EFFECTIVENESS OF CHILD RESTRAINTS
THE AUSTRALIAN EXPERIENCE

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INTRODUCTION

Australia has several decades of experience in the development of child restraint system (CRS). During this time the requirements for child restraints, as set out in Australian Standard 1754, have evolved to incorporate the best features identified from road safety research and to eliminate undesirable characteristics. The most significant development was the introduction of the top tether. The effectiveness of the top tether has been demonstrated in the laboratory and in the real world crashes in Australia. Canada, the USA and recently France have recognised the advantages of the top tethers. Top tether anchorages are now required in North American cars.

International developments

As part of its consumer crash test program, EuroNCAP proposes to introduce performance criteria for child restraints based primarily on child dummy injury measurements. However, Australian crash test experience suggests that forward facing child restraints with top tethers and harnesses will have great difficulty obtaining better than 'poor' scores under the proposed Euro NCAP assessment protocol. In the real world Australian child restraints perform extremely well. There is serious concern that, to achieve reasonable results based on the dummy injury performance criteria proposed by EuroNCAP test, there is potential that the level of protection be offered by Australian child restraints will be reduced. Specifically, laboratory experience suggests that to achieve good Euro NCAP results would mean allowing greater excursion of the child dummy, with consequent increased risk of head contact and serious injury. This would be a retrograde step in Australia.

International endeavours towards harmonisation in the vehicle safety arena can sometimes cause conflict between having universally acceptable test or performance standards and avoiding a reduction in the overall level of protection provided by of a system that has been demonstrated to be performing very well. This is particularly the case with child restraints, where the level of protection provided by Australian restraints is arguably among the best in the world.

Since international harmonisation is currently a priority area in the vehicle safety field it is timely that a review of the Australian experience with child restraints be conducted. In addition, greater attention is currently being given to the safe transport of children in the USA with much debate in that country concerning the potential benefits or otherwise alternative anchorage systems including top tethers.

This document has therefore been prepared to present the Australian experience with child restraints in terms of design, both of restraint systems and methods of anchorage to the vehicle.

Included in this document is a discussion of the development of child restraint systems in Australia, research that has supported this ongoing evolution and issues and related findings of studies investigating the effectiveness of child restraints in Australia and elsewhere in the world. Issues related to directions in testing, performance assessment and anchorage methods in other countries are also given special attention.

CRS effectiveness

Overall effectiveness, in particular comparisons between "effectiveness" of Australian restraints and restraint systems in other countries is a fundamental concern when discussing differences in design and assessment . However, in any discussion it must be remembered that irrespective of fundamental design differences in child restraints between Australia and elsewhere, it is evident that child restraints are highly effective devices when compared with adult seat belts. Certain child restraint designs will be of greater benefit in some situations whereas the reverse might hold in other crash situations. Effectiveness therefore has to be considered very carefully to avoid invalid lines of logic.

Likewise, overall estimates of effectiveness are important as general indicators of the potential injury reduction benefits provided by restraint systems, but it is also important to consider the potential influence of other factors such as crash type, seating position and correct use.

The effectiveness of Australian child restraints compared with other countries is of great interest to any discussion where the benefits of one type of system are to be weighed against another system. But there are a number of limitations in using available Australian data in direct comparisons with estimates reported overseas. This document therefore goes into some detail regarding these limitations and the types of studies necessary to make meaningful comparisons.

HISTORY OF DEVELOPMENT OF CHILD RESTRAINTS IN AUSTRALIA

Australian research on child restraints started in the late 1960s through organisations such as the Traffic Accident Research Unit of New South Wales (TARU). This early work recognised the benefits of children being restrained in the rear seat and "riding down" the crash with the vehicle (Herbert and others 1974).

Australian Standard AS E46 for child restraints was issued in 1970. It required at least three points of attachment between the CRS and the vehicle. Most CRS utilised either three special attachment straps or a combination of an adult seat belt and a top tether to achieve this requirement. However, some designs relied solely on a three point adult seat belt. From the start there were concerns about this arrangement but imminent introduction of retracting inertia reel seat belts for rear seats of cars in the mid-1970s was a factor in a major review of the standard. AS1754-1975 required dynamic tests for the first time and led to greater (although not universal) use of a top tether on CRS sold in Australia. This was aided, in 1976, by an Australian Design Rule (then ADR34) that required standardised top tether anchorage points to be provided on the parcel shelf of all sedans. *Australia has therefore had more than 25 years of experience with top tethers on CRS*.

The performance of CRS in real world crashes has always been closely monitored in Australia and has been complemented by laboratory research using sleds, crash barriers and computer modelling. In the light of this experience the Australian Standard has evolved to eliminate shortcomings (in some cases demonstrated by poor performance in the real world) and to incorporate best practice. In "Crash Protection for Child Passengers: A Review of Best Practice", US child restraint expert Kathleen Webber reports favourably on the configuration of child restraint used in Australia and states "all CRS work on the principle of coupling the child as tightly as possible to the vehicle" (Webber 2000).

The Australian Standard for Child Restraints

All CRS sold in Australia must comply with Australian Standard 1754. This standard sets outs requirements for the design of child restraints, such as ease-of-use, and dynamic performance.

During the 1980s the New South Wales Government set up a network of child restraint fitting stations to improve the quality of installation of CRS, including retrofitting top tether anchorages. From this network road safety researchers gained invaluable first-hand knowledge of the kinds of problems that people encountered using child restraints. They then developed solutions to those problems, and identified areas where improvements in the Standard were required.

This was important, because it meant that when issues were brought to the Standards Committee's notice, the road safety authorities were able to provide good advice based on first-hand experience, and to make specific suggestions for any improvements or changes required. Rarely is such expert, "hands on" experience available for the purpose of developing standards.

Figure 1. Features of Australian CRS

The combination of a standard for CRS and an Australian Design Rule for CRS anchorages in vehicles has some significant outcomes which set them apart from other standards in North America and Europe. These include (see Figure 1):

1) mandatory top tether strap
2) single point of adjustment of the harness

3) six point harness with double crotch straps
4) rear seat mounting is normal practice
5) careful specification of the location of mounting points for top tether straps in vehicles (to assist accessibility and optimise performance)
6) a specially developed infant dummy, much more flexible than overseas infant dummies (hence more prone to ejection)

Some of these features are discussed in more detail below.

Top tether strap

Top tethers provide much more secure attachment of child restraints compared to being attached by the seat belt only. In particular, they provide more rigid attachment at the top part of the child restraint, so that it can “ride down” the crash whilst the vehicle is crushing. This considerably reduces excursion of the child's head relative to the vehicle interior so the head is far less likely to hit other parts of the vehicle interior - the most likely cause of serious injury to a properly restrained child.

A further advantage of top tethers is that they allow good, reliable performance with a lap-only adult seat belt. Therefore the centre rear seating position, which usually has a lap belt, can always be utilised (in NSW 40% of forward facing child seats are installed in the centre rear seat).

Six point harness with double crotch straps

It is evident that both harness and shield styles of CRS are capable of performing exceptionally well but each style also has inferior designs.

During the review of the Australian Standard in the early 1970s shield style CRS were considered as an alternative to the use of a harness. However, dynamic tests of shield style CRS that were sold widely outside Australia revealed structural deficiencies and a risk of ejection. There were also concerns about the application of force to the abdomen rather than the chest and pelvis that are better able to cope with crash forces. For these reasons the performance requirements of the revised standard discouraged shield style CRS and they have never been used in Australia.

Overseas there remain mixed views on the performance of shields. Webber (2000) reports on serious deficiencies with both "tray shield" and "T shield" CRS, common in the USA, and better relative performance of harness restraint. On the other hand, Hummel and others (1993) concluded from German study that "there is a significant higher tendency to severe injuries where 4/5 point (harness) systems are used". However, in the German study the sample sizes were small, the shield systems may have been a more effective design than those in the USA, the harness cases may have included the inferior four point systems and none of the CRS had top tethers. It therefore does not apply to Australian CRS.

In Australia early experience with four point harnesses proved to be very unsatisfactory with a high risk of the child submarining and being exposed to either ejection, dangerous loading of the abdomen or strangulation. Unfortunately there were also cases of children dying in stationary vehicles when they slipped down and were caught by the neck. Single crotch straps reduced the risk of submarining and were required under the standard.

Double crotch straps were initially introduced because of a fear (not substantiated by any actual incidents) of causing damage to the child's reproductive organs. A considerable amount of research was conducted into trying to find a repeatable standards test to measure the pressure applied by child restraints to that part of a child's anatomy, however no reliable method was ever identified. Ultimately, after more than five years of research, the Australian Standards Committee decided to simply mandate the design feature of twin crotch straps, rather than try to find a way of assessing the performance of single crotch straps. Subsequently all child restraints made and imported into Australia have been successfully designed or adapted to incorporate dual crotch straps.

Single point of adjustment of the harness

Early model child restraints had adjusters on many of the harness straps. Road safety researchers found that the more adjusters in a child harness there were, the more potential there was for incorrect or slack adjustment. The decision was made to mandate a design feature of a single harness adjuster only, so as to reduce the potential for loose fitting harnesses. Some single point adjusters were initially awkward, however development has now seen adjusters become a lot easier.

Rear seat mounting

There has been considerable publicity relating to the problems of airbags interacting with child seats installed in the front seat. This has been a major issue in Europe and North America.

Because all Australian CRS must have a top tether and the anchorages for top tethers are exclusively located in the rear of Australian cars, Australia parents have developed the habit of always restraining young children in the rear seat. In fact most of the current generation of Australian parents were, as children, restrained in the rear in similar CRS to those used today.

The exclusive use of rear seats means Australia has not encountered any of the problems due to the interaction of CRS with front airbags and there is no need to disable front passenger airbags in Australia.

International Standards - ISOFIX

Australia has had ongoing involvement in the International Standards Organisation Committee developing a new Standard for child restraint systems (ISO-CRS) since its earliest meeting in the mid 1980s. At that time it was recognised that child restraints needed to be more firmly attached in cars and there was a need for separate attachment systems for child restraints that did not rely on adult seat belts.

The UK representative, Richard Lowne, presented to the committee the results of an evaluation of all possible methods of attachment of child restraints and concluded that the most effective and easily implemented system would be one which had the child restraint attached at two points at the base and a single top tether. Opposition to top tethers, however, was so strong in some parts of Europe that this concept was abandoned and the system proposed was a four point attachment system, with attachments at each of the four corners of the base of the child restraint, with no upper restraint.

Ten years of development of such a system was undertaken, and it was close to implementation when the U.S. automotive manufacturer, General Motors did its own evaluation and concluded that top tethers could offer most, if not all, of the benefits of a four point rigid base system at a fraction of the cost.

This brought about an impasse position on the ISO Committee and stalled progress. Fortunately at that stage the U.S. Government intervened and a special U.S. 'Blue Ribbon' taskforce was set up to look at how better restraint systems could be offered to North American children. An outcome of that review was the LATCH system and a requirement for top tether anchorages in cars and effectively set development of child restraints in North America to those with top tethers (Webber 2000).

This then gave the option of child restraints being attached by a top tether and two lower anchorage points. This caused a review of the ISOFIX so that vehicle seats intended for use with CRS must be provided with two rigid lower anchorages and "a means to limit the pitch rotation of the CRS". In almost all countries the latter requirement will be achieved with a top tether. Remaining opposition to top tethers by some European researchers, and the ongoing disinterest in Sweden (which has unique CRS provisions), is unfortunate but has no significant effect of the global adoption of top tethers.

The provision of top tether anchorages is not an issue with most European, Japanese and Korean manufacturers - all imported vehicles in Australia have the fixings in place. Indeed, many manufacturers include the top-tether anchor/weld nuts on all models in non-Australian markets to reduce manufacturing complexity.

