CHILD RESTRAINTS FOR CHILDREN WITH ADDITIONAL NEEDS

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ABSTRACT

Transporting children with additional needs is challenging because of the range of physical and cognitive impairments, anthropometry, occupant safety, regulations and usability. Not only does the child restraint system (CRS) need to protect the child in a crash but the carer must also be able to assist the child in and out of the seat. In Australia CRS, except those for children with additional needs, must meet AS/NZS 1754. Unlike, European and USA standards, AS/NZS 1754 has a dynamic side impact test. The objective of the paper is to report on the results of dynamic impact tests conducted on a range of CRS for children with additional needs and identify opportunities for improving the crash performance. A secondary objective was to assess the strength requirements of the top tether anchorage point.

Nine CRS models designed for children with additional needs were tested in front and side dynamic impact tests at the NSW Roads and Maritime Services Crashlab. The tests were conducted according to AS/NZS 1754 specifications. The CRS models were not subjected to full certification or compliance tests. A rebound sled was used and the CRS models were tested with a 36 kg, P10 series Anthropomorphic Test Device (ATD). The frontal impact sled pulse was Δv = 49 km/h with acceleration 24-34 g and side impact was Δv = 32 km/h with acceleration 14-20 g. Head and chest resultant acceleration were measured as well as seatbelt and tether forces. CRS models performed relatively well in frontal impacts: peak resultant head accelerations were less than 150 g. In side impacts the average peak headform acceleration across all models was 272 g and the average peak chest acceleration was 178 g, largely because of the lack of ATD restraint and side wings. Those impacts were severe and if they occurred in a real crash would lead to significant head, brain and chest injury. In one test the estimated upper anchorage reached over 10 kN, which is greater than the anchorage strength requirement. There were some breakages or failures of seat and belt components in the tests. Alternative systems to a tether strap for mounting the seat were found to be successful.
CRS for children with additional needs performed well in frontal impacts, which reflects the certification of these models to either USA or European standards. The ATD head invariably struck the door panel in the side impact test. The results identified that the CRS models can accommodate and function in frontal tests with the 36 kg crash test dummy, or child, but their performance for heavier occupants is unknown. Further testing with heavier ATDs and a variety of seated postures would be informative. Suitably biofidelic ATDs and child specific injury assessment reference values are study limitations. Dynamic testing of the CRS models was informative in terms of both policy and practice. Improving impact performance and occupant safety is a demanding proposition when the operational context of these systems is considered.

INTRODUCTION

In Australia and many parts of the developed world it is mandatory for children in motor vehicles to travel in a child restraint system (CRS). Further, those CRS's are required to have been certified to a specific standard, such as AS/NZS 1754, FMVSS 213 and ECE 44. There are some differences between these standards and the CRS variants produced. For example, unlike the European and USA standards AS/NZS 1754 has a dynamic side impact test reqiurement. The European standard accommodates ISOFIX, a topic being reviewed in the Australian standard, and the USA standard has LATCH, an alternative to ISOFIX. Tether strap requirements also differ between the standards. Research and development has helped produce a range of CRS types that can accommodate children of different ages and sizes. These are readily available to the public at a range of price points. The dimensions of the CRS types and the performance requirements are predicated on

assumptions about the anthropometry and biomechanics of the normal population of children and crash risks (severity and likelihood).
In the USA during the period 2006-2008 the prevalence of developmental disabilities was estimated to be one in six children [1]. These ranged from cerebral palsy to profound hearing loss to learning disabilities. The Australian Bureau of Statistics estimated that in 2009 288,000 children in Australia suffered from a disability and around 57% of these were profound/severe [2]. In some cases children with additional needs can also be accommodated in the ordinary range of CRS models, but because of physical, cognitive or other impairments some children require specialised CRS models [3,4].

