risk to children. However, consensus has not always been reached on which adult injury risk functions should be used as the starting point and the proposed scaling techniques and scaling factors vary widely. This paper is not intended to appraise, select or recommend particular scaling techniques or child injury assessment reference values, but it is informative to refer to some of these as they provide a context in which the data from the tests reported in this paper can be considered.

The Recommended Procedures for Evaluating Occupant Injury Risk from Deploying Side Airbags (Side Airbag Out-of-Position Injury Technical Working Group) provided a set of injury reference values and additionally a set of injury research values which specify injury limits for the Hybrid III 3 year old dummy. Some of these are reported in Table 5. Scaling techniques reported in the US National Highway Traffic Safety Administration (NHTSA) report entitled "Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems II" can also be applied to adult injury reference values from UNECE Regulation 94 to determine equivalent injury limits for the Hybrid III 3 year old dummy. Some values determined in this way are also reported in Table 5.

For tests using the Hybrid III 3 year old dummy, some of the injury measures recorded during the tests exceed the injury limits contained in Table 5. This suggests that these tests are relatively severe and represent a condition that may cause injury to a child and hence may serve as a useful comparison in assessing the anchorage loads anticipated during such a crash, as well as providing some basis for comparison of the performance of child restraints attached to the vehicle by various methods.

Table 5.
Injury Limits for Hybrid III 3-year-old Dummy

Injury Measure	Limit Value
15 ms HIC	570*
36 ms HIC	900**
3 ms Head Acceleration	80 g***
Upper Neck Tension	1.13 kN*
Upper Neck Flexion	68 Nm*
Upper Neck Extension	34 Nm*
Upper Neck Shear	0.9 kN**
Thorax Deflection	36 mm*
Thoracic Spine Acceleration	55 g*

* Side Airbag Out-Of Position Technical Working Group Recommended Procedures for Evaluating Occupant Injury Risk from Deploying Side Airbags.

** UNECE Regulation 94 adult injury limit scaled using techniques described in NHTSA report entitled "Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems II".

*** UNECE R94 adult injury limit.

The results using rigid ISOFIX connection with a Hybrid III 3-year old dummy show a reduced risk of head injury, but a slightly increased risk of extension injury to the upper neck and chest injury (thorax deflection and thoracic spine acceleration) when compared to other mounting systems. The results for neck extension moment and chest deflection are below the limit values in the above table. The peak thoracic spine 3 ms acceleration for rigid ISOFIX was around 85 g compared with 75 g for the other mounting systems. All of these values exceed the proposed 55 g limit.

CONCLUSION

The use of lower anchorage systems for mounting of child restraints does not provide increased loading on top tether anchorages when compared to mounting child restraints using the adult 3-point seatbelt. On the basis that the current ADR 34/01 requirement for a 3.4 kN top tether static test load is adequate, static test loads at or above this level would be sufficient to ensure structural integrity of top tether anchorages.

The maximum dynamic lower anchorage loads determined during child restraints tests according to AS/NZS 3629.1 and in a vehicle body under simulated 56 km/h full frontal barrier test conditions are less than or equal to 13.3 kN.

Mounting of child restraints using flexible LATCH straps does not seem to offer any safety improvement over the use of the adult 3-point seatbelt and may reduce the level of safety in some instances.

Mounting of child restraints using rigid ISOFIX anchorages offers some safety benefits over the use of the adult 3-point seatbelt, but may increase the risk of neck and chest injury compared to some child restraint systems currently in use in Australia. However, the neck and chest injury results for the rigid ISOFIX system evaluated in this test series do not indicate an increased injury risk when compared to some child restraint systems that would currently be permitted.

REFERENCES

[1] AS/NZS 3629.1:2004 Methods of Testing Child Restraints (Method 1: Dynamic Testing), Standards Australia, November, 2004.

[2] AS/NZS 1754:2004 Child Restraint Systems for Use in Motor Vehicles, Standards Australia, November, 2004.