Vehicles with ISOFIX anchorages are now on the market. The Australian CRS standard is being reviewed to encourage designs that take advantage of the potentially improved lower restraint provided by ISOFIX, compared with adult seat belts. It is expected that this will improve the performance of Australian CRS in side impact crashes and will also eliminate the main form of misuse in Australia - incorrect use of the adult seat belt for securing the CRS (discussed later).

On the other hand, the lack of ISOFIX lower anchorages for the centre rear seating position will probably reduce the use of this desirable seating position by children in CRS. Although, under the proposed Australian Standard, the CRS must be able to be used in vehicle with and without ISOFIX it is likely that parents will use outboard seating positions that have ISOFIX anchorages in preference to the centre seat that only has a seat belt.

Suggested improvements to the Australian Standard

Despite their proven effectiveness in many types of crashes there are still improvements that can be made to Australian child restraints. For example:

- Boosters with better sides for the sleeping child – these are to allow a child to sleep, which they so often seem to like to do in travelling cars. The sides ensure that the sleeping child doesn't fall out of the booster, and keep the child's torso in position, so that the restraint system and seat can offer protection in the event of a crash.
- Further development or addition of energy-absorbing side wings to all child restraints to protect the head in the event of a side impact. This will also require that the child restraint is secured to the vehicle in a way that the side wing remains interposed between the child's head and the side of the car in the event of a side impact (a situation that could potentially be improved through use of ISOFIX lower anchorages - see next item).
- Tight fitting of the base of the child restraint to the car seat, either through tensioned rear base straps or rigid base fittings. ISOFIX type fittings should enable this to be readily achieved. Firm lower mountings, in conjunction with a tightly fitted top tether strap, should maintain child restraint position so that (amongst other things) side wings can stay between a child's head and the car interior.
- Visual indicator systems which indicate when the child restraint is correctly fitted and all the straps are tensioned correctly. Such systems could be mechanical or electronic.
- Tighter restrictions on (regulated) zones for location of top tether anchorages for child restraints. If anchorages are too far away from the back of the seat they can be both difficult to locate and difficult to attach a strap to. The Australian experience has been that the larger the zone, the more problems. Although this has already been addressed to some degree through the Australian Design Rule system, there is still scope for improvement. Countries considering regulating the location of top tether anchorages should note that many vehicle models sold in North America and Europe are also available in Australia where, for many years, manufacturers have provided anchorages that meet stringent Australian requirements.
- More biofidelic child test dummies and validated injury criteria. Early child test dummies were quite crude and basically designed to assess the strength of the CRS and its ability to restraint the occupant. New test dummies that do have better (but not optimal) biofidelity are available but considerable research is still needed for the setting of injury criteria, for use with these

dummies. In particular it would be inadvisable to base a CRS standard or consumer rating system primarily on dummy injury measurements.

- Australian children are often turned around to forward facing at 5 to 6 months of age. Europeans and North Americans think this is much too early, and that they will be vulnerable to spinal injury at that stage. The Australian experience indicates that these concerns are unfounded, although it is readily agreed that in general it is preferable that a child remains rearward facing for as long as possible.
- Improved protection for the 3-10 year olds. Real world studies have shown children correctly restrained in dedicated infant and child restraint systems with in built harness systems are generally more protected in crash situations than children in other types of restraints and adults in adult seat belts. Children moving out of this restraint too early and even children too big for the type of restraint often move directly into adult belts or adult belt and booster combinations. There is scope for improving the level of protection available to those children through improved booster design (and use).

THE KINETICS OF CHILD RESTRAINTS

Australian practice is to have a firm attachment between the CRS and the vehicle and to have the child firmly restrained by a harness - the intention is that the child "rides down" the crash with the vehicle. There are sound physical principles behind this approach.

The following analysis illustrates this principle and also points out the consequences of having slack in the system. It is important that slack be considered when assessing potential injury mechanisms in real world crashes.

The spring-mass system and effects of slack

Consider the *over-simplified* system of a heavy ball attached to a spring. The ball represents a child and the spring represents the combined elasticity in the CRS, arising from stretch of straps and bending of components. See figure 1, overleaf.

For a system with no initial slack the ball is supported (equivalent to having no acceleration acting on the ball) as shown in diagram A and there is no tension or compression acting in the spring. When the support is taken away the ball will fall until the force in the spring increases sufficiently to stop its motion (B). The ball will then rebound (assuming a perfectly elastic system) and eventually settle at an equilibrium position (C). At this point the force in the spring will be equal to the mass of the ball times the acceleration due to gravity. In this case the equilibrium point is halfway between the position of the ball in diagrams A and B. Since the spring force is proportional to the distance of extension then the force at point B is twice that of point C. In other words, with an *undamped* spring mass system the peak acceleration acting on the sprung mass will be *twice the acceleration of the frame of reference*. Importantly, this outcome is independent of the spring rate.

With a real child restraint system, the harness and other components absorb some of the energy and reduce the peak acceleration acting on the child, but the principles are the same.

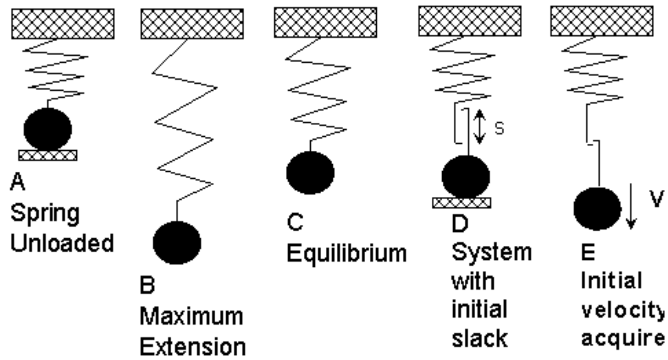

Figure 2. Simplified spring mass system

Now consider the introduction of slack into the system (D). In this case the ball will free-fall (accelerate under gravity) until the slack is taken up (E). At this point its velocity will be:

$$v = \sqrt{2as}$$

where *v* is relative velocity, *a* is the acceleration of the frame of reference and *s* is the amount of slack.

For example, if *a* = 30g ($294 m/s^2$) and the slack *s* = 100mm (0.1m) then the relative velocity *v* = 7.7m/s. The ball has acquired kinetic energy before the spring starts to extend. This extra energy must be absorbed by the spring, which extends further in order to arrest the motion of the ball (the extension is proportional to the square root of the energy). This means that additional force is applied through the spring and consequently the peak acceleration of the ball is greater.

For a hypothetical case where the mass of the child is 20kg, the spring rate of the CRS is 30kN/m (or a 6.5mm extension under the force of gravity) and the car body is decelerating at 30g the theoretical peak acceleration of the child is 60g with no slack and 73g with 100mm of slack. This is illustrated below.

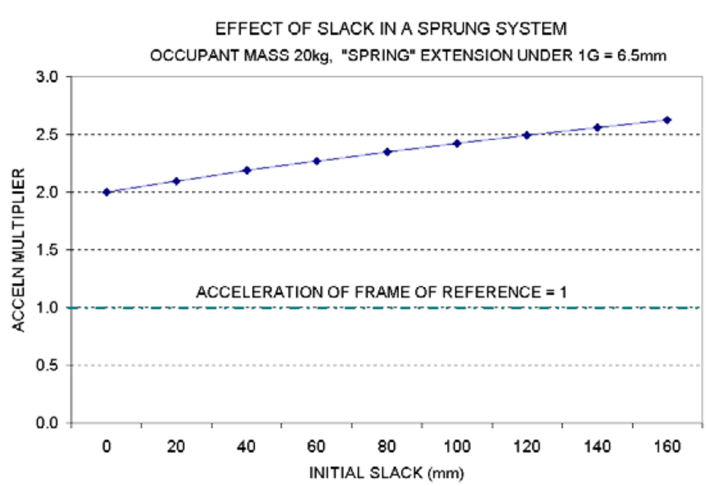

Figure 3. Effect of slack in an *elastic* restraint system

The extra extension of the "spring" (80mm for the above case) needed to absorb the additional kinetic energy is added to the initial slack in the system (100mm) to produce a large overall excursion (180mm) of the occupant - with consequent increased risk of head contacts. This extra excursion could be a greater hazard than the increased acceleration resulting from slack in the system.

It is evident from this analysis that any "give" in the restraint system is only useful if it absorbs and disperses the energy of the moving occupant. Displacement due to slack or *elastic* spring extension will not absorb this energy and could increase the risk of injury. In particular, softly sprung systems that do not effectively absorb energy will not reduce the peak acceleration forces on the occupant but instead will allow greater excursion of the occupant before the peak forces are reached.

Many modern adult seat belt systems have pre-tensioners to remove initial slack. This is in agreement with the principles of restraint of children.

Some adult seat belts also have load-limiters that allow extra extension of the webbing but this is usually a deformation action that absorbs energy. *If* the loads being applied to children by firmly attached CRS were proving to be too high and causing serious injury then it would be appropriate to consider some form of energy-absorbing load limiter in the CRS or harness webbing. However, as discussed later, this has been found to be unnecessary in Australia, even in high speed impacts.

Laboratory Evaluations of top tether performance

The issues under discussion in international task forces, such as ISOFIX, raised a great deal of interest in the potential benefits or otherwise of anchorage systems that incorporated top tethers. One of the most frequently posed potential dis-benefits of such systems had long been related to a theoretical potential for increased neck injury risk. Such a concern arises due to the real anatomical differences that exist between adult and children such as the greater relative mass of a child's head relative to its torso than an adults and a child's relative weaker neck musculature. Concerns based on these differences basically fall into two main groups. Those that are associated with the fear that by tying a forward facing child's torso rigidly to the vehicle, the neck may be at risk in frontal impacts through flexion (bending forward); and, those associated with allowing the neck to be loaded (via inertia) by the mass of the head.

Worldwide concern regarding the increased risk of neck injury in children restrained in forward facing restraints grew throughout the late 1980's. This was largely due to a small number of cases of severe neck injury in restrained children reported in North America and Europe. Significantly no such cases have ever been reported in Australia.

Detailed study of these case reports by an International Task Force found that all European cases involved seats incorporating 4 point harness and the North American cases involved one restraint with a 5 point harness and another with a harness/shield system. None of the restraints used a top tether.

In addition at least half of the cases were judged to have likely involved head contact (Tarriere and others, 1991). Australian experience is that the child's neck is quite resilient when subject to pure tension but is extremely vulnerable to moderate lateral loading when under tension. One of the difficulties with crash investigations involving neck injury is establishing whether a head contact did occur, since even a mild head contact can cause neck injury under some circumstances. Great caution is therefore required in the evaluation of cases involving neck injury.

The influence of anchorage systems on forward facing child restraint performance became a primary study target for researchers trying to understand why these types of injuries had occurred.

One of the first such studies, conducted by the international Task Force looking at the problem found that neck forces and movements were significantly lower in a 3 year old dummy in a tethered restraint compared to a non tethered restraint (Brun Cassai and others 1993).

In contract to this, Janssen and others (1993) reported that in their comparison of tethered and untethered restraint, the presence of top tether slightly increased the neck loads produced in their test dummy, however this dummy was of a completely different design to that used in the above study.

A similiarly designed dummy as that used by Brun Cassan and others (1993) was used by Weber and others (1993) in a similar comparison, but Weber and others also reported little beneficial effect on neck loads by the inclusion of a top tether.