CRS models for children with additional needs are similar to the ordinary range. They offer typically either a three or five point restraint harness and are designed to ensure that the harness loads substantial bony structures. Some CRS models for children with additional needs are ordinary models with a number of minor modifications. Other CRS models are purpose built and may be up to ten to twenty times the cost of generic CRS. Generally, they differ in a number of respects: adjustability, attachments, postural support, body mass range, and usability. The body mass range may exceed the expected range for ordinary seats because the children may not be able to be restrained optimally by the vehicle's restraints even in their teenage years. As has been shown, even under ordinary circumstances suboptimal restraint use is an important factor in the incidence of serious injury [5]. Therefore, it is important that options are provided to transport all children safely. Not only does the CRS need to protect the child in a crash but carers must also be able to assist the child in and out of the seat without placing themselves at risk of musculoskeletal injury. Therefore, some CRS designs include a swivel seat that enables the child to be oriented towards the door opening for placing in and removal from the seat.

The objective of the paper is to report on the results of dynamic impact tests conducted on a range of CRSs for children with additional needs and identify opportunities for improving the crash performance. A secondary objective was to assess the strength requirements of the top tether anchorage point.

METHODS

CRS models

Nine CRS models designed for children with additional needs were tested. These models were selected because: they were currently in use and representative of the range of models available in Australia; met in the intent of AS/NZS 1754:2010; and, were certified to either the USA or European standards. All seats were logged in, weighed and documented. The following models were tested: Columbia 2000 and SPIRIT; Recaro START 2.0 and STARLIGHT SP; SONJA SSCS-2; TIMY; CARROT III; Snug Seat Traveller Plus; and Otto Bock LARS.

Impact test protocol

All tests were conducted at the Roads and Maritime Services Crashlab in Sydney, Australia. Two dynamic tests, a frontal and side impact, were conducted on each model. An untested CRS was used in each test. Where possible a representative of the supplier assisted in the set-up of each restraint system and observed the tests.

The test characteristics were based on:

- AS/NZS 1754:2010: *The Australian and New Zealand Standard for Child restraint systems for use in motor vehicles*; and,
- AS/NZS 3629.1:2010: *The Australian and New Zealand Standard for methods of Testing Child restraint systems. Method 1: Dynamic Testing*.

AS/NZS 1754 applies to all child restraint systems used in the general population in Australia and covers all types of child restraint systems for transporting newborn babies up to ten year olds. AS/NZS 3629.1 describes in detail the testing requirements and test configuration required by AS/NZS 1754.

The target sled impact pulses were:

- Frontal Impact: Δv = 49 km/h, sled acceleration 24-34 g. (Pulse A)
- Side Impact: Δv = 32 km/h, sled acceleration 14-20 g. (Pulse B)

Where Δv ("delta v") is the change in velocity of the sled.

In the side impact tests, the near side position was tested with the door panel positioned directly to the left of the seat. Photographs of the sled configuration are presented in figures 1 and 2. To accommodate the varying lengths of the top tether straps all straps were attached to a horizontal reinforced beam at approximately the height of the top of the seatback. In order to maintain the position of the seat and anthropomorphic test device (ATD) in the side impact tests during the firing of the sled, the seat was held in position with polystyrene blocks. These stopped the seat falling to the ATD's right while the sled was accelerated up to the impact speed. The blocks do not

influence the ATD's performance during the impact phase.

ATD and instrumentation

In order to replicate the most severe loading of the restraint and the anchorage system, the largest ATD that fitted all CRS models and met the mass limits of each device was used. The TNO P10 ATD was used. The P10 had a mass of 35.5 kg. (including ballast and accelerometer packages), stature of 1385 mm and seated height of 730 mm. The P-series ATDs are required to be used in AS/NZS 1754:2010. The P10 represents a 10-year-old child and is the largest of the P series family of ATDs. The seated height of the ATD was checked and it was considered that the seated head height remained within the boundaries of each seat after adjusting each CRS.