[3] Australian Design Rule 34/01 – Child Restraint Anchorages and Child Restraint Anchor Fittings, Federal Register of Legislative Instruments, Canberra, November, 2005.

[4] United Nations Economic Commission for Europe (UNECE) Regulation 14.

[5] Federal Motor Vehicle Safety Standard (FMVSS) No. 225: Child Restraint Anchorage Systems, National Highway Traffic Safety Administration (NHTSA), US Department of Transportation.

[6] SAE J211-1, SAE International, December, 2003.

[7] Recommended Procedures for Evaluating Occupant Injury Risk from Deploying Side Airbags, Side Airbag Out-of-Position Injury Technical Working Group, August, 2000.

[8] Eppinger R, Sun E, Bandak F, Haffner M, Khaewpong N, Maltese M, Kuppa S, Nguyen T, Takhounts E, Tannous R, Zhang A, Saul R. (1999), Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems – II, NHTSA Docket No 1999-6407-5, November, 1999.

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APPENDIX

Table A1.
Summary of Test Results

Sled Test / ID		Restraint	Mounting	Dummy	Top Tether Angle	Sled dV (km/h)	Sled g	Max. Tether Anchorage Load (kN)	Max. Lower Anchorage Load (kN)	Resultant 3 ms Head Accel. (g)	Max. Resultant Chest Accel. (g)	HIC 36	Max. Forward Head Excursion (mm)	Max. Lateral Head Excursion (mm)
SERIES 1														
Calibration		n/a	n/a	n/a	n/a	49.5	26.9	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1	S050308	Model A	Rigid ISOFIX	P3	0	48.8	26.4	6.06	6.01	49.41	59.54	350	509	18
2	S050309	Model B	Flexible LATCH	P3	0	48.1	26.9	8.27	4.11	101.60	56.11	1446	670	32
3	S050310	Model B	3-point Seatbelt	P3	0	48.5	27	7.78	n/a	90.20	55.05	1207	691	30
4	S050311	Model B	3-point Seatbelt	P3	0	48.2	27	7.98	n/a	96.25	57.82	1482	675	17
5	S050312	Model B	3-point Seatbelt	P3	20	47.9	26.9	5.33	n/a	102.90	64.14	1559	681	181
6	S050313	Model A	3-point Seatbelt	P3	0	48.2	26.9	6.31	n/a	68.63	65.53	446	570	105
7	S050314	Model A	3-point Seatbelt	P3	0	48.1	27	3.85	n/a	66.33	51.66	496	552	133
8	S050315	Model A	3-point Seatbelt	P3	0	49.2	26.9	9.38	n/a	60.35	53.49	491	543	19
9	S050316	Model A	3-point Seatbelt	P3	0	47.9	26.7	6.33	n/a	66.70	62.36	451	574	104
10	S050317	Model A	3-point Seatbelt	P3	0	48.1	27	5.11	n/a	72.40	63.75	543	546	67
11	S050318	Model C	3-point Seatbelt	P3	0	48.4	27	5.13	n/a	109.40	50.73	1372	541	93
12	S050319	Model C	3-point Seatbelt	P3	0	48.2	26.8	4.83	n/a	97.26	59.54	1315	570	141
13	S050320	Model A	3-point Seatbelt	P3	20	48.3	27.2	5.26	n/a	69.19	63.43	775	610	200
14	S050321	Model C	3-point Seatbelt	P3	20	48.2	27	3.98	n/a	89.37	58.22	1190	604	464
15	S050322	Model A	Rigid ISOFIX	P3	0	48.8	26.5	5.78	6.18	63.27	58.22	480	522	13