An Australian study (Brown and others, 1995) also comparing the performance of tethered restraints found that the presence of a top tether can significantly improve the protection offered by forward facing seats. However this work noted that the benefit from top tether use was not as significant for all models of forward facing child restraints. Brown and others (1995) observed that geometry of the tether anchorage or the position of the tether mount on the child restraint appeared to have some influence on how much the tether affected the performance of the restraint (when performance is assessed by loads felt on the dummy). This issue was also investigated by Legault and others in 1997. These authors also reported that the presence of a top tether improved the performance of the forward facing restraints. However they believe that although there may be some difference in performance depending on the position of top tether mount, the improved performance introduced by the top tether on any restraint means that the presence of the tether strap is relatively more important than the location of its mounting point.

In this respect, Legault and others (1997) are referring to the major benefit of the top tether in frontal impact -the influence on reducing head excursion. This finding was also highlighted by the Brown and others study (1995).

Since the major reason for many of the top tether studies conducted through out the 1990’s was as a response to the reported neck injury in North America and

Europe, most work was conducted using frontal impact only. The influence of top tethers on child restraint performance in side impact came under scrutiny in the latter part of the 1990's in response to the international debate regarding universal anchorage methods.

Australian researchers, confident of the benefits of anchorage systems incorporating top tether system from real world experience (and laboratory studies such as those cited above) were keen for a universal method that continued to utilise a top tether arrangement. Laboratory work in Australia had shown that this method of anchorage also limited sideways movement of forward facing child restraints in side impact. Kelly and others (1995) reported that the lack of top tether reduced the protection potential of forward facing restraints in both 45º and 90º side impacts, however it was noted that the extent to which the tether influenced the sideways movement was different for different designs of restraint. In rearward facing restraints, the top tether had the greatest influence in minimising unwanted sideways movement of the restraint in side impact. However the degree of beneficial influence of the top tether in side impact was noted to be less then that observed in frontal impact. In fact, the lateral stability of the child restraints in side impacts appears to be more influenced by the geometry and rigidity of the lower anchorages (rather than the top tether). Australian researchers therefore considered that the area where the greatest gains could be achieved in side impact protection was by improving the two lower anchorages.

With respect to the universal anchorage method debate, the Australian position has been that the performance of the current Australian anchorage system, consisting of adult belt and mandatory top tether, works extremely well in frontal crashes. This position was based on laboratory studies such as those discussed above and field studies. However, Australian road safety professionals believed (and still do) that this form of anchorage is less than optimal in side impacts (Brown and others 1997). Almost all Australian child restraints (and probably restraints available elsewhere) when used in conjunction with adult seat belts allow some degree of undesirable sideways motion in side impact.

Further Child Restraint Laboratory Work In Australia

Australia has a long history of crash barrier and sled testing of child restraints. This research has been performed primarily to assist in the development of the Australian or international standards and to better understand the mechanisms of injury (or survival) in real world crashes. More recently a consumer evaluation program for child restraints was introduced.

This section contains a review of the Australian research. Some of the research has not been formally published before but nevertheless made an important contribution to the development of current Australian and international standards.

As discussed previously, some of the most important laboratory work carried out in Australia in recent times concerned the influence of top tethers. This work, together with the anchorage method studies, formed the basis for a series of experimental work carried out in Australia throughout the late 1990s and recent years.

Laboratory investigations of child restraint design

With respect to child restraint design, the top tether work reported by Brown and others (1995) and Kelly and others (1995) and cited above, highlighted differences in performance between restraints of different design. This observation had also been made anecdotally during earlier routine child restraint standards testing and led to the development of the Child Restraint Evaluation Program (CREP) program. Although Brown and others (1994) found some performance differences due to the influence of top tether mounting positions, Australian researchers knew that other design variables theoretically also had the potential to significantly affect the level of protection, in particular the amount of head excursion. One of the first variables examined (after the top tether work) was the influence of harness mounting height.

A range of harness adjustment heights is necessary to ensure a good fit for children across the whole design range for any specific type of dedicated child restraint. For example Australian forward facing child restraints are classed as 'Type B' restraints by the Australian Standard and are required as part of this classification to be designed to carry children from 9kg to 18kg. A laboratory study was conducted in the 1990s to explore the relationship between harness shoulder strap position and dummy shoulder position. This work found that harness straps positioned below a dummy's shoulder causes small decreases in head and neck loads, but significant increases in lumbar loads. Shoulder straps positioned above the shoulder were found to reduce head excursion, allow small increases in peak head acceleration and neck forces but have no effect on lumbar loads (Sampson and others 1994).

The complexity of such influences, when reviewed together with that of top tether mounting height, led researchers at the NSW Roads and Traffic Authority (RTA) to realise that attempting to study each design variable and analysis the parallel influences of each variable using simulated impacts was likely to be a long and costly exercise. Working with the University of Sydney, the RTA designed a program to study these types of variables using mathematical modelling. This research program produced some interesting, but as yet unpublished, information.

In summary, this work ratified the finds of Sampson and others (1995) and Brown and others (1995), and then went further to study design variables such as harness webbing properties, lap belt geometry, top tether length and child restraint seat back angles (Lixang, unpublished). Preliminary findings are ;

(i) of the investigated parameters, design variables such as seat back angle and lap belt position (or the geometry of the bottom anchorage) are the variable most likely to have the greatest potential to influence child restraint performance, and

(ii) all of the design variables investigated (ie seat back angle, top tether length, top tether mounting height, lap belt geometry) have optimal values. In other words, the level of protection afforded by a child restraint will vary within a defined range of design characteristics and at some point in this range lies an optimal design specification.

Other laboratory research

Australian researchers, based on field and laboratory studies like those discussed above, have long been reporting the good performance of child restraints in frontal impact. In side impact, from field experience in particular, it has been evident that the protection of child restraints can be improved significantly by design and anchorage modifications enhancing side impact performance. Results from field studies discussed later in this document highlight this issue in greater detail. Researchers from the NSW RTA have reported on numerous occasions (Brown and others, 1997) that the three main goals of a child restraint system in side impact should be;

(i) ensuring that the child restraint has 'sidewings' that retain the head

(ii) once the head is retained, providing some form of energy absorption in the 'sidewings'

(iii) preventing excessive sideways movement and rotation of the child restraint.

Some, but by no means all, Australian rearward facing and forward facing child restraints already provide relatively effective side structures (or sidewings) that work to retain a child's head in side impact. Very few of these provide some means of energy absorption in the side structure to protect the head from side impacts. An unpublished series of laboratory simulated impacts conducted at NSW's Crashlab in the late 1990s demonstrated that a relatively minor modification aimed at providing energy absorption could greatly improve the potential head protection provided by a popular Australian forward facing restraint. This model of restraint already has well designed side wings that have been shown to satisfactorily retain a dummy's head in most side impact orientations. The energy absorbing characteristics of the side wings were altered by have polystyrene beads poured into the existing gap between the outer and inner surface of the sidewings. The beads were treated in the same manner as that in the manufacture of foam liners for pedal cycle and motor cycle helmets. The result was a significant drop in the head loads measured in child dummies during 90 degree side impacts. This modification was tested with two different types of dummy, and in simulated sled impacts and car to car tests. The side impact protection of the device was found to be improved in all test types.

With respect to limiting sideways movement of restraints in side impact, Australian laboratory work (both on the sled and barrier tests) have demonstrated that an ISOFIX approach,(ie two rigid anchorages at the base of the restraint and a top tether) can significantly limit sideways excursion. (Kelly and others, 1995, Brown and others 1997, NSW RTA Crashlab unpublished work)

Finally the restraint of children in adult restraint systems has also been the subject of laboratory research in Australia. Henderson and others (1997) reported on a sled test series investigating the level of protection provided to a range of child dummies by adult belt systems. This work demonstrated that lap only belts and lap/sash belts potentially do provide some level of protection, for even the very young child (approximately 2 years). However the protection provided by lap/sash belts is far superior to that of lap only belts, and for the very young child a child restraint is the optimal form of restraint. As is discussed in later sections of this report, these findings basically mimic in a laboratory setting was has been observed in field studies.

Computer Modelling

Modelling work described above was achieved using a mathematical package employed widely in the vehicle safety and design area - the lumped mass MADYMO package. Until this work was completed, no MADYMO child dummy database, that was designed to perform in a human like manner, existed. The completion of this database, applicable for frontal crashes, has opened the way for further such complex work in Australia and overseas. Since this database was completed, a second database for the same child dummy but validated for side impact has been reported (Roberts and others, 2002). To date no research using this side impact database has been reported.

Crash Barrier Tests

The NSW RTA Crashlab has conducted a number of unpublished barrier tests that have included child restraints and instrumented child dummies. The most notable of these tests was the Variable Speed Test Program. This program involved a series of crash tests using the same model vehicle at varying impact velocities. The impacts ranged from 40km/hr to 100km/hr. Adult Hybrid III dummies occupied the front seating positions in all but the 100km/hr test. Fully instrumented six month CRABI dummies restrained in forward facing child restraints were positioned in the left and right rear-seat passenger positions for each test, including the 100km/h test.

This test program was conducted very soon after the sled work investigating the influence of top tethers on child restraint performance reported by Brown and others (1994). Since a major finding of this work was the potential difference in performance observed due to different tether mounting positions, the forward facing restraint systems chosen for the variable speed program where models that represented a ‘high’ and ‘low’ mounted top tether. A number of interesting observations related to child occupant protection, and tether position specifically were made from this program.

With respect to the top tether mounting position issue, the results from this program confirmed the observations reported by Brown wt al (1994) that the design of the child restraint can have a potentially significant influence on dummy response. This held true in each individual test speeds and was also apparent at increasing test speeds. In particular, the variable speed test program demonstrated that the difference in the level of protection for the head, chest and some neck loads become relatively greater at high impact speeds. However for other neck loads (axial forces, and flexion moments), the influence of restraint design is less evident with no clear patterns apparent. Overall, the high mount restraint had the most marked effect on limiting head and chest acceleration. The high mount system resulted in significantly lower chest loading (approximately 50% less than low mount restraints) and consistently lower head accelerations. This is an important outcome when considering the results of other laboratory work, and crash investigations, involving CRS with top tethers. The variable speed program also provided interesting insights into the effectiveness of adult protection systems compared to CRS. There was an obvious difference in the patterns of response obtained from the front seat adult dummies and rear seated child dummies. Specifically, the adult HIC values demonstrated an exponential increase with increasing impact speed while the child dummy values tended to level off at speeds over 60km/h. Even in the 100km/h test the HIC for the child dummies was not significantly greater than those at lower speeds. However there were no results available for the adult dummies in the 100km/h test. There was a steady increase in peak chest acceleration in both front seat passengers. There was a significant difference in the peak chest accelerations obtained from the two child dummies in the rear seat. One dummy showed a steady increase while the other increased less rapidly. It is interesting to note that the head and chest regions of the two front seat adult occupants gave similar levels of response in each test. However the two child dummies, as discussed above, often produced differing results particularly in the response of the head, lower neck axial force and chest. (Brown and others, unpublished RTA report)

Figure 4. Variable speed crash tests by Crashlab. Lower image shows peak of 40km/h crash. Top images shows peak of 100km/h crash, which was considered to be survivable for the child dummies in CRS installed in the rear seat.

The difference in the pattern of head response observed between the front seat occupants and rear seat occupants are obviously due to differences in the ride down effect introduced by the differences in the restraint system, contact with the vehicle interior (with gross intrusion into the front occupants survival space at the higher speeds) and the distance from the front of the vehicle to the occupant (in effect, the available crush distance).

This different adult restraint system effectiveness, and the level of protection provided by different seating positions has been reported by statistical investigations of restraint system effectiveness conducted elsewhere in the world (discussed in more detail later in this document). However, no such similar barrier investigation is available in the literature.