Figure 1: Sled, CRS and ATD frontal impact configuration.

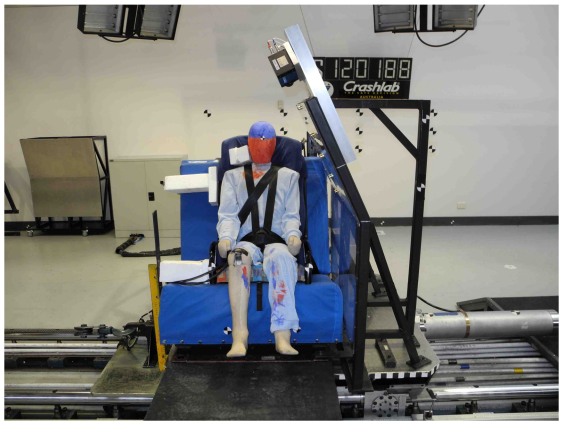

Figure 2. Sled, CRS and ATD side impact configuration.

The following instrumentation was used on the ATD:

- ATD head triaxial acceleration (gravities (g))
- ATD chest triaxial acceleration (g)
- Seatbelt webbing forces (frontal impacts only, Newtons (N))
- Top tether strap force (frontal impacts only) (N)
- On-board camera (frontal impacts only)
- Off-board cameras – side and overhead

The resultant head and chest accelerations were derived as well as the Head Injury Criterion (HIC). In some tests two upper tether anchorage points and straps were used. This results in the top tether strap force being effectively halved. All instruments were conditioned according to AS/NZS 1754: 2010, AS/NZS 3629.1:2010 and SAE J211.

For all CRS models, except one, a representative of the distributor assisted in setting up the seat for the optimal restraint of the ATD. Each CRS pair was set up identically. The CRS was positioned on the sled's test seat, its anchorage system was attached and adjusted as securely as possible, and the ATD was positioned on the seat. A standard spacer was used to ensure that the restraint system was adjusted uniformly. The ATD's back was positioned in the seat against the spacer, the harness and restraint systems were then connected and adjusted as tightly as possible. The spacer was then removed. This introduced a standard amount of slack in the restraint and harness systems.

Evaluation

The reference criteria for frontal and side impacts are presented in Table 1. These are based on the limits defined in AS/NZS 1754:2010.

Table 1.
Reference criteria for CRS tests based on AS/NZS 1754:2010

Criteria	Frontal	Side
Head - (a) Resultant acceleration (g) (b) Proximity to door structure	< 150 g (b) ----	(a) ----- (b) > 10 mm
Chest	Nil	Nil
Seatbelt sash webbing force (N)	Nil	Nil
Seatbelt lap webbing force (N)	Nil	Nil
Top tether strap force (N)	< 7 kN	< 7 kN
Fracture and/or separation of CRS base	No complete or partial separation, ie < 50% of total crack length of the perimeter joining the base to the remainder of the restraint.	
Throat Contact	No hazardous contact	
Lap belt	Shall not penetrate wholly abdomen.	
Shoulder belt slippage	Shall not slip wholly off shoulder	Nil
Maintenance of CRS position	ATD position not compromise	

There is a dearth of valid injury criteria for children and specific ATD's, including the TNO P10. The following criteria were applied (Table 2) [6-10].

Table 2.
Injury ratings for TNO P10 for this project.

	Injury Rating		
Injury Function	Low	Moderate	High
Maximum Resultant Headform Acceleration (g)	< 100	100 to 150	> 150
Head Injury Criterion (36)	< 500	500 to 700	> 700
Maximum Resultant Chest Acceleration (g)	< 40	40 to 60	> 60
3 ms Resultant Chest Acceleration (g)	<35	35 to 55	>55

Data were aggregated and de-identified for the purposes of this paper. All videos were reviewed and seats inspected thoroughly post-test.