16	S050323	Model A	Rigid ISOFIX	P3	0	49	26.7	5.66	6.30	89.56	60.17	717	553	8
17	S050324	Model A	Rigid ISOFIX	P3	20	48.9	26.8	4.82	7.17	65.16	66.34	486	561	231
18	S050325	Model A	Flexible LATCH	P3	0	48.2	26.8	8.28	5.39	106.80	59.77	1421	636	56
19	S050326	Model A	Flexible LATCH	P3	0	48.7	26.8	9.06	4.92	76.15	51.33	882	593	37
20	S050327	Model A	Flexible LATCH	P3	0	47.9	26.8	8.39	5.19	102.20	57.03	1212	631	72
21	S050328	Model A	Flexible LATCH	P3	20	47.4	26.9	6.19	6.14	94.30	59.53	972	639	140
22	S050329	Model B	Flexible LATCH	P3	0	47.9	27.1	8.10	4.03	118.20	52.94	1641	711	17
23	S050330	Model B	Flexible LATCH	P3	20	47.7	27	6.48	4.17	100.20	58.26	1219	692	170
24	S050331	Model C	Flexible LATCH	P3	0	47.9	26.8	5.08	5.97	120.30	58.73	1568	555	40
25	S050332	Model C	Flexible LATCH	P3	0	48.4	26.9	5.10	5.88	132.80	51.00	1442	557	99
26	S050333	Model C	Flexible LATCH	P3	20	48.2	27	4.39	6.81	87.51	55.14	945	557	336
27	S050334	Model A	Rigid ISOFIX	P3	n/a	48.1	26.7	n/a	10.63	89.40	56.29	749	647	39
28	S050335	Model A	Rigid ISOFIX	P3	n/a	48.2	26.8	n/a	11.04	79.92	54.59	717	668	8
SERIES 2														
1	20310-01L	Model A	Rigid ISOFIX	P3	0	63.2	51.4	1.86	-	109.30	70.51	1541	411	48
	20310-01R	Model B	Flexible LATCH	P3	0	63.2	50.4	5.02	7.87	138.50	99.54	2545	470	96
2	20310-02L	Model A	Rigid ISOFIX	P3	0	62.7	52.3	4.31	-	95.40	82.16	1308	365	123
	20310-02R	Model B	Flexible LATCH	P3	0	62.7	48.7	6.79	6.29	150.40	89.94	2835	460	51
3	20310-03L	Model A	3-point Seatbelt (P)	P3	20	63.1	50.5	5.68	n/a	114.20	80.58	1617	453	200
	20310-03R	Model A	3-point Seatbelt (P)	P3	0	63.1	48.2	4.76	n/a	108.90	124.13	1488	433	40
4	20310-04L	Model B	3-point Seatbelt	P3	0	63.1	52.7	6.12	n/a	214.50	114.23	4896	493	220
	20310-04R	Model B	3-point Seatbelt (P)	P3	0	63.1	50.7	7.73	n/a	129.30	84.61	2632	420	71
5	20310-05L	Model B	Flexible LATCH	P3	20	62.7	47.8	6.88	6.68	143.90	88.72	3045	489	159
	20310-05R	Model B	3-point Seatbelt	P3	0	62.7	50.5	7.28	n/a	164.50	82.77	2930	439	65
6	20310-06L	Model A	Rigid ISOFIX	P3	20	62.2	46.2	4.45	-	93.79	69.47	1087	370	66
	20310-06R	Model A	3-point Seatbelt (P)	HIII 3 y.o.	0	62.2	47.4	4.56	n/a	95.32	81.16	1673	431	73
7	20310-07L	Model A	Rigid ISOFIX	HIII 3 y.o.	0	62.9	49.9	4.39	-	103.40	88.46	1578	376	33
	20310-07R	Model A	3-point Seatbelt	P3	0	62.9	46.9	4.95	n/a	114.10	90.47	1517	437	29
8	20310-08L	Model A	3-point Seatbelt	P3	20	62.5	51.9	4.16	n/a	158.60	130.57	2972	486	162
	20310-08R	Model A	3-point Seatbelt	HIII 3 y.o.	0	62.5	48.2	4.79	n/a	132.90	81.45	1853	467	150
9	20310-09L	Model B	3-point Seatbelt (P)	P3	20	62.8	48.2	6.88	n/a	170.00	94.11	3851	473	189
	20310-09R	Model C	3-point Seatbelt	P3	0	62.8	52	5.49	n/a	102.10	101.63	1579	468	75