Finally, the variable speed test program provided a number of results that raise serious doubts about proposals to use child injury measurements for assessing CRS performance. For example, the problem becomes clear if the CRABI six month neck measurements obtained from this program are compared to neck injury limits proposed by Mertz and others. (See figure 5).The measured axial neck loads in both child dummies are significantly greater than the injury threshold levels proposed by Mertz. This is even the case with the low speed 40km/h test. As discussed later in this document, neck injury (without head contact) has never been reported or observed in Australian child restraint field studies even though these studies have included crashes of much greater severity than the 40km/h barrier test. This raises serious questions about the proposed neck injury criteria and further work is needed before these criteria can be confidently used in any assessment of CRS performance.

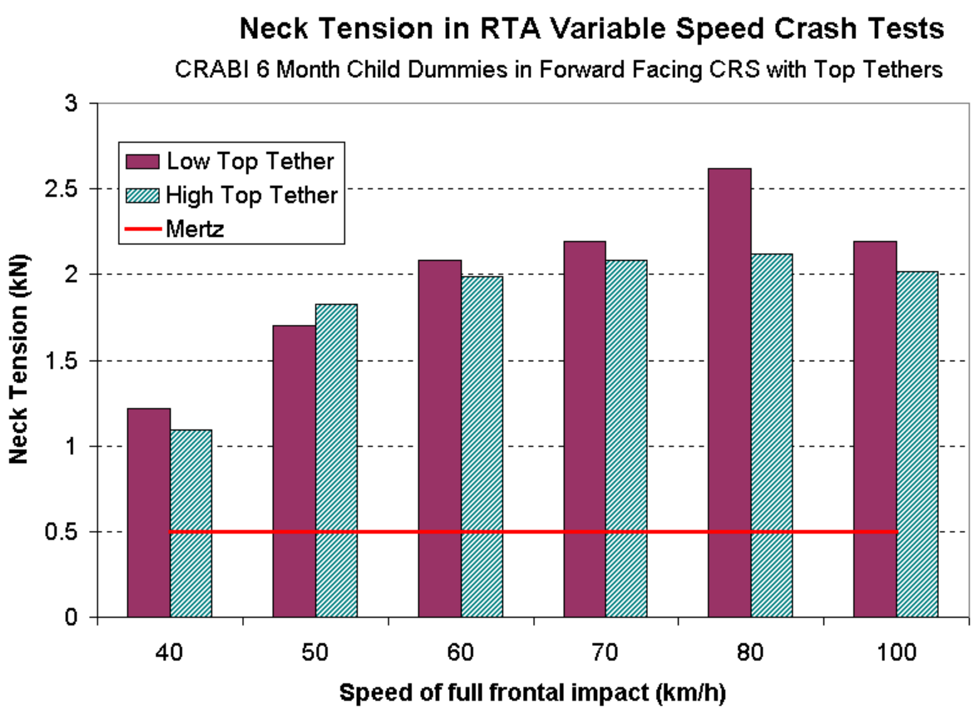

Figure 5. Upper Neck Maximum Fz compared with AIS 3+ IARV (Mertz)

Simulations of real world crashes

The NSW RTA has conducted a small number of real world crash reconstructions, and simulated reported real world problems. None of these have been formally published. In summary these tests have involved;

(i) reconstruction of improper use of child restraints observed in the field including analysis of kinematics and mechanisms of injury

(ii) reconstruction of impacts involving catastrophic injury to restrained children. These cases have shown that problems with rear seat design contributed to injury in the real world

(iii) investigation of possible sub optimal features of child restraints. Results from some of these investigations have led to revisions to the Australian Standard..

Standards and consumer programs

Child restraints used in Australia must comply with AS1754. The dynamic tests for CRS are set out in AS3629.1. This specifies sled tests for forward facing child seats (type B restraints) as follows:

- a frontal impact at about 49km/h with a peak deceleration of 24g and
- a 90 degree side impact test with a peak deceleration of 14g and an impact speed of 32km/h.
- a rear impact test with a peak deceleration of 14g and an impact speed of 32km/h.
- Inverted test at 16km/h to simulate a rollover crash (rearward facing restraints).

Systems are assessed for:

- retention of the CR
- retention of the dummy
- separation of load bearing components
- fragmentation of rigid components
- adjuster slip

These assessments are made in all test configurations.

Child Restraint Evaluation Program (CREP)

Australia has operated CREP for more than a decade. CRS are subjected to dynamic tests (some more severe than the Australian Standard) and usability trials. Consumers are advised of the best performing restraints (via brochures and the internet).

It was realised early in the development of CREP that it would not be appropriate to apply dummy injury performance limits to the ratings due to a lack of biofidelity of the dummies and uncertainty about the application of dummy injury measurements to injury risk in children. Dummy injury measurements are considered during the assessment process but are secondary factors - head excursion and risk of head contact are considered far more important (Kelly and others, 1996).

Of particular concern to Australian researchers is that a misguided attempt to reduce dummy injury measurements could result in greater head excursion and therefore greatly increased risk of a head contact, resulting in serious head and neck injury. Real crash experience in Australia, where children have been found to survive extremely severe crashes without serious injury, calls into question current injury limits for children, which are mostly based on extrapolation of adult limits (Brown and others 2001, Trosseille and others 2001, Melvin 1995, Beusenberg and others 1993).

NHTSA is considering the introduction of a consumer rating program for CRS in the USA (NHTSA website). Submissions to NHTSA have expressed concern about the reliance on dummy injury measurements. Australian experience support such caution: *at the current state of dummy development and knowledge about child injury tolerances, it would be inappropriate, and quite likely counter-productive, to base a CRS consumer rating program primarily on child dummy injury measurements*.

Similar concerns apply to a CRS assessment protocol being developed by the European New Car Assessment Program (EuroNCAP). Child dummies are restrained in CRS in the rear seat of vehicles that are crash-tested under the program. Australian NCAP has found that, in general, Australian CRS do not meet the unvalidated dummy injury limits proposed by EuroNCAP. Furthermore, the EuroNCAP protocol explains that the vertical chest acceleration limits are based on those set out in ECE Regulation 44 for CRS. In effect, the Regulation limits compression of the spine (a concern with rearward facing restraints) but without explanation, EuroNCAP applies the limit in both directions. Forward facing restraints normally load the spine in tension and so the ECE 44 limits are considered inappropriate.

Australian researchers, consumer organisations and state authorities involved in ANCAP are concerned that insistence by EuroNCAP on inappropriate injury limits might encourage CRS that offer inferior real world protection (Paine and Brown 2001). ANCAP maintains a strong position and input to EuroNCAP regarding this issue.

CREP Assessments

CREP assessments are based on the Australian Standard but involve higher crash forces and additional test procedures. In addition to the AS1754 tests an extra frontal test at 56km/h and 34g is conducted. In addition, the CREP side impact test, although conducted at the same severity and orientation (90 degrees) as required by AS, includes a structure that is intended to replicate the interior of a side door as part of the test configuration. An extra side impact test is also conducted. This second side impact is conducted at the same severity with the same test set up but uses an impact angle of 45 degrees.

Forward facing child restraints are assessed using a P6 dummy for the frontal test and a P3/4 for the other tests.

Figure 6. CREP Test at 45 degrees

The CREP assessment criteria include those covered under AS1754. The following measurements are also recorded.

- Harness strap forces (frontal test)
- Tether forces, harness forces and seat belt forces (frontal test)
- Head acceleration
- Head displacement (frontal test) – including rebound – limits apply to upward and rearward excursion (during rebound) *but not to forward excursion*.
- Head retention (containment) – side impact tests
- HIC
- Retention of device and dummy
- Adjuster slip
- Buckle release force (frontal tests)

Note that chest decelerations are measured for infant capsules (Type A) but not child seats.

For most criteria *there are no limits set for performance* – the models of restraint are simply ranked in order of measured values and good performers tend to stand out in these lists. There are specific reasons for excluding child restraints from the 'preferred buy' list. These include;

- Not passing requirements of Australian Standard in all test configurations
- Head excursion outside prescribed limits in frontal test or rear impact test
- Head contact with test rig during side impact test

Ease of use and compatibility issues are also taken into account in deciding which restraints should be given a 'preferred buy'.

The procedures used to rank the ease of use, include a judgement regarding how simple it is to put each restraint into a vehicle, and how easy it is to secure a child in the restraint. (Kelly and others, 1996).

Installation judgements in the first CREP series were made in the following manner:

- A panel of “trialists” were used who had no or limited installation experience
- Trialists installed each model of restraint into a vehicle and an assessor scored each attempt.
- Scoring was based on
  - ease of reading and understanding instructions
  - placing the restraint in the car
  - routing the seat belt
  - adjusting and attaching the top tether

Ease of securing the child in the restraint was assessed in the following manner:

- trialists who had no or limited child restraint experience were required to secure a child into each restraint
- scoring included
  - ease of reading and using instructions
  - ease of adjusting harness
  - ease of putting the child into the restraint and the harness
  - ease of using a buckle and harness straps or tether (as appropriate)
  - ease of releasing the child from the restraint
  - ease of placing the bassinette in the car (if removable)

(It is assumed that ease of use is still assessed in the same manner since no detailed report regarding this in the latest CREP series has been released. Likewise, vehicle and child restraint compatibility was included in both the original and latest version of the program but methodology details have only been published for the first series. Kelly and others (1996) described this procedure as involving all child restraints being fitted into two positions in the rear of six different vehicles. Each vehicle was one of the top four Australian selling models in six different vehicle categories. The restraints were fitted into the left rear and centre seating position. Observations and measurements were then made regarding how well the restraint “fitted” each vehicle, or in other words, the compatibility between each restraint and each vehicle.

Since a number of vehicles require forward front seat adjustment to allow enough space in the rear compartment for installation of a child restraint, the CREP compatibility assessment also includes an evaluation of front seat ‘comfort’ when the child restraint is in place.

There is potential, however to make the ease of use assessment more objective. A draft assessment protocol has been developed for Australian NCAP and is being considered for both NCAP and CREP child restraint /vehicle assessments. The draft protocol is included as an Appendix to this report. In brief, it sets out an objective scoring system for assessing: installation instructions, use of adult seat belt (belt paths and angles), location of top tether, ease of adjustment of top tether tension, yaw rotation, adjustment of harness shoulder height, ease of placing dummy in the CRS, ease of adjustment of harness, harness fit, clearance to vehicle components, quick extrication of dummy (usually with CRS), ease of maintenance (disassembly for cleaning).

Australian NCAP

In late 1999, the Australian New Car Assessment Program (NCAP) aligned its test and assessment protocols with EuroNCAP.

NCAP assesses the crashworthiness of new vehicles and provides a star rating for the protection provided to front seat occupants. The primary purpose of providing consumers with useful information is to assist purchasing decisions.

From a road safety perspective this program is beneficial in that the purchasing pressure applied by consumers on vehicle manufacturers for good safety performance will drive vehicle designers to incorporate more and more safety technology into their new vehicles.

Two types of crash test are used in the assessment - an offset frontal crash test and a side impact crash test. The offset frontal crash is conducted at 64km/h. In this test, the vehicle hits a crushable barrier and the crash forces are concentrated on the driver's half of the vehicle. The side impact test involves a moving barrier, fitted with a crushable front, impacting the driver's side of the car at 50km/h. In both tests, anthropomorphic dummies with standard instrumentation are used as surrogate occupants. The offset frontal test occupants uses two adult Hybrid III dummies instrumented to record head, neck, chest, upper and lower leg loads in the driver and front seat positions. In the side impact test, a specially designed side impact dummy, the adult Euro-SID is placed in the drivers position and injury measurements are recorded from the head, ribs, lumbar spine, abdomen and pelvis of the dummy.