RESULTS

All tests were conducted without any data loss. Exemplar time-histories for the sled, ATD measurements, belt and tether forces are presented in figures 3 and 4. The results are summarised in Table 3.

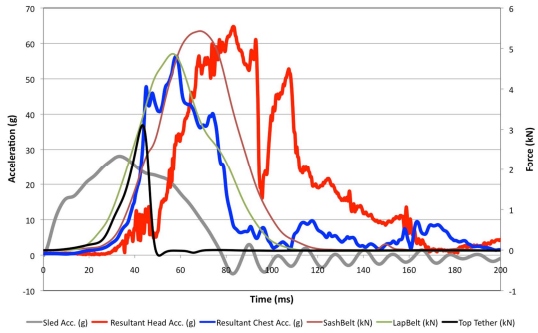

Figure 3. Time-histories from an exemplar frontal impact test (Test S120172)

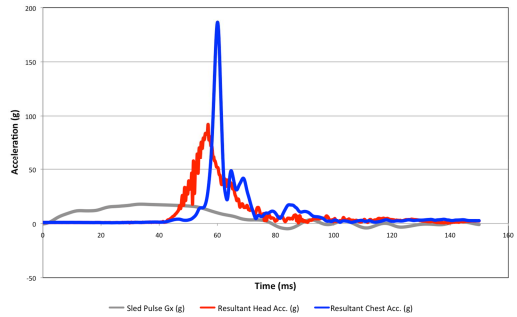

Figure 4. Time-histories from an exemplar side impact test (Test S120183)

Table 3.
Summary of main results. Results from all seats have been aggregated. Rhd and Rth are the peak resultant head and thorax accelerations respectively. CV is the coefficient of variation.

	Rhd (g)	HIC (36)	Rth (g)	Sash belt (kN)	Lap belt (kN)	Tether (kN)
Frontal Impact Test						
Mean	83	591	73	3.5	4.8	2.8
SD	35	216	17	1.7	1.1	1.0
CV (%)	42	37	23	47	24	37
Min	46	225	51	0.3	3.0	1.4
Max	141	790	103	5.4	6.5	5.1
Side Impact Test						
Mean	272	1613	178			
SD	112	1125	73			
CV (%)	41	70	41			
Min	92	324	72			
Max	484	4287	302			

Frontal impacts

All peak resultant head accelerations were less than 150 g and upper tether forces were less than 7 kN in the frontal impacts (Table 3). However, the upper tether strap attached to two models failed in the frontal test. In both cases there were large forward excursions of the seatback after this failure. The stitching on the tether looped around the restraint came undone during the test for both restraints. The force applied to the tether anchorage point in three seats would have been approximately double the measured webbing force because of the "V" arrangement of the tether strap (two attachment points on seat and one to the vehicle). The anchorage forces would have been between 6 kN and 10.2 kN. Therefore, the upper dynamic anchorage force limit of 7kN was exceeded. For that seat it is possible to attach the tether strap to two anchorage points, which would manage this issue.

There was fracturing of one seat frame in the frontal test. In this case, the seat base slid forward whilst the seat back was restrained by the tether system. The seatback-seat pan failed at approximately 56 ms fracturing at the junction. The crotch strap attachment also broke free and the seat's integral positioning harness penetrated the abdomen of the ATD. A potential penetration of the lap belt into ATD abdomen and a potential choking hazard via the sash belt interacting with ATD neck were difficult to observe visually. During the post impact period 54.5 ms to 56.5 ms, the approximate time point of failure, the range of forces in the lap belt were 1.9 to 2.6 kN, in the sash belt 3.0 to 3.3 kN and the upper tether strap was 2.6 to 2.9 kN. There was no abrupt change in the belt loads around the time of seatback failure and it occurred slightly after the peak resultant chest acceleration. The positioning harness was not instrumented. There was substantial slippage of the in-built positioning harness in one seat. In most cases the ATD slid forward away from the seat and in some cases the seat slid forward a substantial amount.