Table A2.
Seatbelt Webbing Load Cell Measurements

Sled Test / ID	Restraint	Mounting	Dummy	Top Tether Angle	Outer Lap Belt Load (kN)	Inner Lap Belt Load (kN)	Inner Sash Belt Load (kN)	Outer Sash Belt Load (kN)
SERIES 1								
S050310	Model B	3-point Seatbelt	P3	0	2.06	1.47	-	0.34
S050311	Model B	3-point Seatbelt	P3	0	2.07	1.71	-	0.39
S050312	Model B	3-point Seatbelt	P3	20	2.1	1.64	-	0.96
S050313	Model A	3-point Seatbelt	P3	0	4.56	3.27	-	1.92
S050314	Model A	3-point Seatbelt	P3	0	3.46	2.58	-	1.77
S050315	Model A	3-point Seatbelt	P3	0	2.79	1.92	-	0.68
S050316	Model A	3-point Seatbelt	P3	0	4.3	3.42	-	2.91
S050317	Model A	3-point Seatbelt	P3	0	3.56	2.61	-	1.57
S050318	Model C	3-point Seatbelt	P3	0	2.98	1.68	-	0.58
S050319	Model C	3-point Seatbelt	P3	0	2.65	1.49	-	0.47
S050320	Model A	3-point Seatbelt	P3	20	3.18	2.45	-	1.42
S050321	Model C	3-point Seatbelt	P3	20	3.54	1.72	-	1.01
SERIES 2								
20310-03L	Model A	3-point Seatbelt (P)	P3	20	5.31	5.09	4.21	6.24
20310-03R	Model A	3-point Seatbelt (P)	P3	0	5.62	4.44	-	6.58
20310-04L	Model B	3-point Seatbelt	P3	0	4.36	3.88	3.27	4.15
20310-04R	Model B	3-point Seatbelt (P)	P3	0	3.65	3.13	3.39	4.38
20310-05R	Model B	3-point Seatbelt	P3	0	3.49	2.8	1.66	2.48
20310-06R	Model A	3-point Seatbelt (P)	HIII 3 y.o.	0	5.33	4.26	4.69	6.11
20310-07R	Model A	3-point Seatbelt	P3	0	5.93	4.15	4.56	5.71
20310-08L	Model A	3-point Seatbelt	P3	20	5.85	5.35	5.27	6.43
20310-08R	Model A	3-point Seatbelt	HIII 3 y.o.	0	5.18	5.1	3.98	6.57
20310-09L	Model B	3-point Seatbelt (P)	P3	20	4.06	5.82	-	-
20310-09R	Model C	3-point Seatbelt	P3	0	5.24	4.98	3.89	3.11

Notes:

S050313, S050316: The restraint top tether failed due to fracture of the plastic shell at the left side top tether slot. This allowed the tether webbing end plate to pull through the back of the restraint. The restraints used for these tests were not originally fitted with top tether straps. The initial method of attaching tether straps was found to be inadequate.

S050314, S050317: Re-test of the previous failed restraint (with tether modification)

S050310, S050320, S050322, S050334, S050335: Chalk paint evidence of possible head contact with harness buckle assembly.

20310-01L, 20310-01R: Vehicle rear seat back deformation occurred. Seats were then supported with an additional cross member along their upper edge for the remainder of the test series. Results provided, but not used for analysis purposes.

20310-04L: The top tether webbing cut on an exposed bolt head which was part of the additional seat back strengthening cross member. Results provided, but not used for analysis purposes.

Rebound was ignored for the calculation of maximum values (eg. 3 ms head acceleration).

20310-02R, 20310-05L, 20310-05R, 20310-08L, 20310-08R, 20310-09L: Dummy head collided with polycarbonate sheet.