The EuroNCAP protocol also requires two child restraints to be installed in the rear seat of the vehicle being tested. The child dummies used are the TNO P1.5 and P3, simulating 18 month and 3 year old children respectively. In the offset frontal crash the P3 sits behind the driver and the P1.5 sits behind the front passenger. The positions are swapped for the side impact crash test. These child dummies are instrumented with head and chest accelerometers. Dummy movement is recorded on high speed film and is analysed to assess the movement of each dummy.

Figure 7. ANCAP Offset Frontal Crash at 64km/h

Currently, under the EuroNCAP Assessment Protocol, child restraint performance is primarily based on dummy injury measurements. EuroNCAP is currently reviewing the assessment criteria, partly in response to concerns expressed by Australian NCAP. These concerns are discussed in the next section.

Since late 1999Australian NCAP has included child restraints and dummies (in line with the EuroNCAP protocol) in vehicles being tested in both offset frontal and side impacts. Due to the fundamentally different design of child restraints in Australia, ANCAP does not currently apply the child restraint portions of this protocol and hence does not report the results of child restraint performance.

Key Findings from Laboratory Research

The extent of laboratory, both sled and barrier, research conducted in Australia has given Australian researchers an enormous amount of background experience in the are of child restraint design and particularly child restraint performance assessment.

Together with experienced gained from decade of real world investigations, this experience means that Australian researchers have an informed grasp on the qualities of child restraints that have particular significance on their ability to protect children in the real world. The most important example would be a restraint ability to limit head excursion and in turn to provide head protection. It is for this reason, that most assessment programs and research programs conducted in Australia to date have use head excursion (and in side impact, the ability of a restraint to protect the head) as the primary assessment feature.

To some extent, this approach (and the experience underlying this approach) is at odds with some developing assessment procedures elsewhere in the world, or in the case of Euro-NCAP, assessment procedure currently in place.

Concerns about EuroNCAP Assessment Protocol

Based on a number of the key findings of Australian research to date, there are two primary problems with the assessment protocol being used by EuroNCAP.

Firstly, the Euro-NCAP test method uses the TNO 'P series' dummies. Although Australian Standards testing (and most regulatory most testing worldwide) uses this type of dummy, the fact that the TNO P-series dummies are non-biofidelic means that the use of such dummies in injury criteria based assessment is not really acceptable. Trosseille and others (2001) sum up the problem with P-series child dummies: "*The current child dummies (P-dummies) were developed in the late 1970’s and early 1980’s... To further improve child safety it seems necessary to replace the P-dummies with child dummies that are not only more advanced, but can also evaluate the protection offered to children in lateral impacts and the interaction of children with deploying airbags. Indeed, P dummies are quite rudimentary and are not able to evaluate the protection in detail"..."When the CREST project started, only the conventional TNO P-series dummies were available. It appeared very quickly to the experts that the behaviour of these dummies was not biofidelic.*" (it is noted that co-author Schrooten is an employee of TNO, the dummy manufacturer).

It is common in Australian child restraint tests with P-series dummies for the legs to swing upwards and there is contact between the head and the legs. It seems unlikely that humans will move in this way but, in any case, the head to leg contact is far from being realistic since the properties of both the dummy head and legs have no correlation with that of a human child.

Standards type testing does not include any biomechanical based performance requirements. Instead, requirements mainly centre on ensuring that the child restraints remains in tact and contains the test dummy in various impact configurations. For forward facing child restraints, the European Standard and the North American standard also includes a requirement related to a head excursion limit. Although not a true biomechanical performance measure, as discussed above, this is directly related to the restraints' ability to prevent injury.

Euro-NCAP on the other hand primarily assesses child restraint performance using injury criteria. An example of the criteria used for frontal impact is shown in Table 1.

Table 1. EuroNCAP Frontal Impact Injury Criteria

Parameter	**P 1½ Child Dummy**		**P 3 Child Dummy**	
	1 point scored up to	0 points scored at and beyond	1 point scored up to	0 points scored at and beyond
Head excursion *	450 mm *	550 mm*	450 mm*	550 mm*
Head Vertical acceleration, 3 ms exceedence	20 g	40 g	Not measured	Not measured
Chest resultant acceleration, 3 ms exceedence	41 g	55 g	41 g	55 g
Chest vertical acceleration, 3 ms exceedence	23 g	30 g	23 g	30 g

Further, the protocol requires that "in the event of a hard contact occurring on a structure other than the car interior, as indicated by either direct evidence of contact or a peak resultant head acceleration in excess of 80g, the limits in" the table 2 should be used.

Table 2: EuroNCAP Frontal Impact Head Contact Criteria

Parameter	P 1½ Child Dummy		P 3 Child Dummy	
	1 point scored up to	0 points scored at and beyond	1 point scored up to	0 points scored at and beyond
HIC 36	650	1000	650	1000
Head Resultant acceleration, 3 ms exceedence	72 g	88 g	72 g	88 g

The overall score for each child restraint in frontal impact recorded for assessment is the worst scoring parameter from the above tables.

Australian NCAP has included child dummies in its crash tests since late 1999. All of the dummies were restrained in forward facing child seats with top tethers. The results of these tests are shown in Figures 8 and 9. It can be seen that all exceed the limit on vertical head acceleration (40g) and many exceed the limit on vertical chest deceleration.

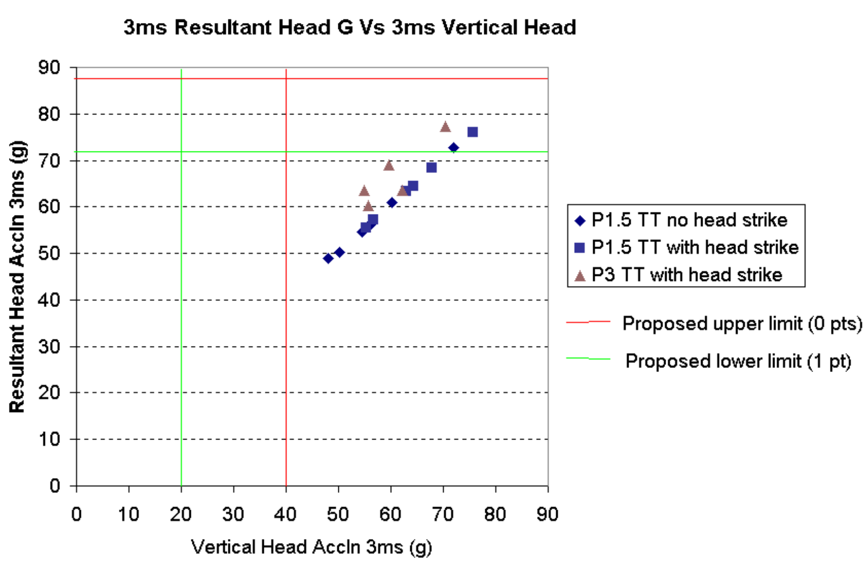

Figure 8. ANCAP CRS Measurements - head deceleratrions

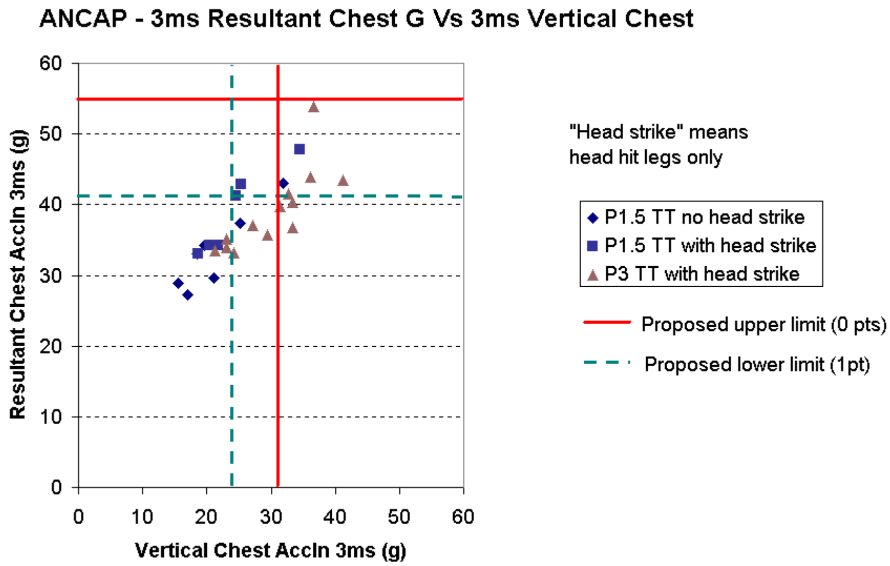

Figure 9. ANCAP CRS measurements - chest deceleration

However, as stated above TNO P Series dummies are the prescribed dummies in this protocol and these dummies are not, and have never had any claim to biofidelity when used in forward facing CRS (Trosseille and others 2001). Most significantly, there has never been any validated injury criteria set for use with the TNO P series dummies. Given the excellent experience with CRS in Australia the assessment criteria proposed by EuroNCAP are considered to be seriously flawed.

There are, however, two different sets of proposed criteria available for use with CRABI and child Hybrid III dummies. This data can not be extrapolated to the TNO P- Series dummies because different dummies respond in different ways. This has been clearly demonstrated both in Australian and overseas (Brown and others 2001). Trosseille (2001) address the problem of assessing injury risk for child in vehicle crashes: "The analysis of accidents involving children reveals that child restraint systems (CRS) in compliance with European regulations give highly contrasted levels of protection in real-world accidents. The main reasons for this are on the one hand the lack of biofidelity of the dummies, and on the other hand the insufficient biomechanical knowledge on injury mechanisms and associated physical parameters. Unlike for the adult, child impact tolerance or behaviour cannot be determined directly by experiments on human bodies...".

Melvin (1995) also points out the difficulty in obtaining injury tolerance for children. For example, current neck tension tolerances are partly based on tests of stillborn children conducted in the late 1800s (for use in obstetrics).

Australian work studying head acceleration results from sled testing using the same child restraint subjected to same crash severity but using two different dummies, illustrated significant differences in dummy response. The test involved a frontal impact using the same impact conditions required by Standard Australia. The head acceleration result obtained with the TNO dummy was about 200g, while the result obtained with the CRABI six month dummy was in the vicinity of 60g.

Likewise the conditions under which the same dummy is tested can have some influence. For example head accelerations obtained with the same dummy in an impact of equal severity on a sled compared to in a full scale barrier test can produce significantly different results. In one such comparison using the CRABI six month dummy the peak head acceleration was 60g in the sled test, while in the full scale barrier test the head acceleration was somewhat higher at 79g (unpublished RTA Crashlab research).

Similar results were reported by Duma and others (1999) when they compared the head and neck response of two different dummies,the Q3 dummy and the Hybrid III three-year-old dummy. They found substantial kinematic and kinetic differences between these dummies due to differences in head geometry and mass, and neck stiffness. In addition significant difference were also noted in the neck tension, flexion moment and lateral bending responses between the two dummies.

The fact that different dummies responded differently to each other and the same dummy will give different results depending on the test environment has two important implications. Firstly, results obtained from similar test situations using different test dummies cannot really be directly compared (in terms of biomechanical performance). As a result, care needs to be taken when comparing the responses obtained with the same dummy in different test environments, even when testing occurs at similar severity. (In the sled v barrier example here the main differences in test environment would be the crash pulse, characteristics of the seat on which the child restraint was placed and the geometry and properties of the seat belts used to anchor the child restraints.)

Secondly, injury assessment curves and values, however they are derived cannot be transferred to dummies other than those for which they were developed. This was also the conclusion of Duma and others (1999) following their comparison of the Q3 and the Hybrid III three-year-old. They stated “these tests suggest that separate injury criteria are needed for each dummy”.