Side impacts

In the side impacts head accelerations were all high, except for one model (Table 3). The average peak resultant head acceleration was 272.4 g, indicating that a forceful head impact had occurred against the door panel. Chest accelerations were also high, with an average of 177.6 g, indicating that the chest or shoulder had struck the door panel. The videos of the side impacts were reviewed and this confirmed the interpretation of the ATD instrumentation. In one case no direct head strike occurred because the head was contained by the upper side wing. The side wing was compressed by the head against the door panel. This model exhibited the lowest head acceleration in the side impact, which was consistent with it providing the greatest distance between the door panel and the head of all CRS models.

Injury assessment

The results for each CRS model were analysed according to the injury rating scales in Table 2. The mean head injury risk in frontal impacts was low, based on peak resultant head acceleration, and medium based on HIC. The mean chest injury risk was high using both peak and 3 ms chest accelerations. For side impacts head and chest injury risks were high based on all criteria. The authors of this paper acknowledge that the injury rating criteria used in this study are basic and open to debate due to the lack of research study in this area. However, the authors believe that the injury assessment criteria applied are the best available.

DISCUSSION

The child restraints assessed in this program performed relatively well in the frontal impacts but poorly in the side impacts compared to AS/NZS

1754 requirements. This reflects that the international standards that they comply with do have frontal impact performance requirements, but no side impact performance requirements, in contrast to the Australian Standard. The two seats that would have 'failed' the Australian Standards test in the frontal impact because of the tether strap failure, performed best in the side impacts, due to the presence of substantial side wings. Later retesting of two exemplar seats with reconfigured tether straps found no failures.

There did not appear to be any consistent differences between seats that had been certified to the European (ECE 44) or USA (FMVSS 213) standards, or the purported place of manufacture. The sled test parameters in ECE 44 for frontal impact tests are a Δv = 52 km/h with the peak acceleration in the range 20 to 28 g. The TNO "P" series ATDs are specified in ECE 44, and were used in this project. The sled test parameters in FMVSS 213 for frontal impact tests are a Δv = 48 km/h with the peak acceleration in the range 19 to 25 g. The sled test parameters used in this study for frontal tests, Δv 49.5 km/h and 27.4 g, are comparable to both ECE 44 and FMVSS 213. This helps to explain why the child restraint systems could meet the USA or European standard and meet the frontal impact requirements of AS/NZS 1754. In general, the results identified that the seats can accommodate and function with the 36 kg ATD but may not be adequate for heavier occupants.

In the frontal impacts two models would have failed the requirements of AS/NZS 1754 because the tether straps failed. However, the resultant head accelerations were around 65 g indicating that the head acceleration was managed by the seat and restraint combination. It is noted that AS/NZS 1754 prohibits this event: "It is not intended that excessive excursion be the means by which the recommended force limit be met." An adverse outcome of this might be the child striking the seat or console in front. A third seat exhibited fracturing of the seat frame. In this case the head acceleration was high, 141 g and there was potential penetration of the lap belt into the abdomen and strangulation. The strength and effectiveness of the top tether strap in this seat appeared to contribute to the failure of the seat frame, as well as the loading of the ATD. The attachment of the seatbase to the sled seat via a U-shaped section of tubing did not secure the seat during the impact. This attachment might only be useful to enable the seat's swivel function to facilitate getting a child in and out of the seat. Once the seat frame failed, the ATD slid further forward and the lap belt rode up into the abdomen and the sash belt interacted with the ATD's neck. The failure of the seat frame reduced the effectiveness of the seat belt greatly and changed its orientation on the ATD.