The other major problem with the child restraint injury criteria used by EuroNCAP is that there is no correlation between the performance limits set by EuroNCAP and the risk of injury in the real world. In fact, currently there has been no validation (in terms of real word injury potential) of any or the proposed child injury criteria regardless of the dummy used (Brown and others, 2001).

All of these issues are extremely significant in discussing results, or methodologies intended to evaluate child restraint effectiveness in the laboratory. Basically the state of art of child dummies and child injury criteria means that child restraint effectiveness cannot, with any scientific validity, be assessed in terms of real world injury potential. Rather, as has been the case in Australian research and assessment procedure to date, child restraint performance in the laboratory can really only be evaluated

(i) in terms of dummy movement

(ii) in terms of relative protection

Therefore, at the current state of child dummy development, the only way to realistically evaluate effectiveness is by studying how child restraints perform in the real world.

STUDIES OF THE EFFECTIVENESS OF CRS

Most studies of child restraint effectiveness have used some form of real world data. This data is usually gathered from one of two sources. These are; mass crash databases or in-depth studies. Different types of data source provide different levels of information. Sample numbers are much higher in mass crash data investigations but the level of detail can be limited. On the other hand, detailed information can easily be produced through vigorous investigation of real world crashes, but the numbers involved are usually smaller and less representative of any particular population.

Although estimates of child restraint effectiveness have been reported from a number of different researchers around the world using data such as that described, most estimates have been fairly general in their methodology. For example, the effectiveness of child restraints, like any occupant protection system, is going to depend on a number of variables that have the potential to directly impact effectiveness. Most studies reported to date have not taken into account variations introduced by different types of restraint systems, seating position and crash severity and orientation. Incorrect use and/or inappropriate use of different types of restraint by different age groups can also influence effectiveness.

Subject to these limitations, overall estimates of effectiveness can be important general indicators of potential injury reducing ability of restraint systems., as long as the potential for other factors (such as crash type, seating position and correct use) to influence the level of protection is kept in mind.

Overall estimates of effectiveness

Child restraints have been demonstrated in numerous studies, to significantly reduce the risk of death and serious injury. In North America and Europe, studies have estimated this reduction to be in the order of 70%. (Weber, 2000; Partyka 1990; Carlsson 1991; Tingvall 1987; Cuny 1997 and Isaksson –Hellman and others 1997). Similar estimates of the effectiveness of adult belts in reducing the likelihood of serious injury in the adult population have been in the order of 50%. (Weber 2000; Huelke and others 1979; and Malliaris and others 1982). It therefore appears that dedicated child restraints have the potential to reduce

injury risk by a greater extent than adult belts reduce the risk of injury in the adult population.
There appears to have been little in the way of formal evaluation of child restraint effectiveness conducted in Australia

In 1980, an estimation of the effect of NSW legislation requiring children under eight years to be restrained found that this legislation reduced casualties by about 30% (Herbert & Freedman 1980). However, this was not a true measure of restraint effectiveness since this figure was based on reduction of all child occupant casualties. That is casualty numbers included children restrained in child restraints, seat belts and travelling unrestrained in the rear of the vehicle and was not a direct before and after count for children of child restraint age.
A more recent Australian analysis was conducted in 1994. This study compared injury in Western Australian child occupants two years and younger to that reported for children of the dame age in NSW. The study found "children reported to be wearing a restraint were 50% less likely to sustain an injury requiring hospitalisation". This figure refers to all levels of severity and is not confined to the reduction in the more serious end of injuries (as was the case the North American and European estimates cited above).

The most recent and most comprehensive Australian study of children and child restraint performance in real world crashes was conducted in NSW throughout the year 1993 (Henderson 1994; Henderson and others 1994). The primary objectives of this study did not include the statistical investigation of the effectiveness of child restraint systems but was designed to investigate the general performance of the child restraint systems available at the time. The ability of Australian child restraint systems to provide effective crash protection was confirmed by this study. Of the 247 children aged 14 years or younger included in this study, 228 were using some form of restraint and very few sustained serious injury. This was the case even though the sampling methods were such that data collection was skewed towards the serious end of crashes. Figure 18 is reproduced from the Henderson (1994) report and illustrates the restraint type by maximum AIS for all restrained children in the study. From these figures it can be seen that 88% of the restrained children received injuries of a severity MAIS 2 or less.

This study also provided valuable information regarding the types of injuries and sources of injury observed in restrained children in Australia. Although not strictly effectiveness studies, in-depth investigation of injury and injury mechanisms are vital to ensuring optimum occupant protection (for both children and adults). This type of study will be discussed in greater detail in the next section.

Problems with studies that simply attempt to report the overall effectiveness without taking into account specific influential factors are particularly relevant to the Australian situation. The effectiveness figures from Australian studies cited above (50% - Herbert & Freedman, 1980; 30% Palamara & Stevenson, 1994) are lower than those figures reported in North American and European studies, but it is unlikely that this actually proves that Australian restraints are less effective than their overseas counterparts.

In fact the performance of Australian child restraints in laboratory and in-depth field studies suggests Australian restraints would have to be at least as effective, if not more effective, than many of the restraints available in other countries. It must therefore be remembered, that not all studies such as those cited above are not designed to deliver true estimates of effectiveness.

At a recent Australian seminar regarding child restraint design, a claim was made that Swedish restraints were much more effective that those in Australia. This claim was based on the number of deaths due to road trauma for every 100,000 of population. This is a measure of the public health risk associated with road trauma. Although these figures relate to all deaths including both adults and children, it is useful to discuss them in terms of their appropriateness as a measure of restraint effectiveness. This type of comparison does not take into account the degree of motorization or the kilometres travelled. For child restraints (and other restraint systems) there is also the complication that the total number of fatalities does not separate those who died while on the road as vehicle occupants from those who were killed riding bicycles or as pedestrians. In addition fatality rates presented make no discrimination between those unrestrained and those using available restraint systems. For these reasons alone, it is inappropriate to make measures of effectiveness based fatality rates.

One possible method of accounting for exposure is to compare fatality rates - that is the ratio of persons killed to persons injured. Figure 10 shows the results of a tentative analysis of road accident fatality rates for children (AIT 2001). This *appears* to indicate remarkably low fatality rates in the USA, Germany and UK compared with Australia, Sweden and France. However there are numerous problems with these data that make it impossible to draw valid conclusions:

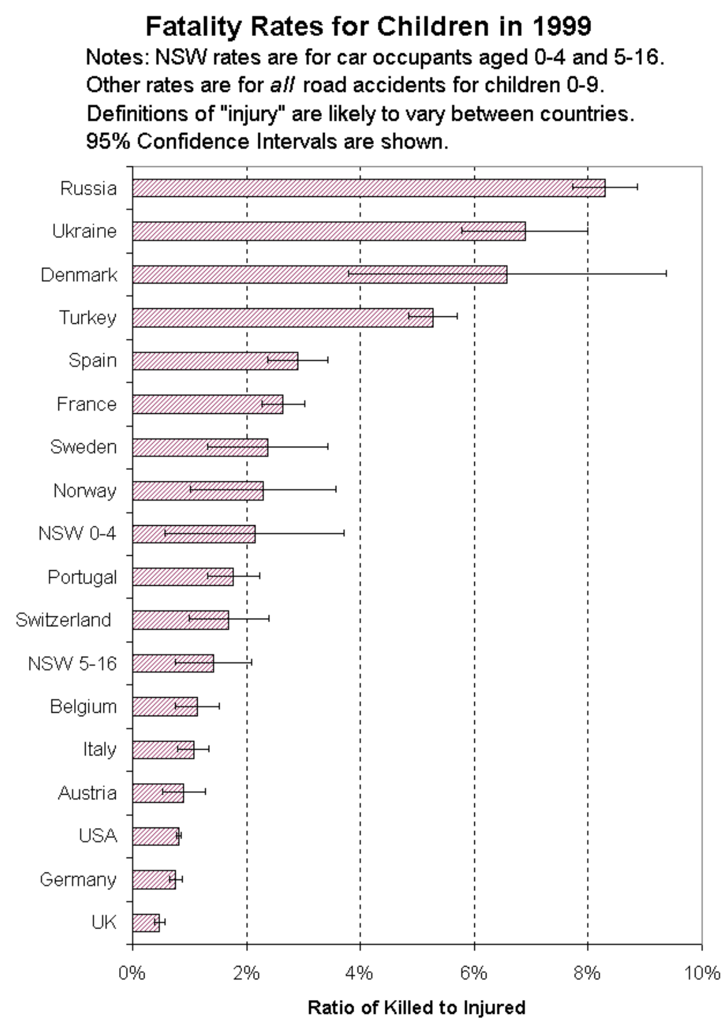

Figure 10. Tentative Analysis of Fatality Rates. There are many confounding factors that make this type of analysis *invalid*.

- most rates are for all road accidents involving children, including pedestrians and cyclists. New South Wales data are for car occupants only (RTA 2000).
- The definition of "injury" is likely to vary considerable between countries.
- For some countries samples sizes are small and resulting confidence intervals are large (error bars on graph).

The main problem with this type of comparison, however, is that a system which does well at preventing any injury, such as a well-designed CRS, is disadvantaged because injuries only occur in the severest crashes.

Effectiveness of different types of child restraint

Unless otherwise stated, "effectiveness" compares outcomes with an unrestrained occupant.

The differences in effectiveness, depending on the type of restraint (and the inherent design of different types of restraint) can be seen from European and Swedish studies. As Australian researchers would expect from experience gained in the laboratory, it appears that rearward-facing restraints provide the greatest level of protection. Most studies have estimated that rearward facing restraints reduce the risk of serious injury by about 80-90% (Tingvall 1987, Carlsson and others 1991; and Cuny and others, 1997). A recent analysis of the Swedish Volvo crash database reported that the injury reducing effect of rearward facing child restraints might be as high as 96% (Isaksson-Hellman and others, 1997).

Estimates of the effectiveness of forward facing child restraints have been closer to the 70% overall estimate of effectiveness (Weber, 2000; Cuny and others, 1997).

Also as Australian researchers would expect from laboratory experience, booster seats (and belt positioning boosters) although providing improved protection compared to an adult belt system, provide a lower level of protection than other forms of dedicated child restraint. Carlsson and others (1991) reported that forward facing booster type restraints in Sweden reduce the risk of injury by 30-60%. Cuny and others (1997) in France estimated this type of restraint to reduce injury by about 30%.

The highest level of injury reducing effect introduced by booster type restraints was recently reported by Isaksson-Hellman and others (1997) from their analysis of the Volvo crash database. These authors found the Swedish belt positioning boosters reduce injury by about 77%. It is likely that these differences in booster estimates indicate the potential influence of inherent design for any particular ‘type’ of restraint. Such differences design differences (and their likely influence on effectiveness) are extremely relevant to the Australian situation where child restraints of any particular ‘type’ can vary markedly from their European counterparts. This provides another example of the difficulties encountered in trying to compare the effectiveness of restraints between countries.

Estimates of the effectiveness of adult belts used by children have also been made by a number of researchers. These estimates vary widely between 30% and 60%. The effectiveness of the adult belts in protecting children appears to depend on the age of the child (Partyka, 1988; Cuny and others 1997 and Isaksson man and others, 1997).

The use of a lap belt compared to a lap/sash belt is generally estimated to reduce the level of protection by about 20% (Mallieris & Digges, 1987; Lundell and others, 1991).

Therefore in terms of the level of protection these studies have found that rearward facing restraints provide the highest level of protection while adult belts provide the lowest.