Because of the lack of substantial side wings and lateral restraint, most CRS models did not meet the side impact requirements of AS/NZS 1754. Except for two seats, direct head impacts occurred against the door in side impacts. Those impacts were severe and if they occurred in a real crash would lead to significant head and brain injury. High chest loadings were also observed which would also lead to significant chest injury if they occurred in a real world crash. The performance in side impacts reflects that the CRS models have been tested to USA (FMVSS 213) and European (ECE 44) standards that do not have a side impact performance requirement, unlike AS/NZS 1754. The use of the side impact test with the door, which simulates a near-side impact, is appropriate because the seats would normally be installed adjacent to the door to make it easier for an adult to operate the seat.

The upper anchorage strength was assessed indirectly through measurement of the top tether strap belt load. This was an important consideration because that strength is specified in Australian Design rule 34/02. Using the largest and heaviest ATD, almost 36 kg, that could fit the selection of seats, the top tether strap load typically did not exceed 7 kN in the dynamic tests. In one case the estimated upper anchorage force exceeded 7 kN and reached over 10 kN. That seat model provided the option of attaching the tether strap to two vehicle anchorage points. This would manage the issue and reduce the force applied to each anchorage point. There was no failure of the anchorage point or its components even under this load; however the sled anchorage point is reinforced and does not reflect a standard vehicle. There might be a concern about upper anchorage strength if a heavier child, say 45 kg, was restrained and the vehicle underwent a crash similar to the test pulse. However, failure of the tether strap or hypothetically the anchorage point, might occur after they have attenuated some of the impact energy. In that case, the occupant will have derived some benefit, although if there is too great head excursion the child's head might hit the front seat, centre console or other structure. In this case, there might be an increased risk of head injury. The top tether strap provides an important function in frontal impacts, but little function in near-side side impacts. In the frontal impacts the tether strap was loaded and this maintained either the orientation of the seat and ATD to the three-point belt or in combination with the three-point belt restrained the seat. The top tether strap should play a more important role in a far-side impact than

in the near side impact tests undertaken for this report. It might at least assist in retaining the CRS in proximity to the original seating position. The one model which did not have a top tether strap, performed well in the frontal impact. That seat's tubular frame is anchored symmetrically to the vehicle frame via a restraint strap. Therefore, if there is a suitable alternative anchorage and attachment system, a top tether strap may not be required.

The injury rating system applied in this report is basic and open to debate. The head injury rating criteria are fairly robust, but there could be some argument to increase the permissible peak resultant chest acceleration boundaries. The injury ratings are confounded by the P10's limited biofidelity. This means, for example, that without a deformable chest, the chest accelerations may be greater than in a more biofidelic test device. Such devices, e.g. the Hybrid III or WorldSID, do exist but they are representative of adults. "Q" series child dummies could also be used. Ideally the future use of Q series ATDs in dynamic testing of CRS for children with additional needs would be in parallel with their use in AS/NZS 1754, so there is a point of comparison. The injury ratings reflect the limited performance of the models in side impacts. These tests are severe, because without any CRS structure between the ATD and the rigid door structure, the ATD strikes the door at close to the peak change in velocity. The door structure has no padding; therefore it is not surprising that high head and chest accelerations were measured.

There appears to be a variety of methods that manufacturers can employ to achieve frontal impact performance whilst offering ease of use, eg. swivel base, sizing adjustment, and provision of attachments. In recognition of this, the best mode of assessment in the future is to undertake dynamic tests of each seat that is offered for use for children with disabilities. It is clear from the data presented in Table 3 that there is scope to offer greater head and chest protection to the CRS occupants of these specific models. This is a challenging proposition when the operational context of the CRS's is considered. That context is: the range of physical, cognitive and developmental impairments of the target population; the need for the manual transfer of the child into the seat which might mean the carer exposing themselves to musculoskeletal injury risks; the size range of the target population; the physical capacity of the carer; and, the need to offer adjustability and provision for attachments. Therefore, to assist the carer and the child, these seats come in different configurations and a level of adjustability most likely greater than the standard CRS. It is clearly imperative that the child is transported safely and the carer is able to continue functioning in that role.

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