A final problem with comparing overseas mass crash data with Australian data is the disparities in general occupant protection practices in Australia compared to overseas. Most notable is the practice in some countries of carrying children in the front passenger position, while in Australia, most dedicated restraints are used only in the rear seats. As will be seen in later discussions, this difference in practice suggests that Australian child restraint effectiveness estimate, if conducted in a similar manner to those studies cited above would yield even higher injury reducing rates.

Influence of seating position on CRS effectiveness

The rear seat (where children in Australia are most often positioned) has been demonstrated to provide a greater level of protection for both adults and children in an number of overseas studies (Kelleher-Walsh and others; Morris 1983; Evans and others 1988; Partyka 1988 and Braver and others 1997). An analysis of North American mass crash data found ‘rates of injury at any given severity level are uniformly and monotonically declining in the following order: unrestrained, front seated; unrestrained, rear seated; restrained, front seated and restrained, rear seated.” (Morris, 1983)

However, somewhat surprisingly, some studies have failed to find any protective benefits of the rear seat for restrained occupants (Kraft and others 1989). It is possible that the absolute results of many of these studies, those that have found positive effects for rear seating positions and those that have not, have been confounded by the type of restraint being used (and possibly to some extent the types of impacts). This issue is particularly significant if we note that most seating position comparisons involve adult belt systems and there is a known difference in the level of protection afforded by three point adult belts compared to two point belts. Similarly the exposure of different age groups is likely to be different in different seating positions. It is also likely that the usage rates of different seating positions by different age groups will vary between different countries.

A very thorough recent study of risk of death among child occupants in front and rear seating position was reported by Braver and others in 1997. This study found an overwhelming increase in protection for rear seated occupants. Variables such as restraint use, airbag status, restraint type, impact locations, speed limit and vehicle type and their influence on the protection provided by the rear seat compared to the front seat were studied. In summary Braver and others found injury risk reductions for rear seat occupants in the following circumstances:

- An overall 36% reduction for children 12 years or younger.
- An overall 32% reduction for occupants 13 years and over.
- An overall 41% reduction for children aged 1-4 years.
- An overall 30% reduction for children aged 5-12 years.
- A 37% reduction in children not using restraints compared to non users of restraints in the front seat.
- A 38% reduction in restrained children compared to restrained front seat occupants.
- In vehicles without airbags in the front position, there was a 35% reduction for children in the rear.
- In vehicles without airbags the injury risk reduction in the rear ranged from 26% to 43% depending on the restraint status and type of restraint used by the child in the rear (26% for unrestrained, 31% for those using adult belts and 43% for those using child seats).
- In vehicles with dual airbags there was an 80% reduction in injury risk for children using dedicated restrains.
- Benefits of rear seat positions were slightly lower in areas of high speed limits compared to those of lower speed limits (33% in high speed areas, 48% in low speed areas).
- Type of vehicle had influence on the benefits of rear seat positions. Rear seat benefits higher in midsize 2 door passenger cars (45%) than 4 door passenger cars and midsize station wagons (28%).
- Rear seat injury risk reductions depending on type of impact were
  - 47% for frontal impacts
  - 43% for rollovers
  - 32% for side impacts
- There was an increase in injury risk for children in the rear seat in rear impacts. This was a significant increase (61%). But only 5% of fatal car collisions involve rear impacts.

Crash characteristics and the effectiveness of CRS

As discussed above, different types of child restraint provide different levels of protection, depending on crash conditions. Effectiveness of any restraint system is therefore likely to be influenced by both the severity and type of impact.

Braver and others (1997) findings illustrate the type of influence crash severity (in terms of impact speed) that crash conditions can have on restraint effectiveness. Braver and others (1997) noted that the benefits of rear seat positions were slightly lower in areas of high speed limits compared to those of lower speed limits. Cuny and others (1997) also reported impact velocity to have a significant influence on restraint effectiveness. In particular Cuny and others found that in frontal impacts, both forward facing child seats and booster seats provided lower levels of protection in impacts of higher velocity. For booster seats they reported an 80% reduction of MAIS 2 and greater injuries in impacts occurring at less than 40km/h and a 23% reduction in impacts of 40km/h and greater. In addition, the reductions in higher impact velocities found in forward facing child seats were not as large as those observed in the case of boosters. In frontal impacts, with impact velocities of less than 40km/h Cuny and others (1997) found forward facing child seats to provide an injury reduction of MAIS 2 and greater injuries of 78% while in impact velocities of 40km/h and greater, the injury reducing effect was 65%.

Braver and others (1997) also noted differences in the level of protection depending on impact orientation. They found rear seat injury reductions were 47% for frontal impacts; 43% for rollovers; 32% for side impacts and an increase in risk of 61% in rear impacts.

For child restraint systems the greatest difference in effectiveness has been noted in injury and survival rates that occur in frontal and side impacts. Side impacts are much more likely to result in serious and fatal injuries to children than frontal impacts (Braver and others, 1998; Rattenbury and others 1993, Langweider and others 1996). Weber (2000) sums up these type of findings by stating that “approximately twice as many crashes with a child fatality are frontal compared to lateral, but side impacts are nearly twice as likely to result in a child fatality regardless of restraint status and seating position”. French and German studies have confirmed these findings and gone further to demonstrate that the fatality rate of children involved in frontal impact is the lowest of all crash configurations while in side impacts the fatality rate is the highest (Langweider and others 1996, Vallee and others 1993). Henderson (1994) noted in the Australian study of real world crashes involving children that “ side impacts were the crash configuration most likely to result in significant injury’. Hummel and others (1997) note that the risk to children on the struck side in side impacts is particularly high.

Rear impacts have also been observed to pose a significant risk for children restrained in rear seats. However, the overall frequency of severe rear impacts is generally low (Braver and others 1997; Vallee and others 1993).

STUDIES OF REAL WORLD CRASHES

Most of the effectiveness studies discussed above involve the analysis of mass crash data. Effectiveness can also be studied by in-depth investigation of real world crashes but such investigations do not usually involve enough cases to yield statistically significant estimates. In-depth studies can, however provide essential information regarding the good and bad performance characteristics of child restraint design. Design characteristics and their influence on protection is probably best studied through investigations aimed at identifying the type and pattern of injuries sustained by both restrained and unrestrained children.

In-depth real world impacts involving child occupants have been studied by numerous teams of both Australian and overseas researchers. These studies have included all levels of investigation.

Investigation of injury type and pattern can also be studied using mass crash data, however in such studies identification of injury patterns is usually the primary aim and hence overall effectiveness estimates have not been attempted.

Injuries to restrained children

One of the most interesting thing from review of Australian and international in-depth child occupant/injury pattern studies, is that a number of very similar findings regarding the overall injury pattern has been reported by a number of researchers. The most important of these are that most injuries suffered by restrained children are minor, the head (and face) is the most commonly injured region, and the head is the most seriously injured region. The type of study or where in the world the study is conducted appears to have no bearing on this overall pattern of injury to restrained children.

It should be noted that the head is also the most frequently injured and frequently seriously injured region of unrestrained children in the real world impacts. But according to Upledger et at(1997) the incidence, and severity of head injury among unrestrained children is much higher than seen in restrained children). (Henderson, 1994; Rattenbury & Gloyns ,1993; Tingvall, 1987; Agran and others, 1988; Upledger and others, 1997; Newgard and Jolly in 1998; Isaksson-Hellman, 1997; Khaewpong and others 1995).

In the real world, the type of injury sustained by any restrained child, like the effectiveness of any particular restraint is complicated by many different variables. In terms of injury the most influential variables are: age range, type of restraint, seating position, crash type and crash severity. The influence of these factors is discussed in detail below.

The influence of restraint type, seating position and crash characteristics on injury pattern

Although the head remains commonly injured region in all children involved in car accidents, studies have shown that factors such as those listed above all influence the severity of injuries and the pattern of injuries over the rest of the body.

Age range influences are intimately related to those of restraint type, since restraint design vary (sometimes slightly, and sometimes significantly) for different age ranges of children. This means that although some researches have reported age related differences, in most cases these differences can generally be explained by differences in restraint system (and their appropriateness for the specific grouping of ages in any particular study).

For example Agran and others (1997) looked at the injuries suffered by three groups; 0- 3 years, 4- 9 years and 10 –14 years. They found that in the injuries, in the 0-3 age group no other region besides the head appeared to suffer injury with any significant frequency. They noted that in this age group the most infrequently injured regions were the chest, abdomen and spine. However in the 4- 9 age group the author's found a significant rise in the number of injuries to the abdomen and the extremities. And spinal strains began to be prominent in the 10 – 14 year age groups. The author's also noted that there was a relative decrease in the number of head injuries suffered by this older age group. Newgard and Jolly (1998) reported similar findings. They analysed a database consisting of 2141 child passengers and grouped the children into those aged 1 year, 1-4 years, 5-10 years and 11-16 years. Like the Agran and others (1997) study, these authors found that for children under 4 years, the head region was the only body region that was injured with any significant frequency. In terms of head injury in this age group the findings reported were more specific than the Agram and others (1997) study. For instance Newgard and Jolly (1998) reported that for children aged less than one, minor facial injuries were the predominant type of head injury (60% of the sample). And only 1 in 10 of the total sample (of children under 1) actually had a "head" injury, but 40% of these head injuries were serious. A similar pattern of facial and head injuries were observed by Newgard and Jolly in their 1-4 year group. But here (unlike Agran and others) they also noted an increase in frequency of abdominal injuries and injuries to the extremities.

Newgard and Jollys (1998) findings for their older age ranges were also similar to that reported by Agran and others (1997). In the 5 – 10 years age group the extremities and the abdomen were also injured with significant frequency, however of interest is the appearance of significant numbers of injuries to the chest and spine. In the oldest age group, 11-16, injury to the extremities and the spine occurred in even greater numbers than injuries to the head and face. The children on this study less than 1 years old were almost all using a child restraint (50%) or were unrestrained (43%). Most of the children 1 – 4 years were using an adult belt (42%) or a child restraint (34%), but a significant number were unrestrained (24%). Most of the 5-10 years children were also using adult belts (63%) but again a significant number were also unrestrained (37%). Similar proportions of restraint use were observed in the oldest group (11-16) with 55% using adult belts and 45% unrestrained. Newgard and Jolly (1998) did not discriminate between children restrained and unrestrained in describing the frequency of injury to different body regions.

The findings of both these studies, demonstrate how similarities and differences can be largely be explained by the type of restraint being used by the majority of the children in each age range.

A number of more in depth studies of children in car crashes have studies the importance of type of restraint on injury patterns in detail. Because of the nature of these type of investigations, these studies have involved much smaller sample numbers. Khaewpong and others (1995) using a sample of 103 children reported that. that for children in infant seats (birth to 9kg) the only body region injured with any significant frequency was the head. For children in convertible child restraints (birth to 18kg), the head and the face were the most frequently injured regions with 79% of the children receiving head injuries and 71% receiving facial injuries. The upper extremities were also injured with some degree of frequency in this age group (29% of children receiving injuries). In booster seats the head and face was also the most injured, however injury to the abdomen was also observed in 42% of the children. In children using lap belts, the abdomen was the most frequently injured region (78% of the children), followed by the face (59%), head (44%) and chest (26%). In lap/sash belts Injury appeared to be generally more widespread with the following frequencies; face 67%; head 60%; abdomen 60%; upper extremities 40%; neck 33%; chest 30%; and lower extremity 23%. By superimposing age ranges on to these restraint types the similarity between this study and those of Agran and others and Newgard and Jolly becomes evident.

The significance of abdominal injury in children using belt-positioning boosters was also highlighted by Troisseile and others (1997). The authors noted that in an analysis of French crash databases, abdominal injuries occurred in similar frequencies for children using booster seats as they did for children using adult belt systems alone.

Henderson (1994) also described the types of injuries sustained by children using different types of restraints in Australia. This study consisted of a sample of 247 restrained children aged 0 to 16 who were using infant restraints, child seats, belt-positioning boosters and adult belts. Most of the children in this study received only minor injuries (AIS 1) or moderate (AIS 2) injuries (80% of sample). Specific information related to the body regions injured in each type of restraint was only provided for the more serious injuries. Head injuries were the predominant serious injury observed in both children restrained in infant seats and forward facing restraints. Head injuries were also the most often observed serious injury in children using booster seats, although injury (fractures) to the extremities were also observed in a number of these children.

A large number of the children in the Henderson (1994) study were using lap/sash belts (almost 50%). The pattern of injuries suffered by these children was similar to that described by Khaewpong and others (1995). That is, in general the injury was more widespread and the head/face and extremities were the regions most often injured in the children using adult seta belts. However in the Henderson (1994) study, the neck, chest and abdomen of children using lap/sash belts were injured with almost the same frequency as the head. Also similar to the Khaewpong and others (1995) study, Henderson (1994) reported the head and the abdomen to be the most frequently injured regions in children using lap only belts.

Isaksson-Hellman (1997) also described the pattern of injury sustained by children using different restraint systems. This study, using a Swedish crash data base included only rearward facing child restraints (used by children 0-3), belt positioning boosters and adult belts (used by children over 3years). The authors found almost no injury at all in their sample of rearward facing restraints. Only 3 injuries were reported from a total of 421 children and these were all relatively minor. They involved two instances of leg fracture and one minor brain concussion. For belt positioning boosters their observations agreed somewhat with that reported by others ie: the most frequent body region injured was the head. However they also reported a relatively high frequency of serious spinal injury and some chest injuries using this restraint system. The same widespread pattern of injury in children using adult belts was observed. The authors also noted that spinal injuries in older children were typically positioned in the thoracic regions while spinal injuries to small children were mainly found in the cervical region.

One or two studies have also attempted to study differences in injury patterns depending on the type of impacts and where in the vehicle the child was seated. Agran and others (1989) reported an increase in spinal injuries in children restrained in the front seat of vehicles involved in rear impacts. These author's also noted more severe head and facial injuries occurred in same side child passengers involved in side impacts compared to children in other seating positions and in other types of impact. Interestingly Khaewpong and others (1995) found the opposite, i.e. more severe head injuries in the far side seating position in side impact. A possible explanation for this is non struck side child restraints without top tethers will pivot and point towards the area of impact/intrusion, while struck side child restraints are engages directly at a lower level by the side of the car

Isaksson-Hellman and others looked in detail at the frequency of injury to specific regions (head, spine and abdomen) in frontal impacts and side impacts. They found that for children restrained in belt-positioning boosters, serious head injury occurs at about the same rate for both frontal and side impacts. However for children restrained by adult belts serious head injury appears to occur much more frequently in side impact. Spinal injury was found to be more common in frontal impacts for both types of restraint system. Abdominal injury in children using belt –positioning boosters was found only in frontal impacts while for children in adult belts in occurred in both frontal and side impacts (albeit much more frequently in frontal impacts.)

Injury sources for restrained children

Studies that describe injury sources for restrained children are also important to understanding the good and bad characteristics of child restraint practices.

An example of such a study where sources of injury, by injured body region, were described in some detail is the study by Khaewpong and others (1995). For head injuries, these authors found that most serious injury occurs following a head strike with an interior hard surface. The surface struck depends on the seating position and the type of restraint used. The types of surfaces involved include the instrument panel, dashboard, A and B pillar, interior door panel and doorframe. Minor head injuries, in most cases, were attributed to contact with the restraint system itself. For facial injuries the authors noted that most injury to this region was minor involving cuts and bruises but no injury source was described for these injuries.

The overwhelming source of neck injuries in the Khaewpong and others (1995) study were due to contact with seat belt webbing. Inappropriate use of adult belts was also observed to be a causal factor of injury to this region in a significant number of cases. No specific contact/causal factor for upper extremity injury was observed. For chest injuries, the authors noted that this was primarily a problem for children using adult belts. Serious injury was most often caused by contact with hard interior surfaces while minor injury could be attributed to contact with softer surfaces and the restraint system itself. Pelvic and abdominal injury was also really only a problem for children using adult belts, particularly lap only belts. And 90% of these injuries arose from contact with the restraint system. Lower extremity injuries were reported to have occurred most frequently when the restraint system was correctly used and the occupant was seated in the rear, no specific injury source was identified.
Contact with the hard interior was also described as the major source of head injury in restrained children in Sweden (Isaksson – Hellman and others 1997). Fatal spinal injuries were also reported to have occurred in conjunction with head contact with interior surfaces. The authors noted that spinal injury mainly occurred in frontal impact and was associated with belt use. Abdominal injuries were mostly attributed to inappropriate belt geometry for children using adult belts systems.

Troiselle and others (1997) believe the majority of abdominal injuries observed in children using belt positioning boosters is caused by the design of many boosters which allow children to submarine the lap belt.

The Australian study conducted by (Henderson, 1994) reported the types of injury source for different types of restraint system in great detail. For rearward facing restraints, Henderson (1994) reported serious injury to mainly occur following contact with the vehicle interior. In most cases this involved intrusion of the vehicle. In forward facing child restraints, Henderson (1994) also noted that most head injury occurred following contact with a surface of the vehicle interior. Injuries to the neck, chest and abdomen (all mainly minor) were attributed to contact with the restraint system. Injuries to the extremities were found to have occurred following contact with vehicle door, other seats in the vehicle and other child restraints in the vehicle. Minor injuries involving bruises and abrasions were found to have occurred predominantly by contact with restraint webbing. Lacerations were mainly due to flying glass.

With respect to forward facing child restraints Henderson (1994) concluded "injury is most likely to be a result of intrusion, contact with nearby parts of the vehicle interior and other occupants, invasion of the child's space by collapsing seta backs, flying glass and other such mechanisms. Injury is unlikely to occur from the forces of deceleration alone."

Serious head and neck injury observed in children using boosters by Henderson (1994) was found to occur in conjunction with misuse and was mainly related to head contact with the vehicle interior. Extremity fractures observed in children using this type of restraint were found to occur following contact of the extremity with other seats in the vehicle, other child restraints in the vehicle and the dashboard. Minor injuries sustained by children using booster seat predominantly involved bruising from contact with seat belt webbing.

Head and facial injury sustained by children using adult belts was also mainly found to be caused by contact with the vehicle interior. Contact sources included the console, the door or window, other car seats, the roof, the windshield, and dashboard. Flying glass was also a common source of injury for these regions. Injuries to the neck, thorax, spine and abdomen were almost all attributed to the seat belt. Injuries to the extremities occurred mainly as a result of contact with parts of the vehicle interior. There was also a number of minor neck injuries reported in children using adult belts in which there was no contact.

A major study of children injured in car crashes is being conducted by The Children's Hospital of Philadelphia. The study has collected data for over 150,000 car crashes. From these important cases are selected for more in-depth studies. To date, published research findings have covered low usage of booster seats by children around 4 years of age, injury patterns in side impact crashes, facial injuries, extra risk of side facing seats in pick-up trucks and injuries from seat belts (CHOP 2002). One of us (Griffiths) is on the Advisory Board for this study.

Survival of children in severe crashes

Some in-depth studies have looked at severe crashes where children were not seriously injured, primarily understand why the restraint system worked so well. Many of these crashes come to attention due to adult fatalities.

Henderson and others (1994) describes several cases from the CAPFA study where children survived severe crashes. Figures 11a to 11b illustrate some of these cases. Henderson concludes:

"*There are few safety devices that are as effective as child restraints. We found in our study that the only injuries caused by deceleration alone were bruising and abrasion from loads imparted from harness and seat-belt webbing, and there were no cases of cervical spine injury in high-speed frontal impacts when restraints were correctly used. The head remains the most important part of the body to be protected. The principal threat to the restrained child is from invasion of the child's space through impact intrusion, collapsing seat backs, and flying glass and loose objects. The child is also at risk if allowed to move out of its space, and restraint design should place a high priority on the minimisation of excursion of the upper body in order to prevent head contact.*"

Herbert and others (1974) report on similar remarkable cases during the early years of experience with top tethers.

For more than two decades the NSW RTA has informally monitored reports of fatal road crashes and, where possible, has investigated cases involving serious injuries to children. During that time no cases of severe injuries caused by deceleration forces alone have come to attention, where the children were correctly restrained in a properly installed child seat. Serious misuse or gross intrusion have been the main factors in the few cases of severe injury or fatality.

Misuse of CRS

Restraint systems designed for use by children have been shown to be extremely effective in preventing injury. However to provide optimum benefit they must be used by appropriately aged children and be used correctly. In some cases, incorrect use of a child restraint can actually increase the risk of injury or the severity of injuries sustained by children in crashes.

Misuse is a common problem. In North America, recent observational surveys have shown that about 80% of child restraints were not being used as intended (Weber, 2000) Misuse rates are lower in Australia but are still a concern.

Misuse of CRS in Australia

CRS misuse has been regularly monitored in Australia and this has led to improvements to the Australian Standard.

SOME CASES FROM THE CAPFA STUDY

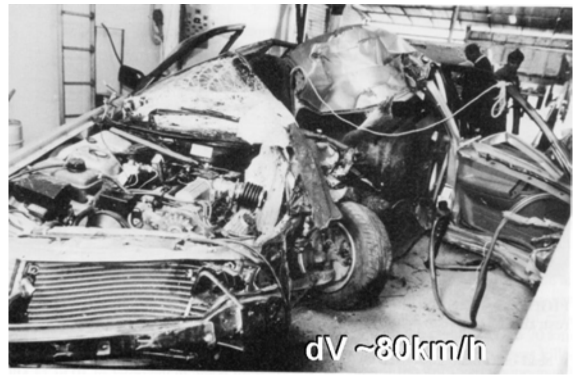

Figure 11a. Two year old child in FFCR in centre rear position uninjured.

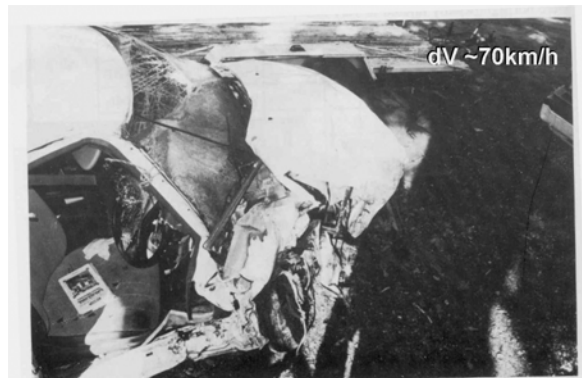

Figure 11b. 18 month old child in FFCR in left rear seat uninjured

Figure 11c. Nine month old child in FFCR sustained only bruising.

Figure 11d. Three year old in FFCR in centre rear seat broke arm from adjacent occupant. Three adults killed.

Top tethers

An early concern with top tethers was that they might not be used. This concern may have been a factor in the reluctance, in the 1970s and 1980s, of USA and Europe to use top tethers. Australian experience showed that these concerns were unfounded after the initial implementation period. The latest usage survey revealed less than 5% of child seats in New South Wales were being used without a top tether (Paine and Vertsonis 1998). In any case, early crash studies revealed that the CRS still performed reasonably well when restrained solely by the adult seat belt - an undesirable situation, but not necessarily dangerous.

Use of adult seat belt for attaching CRS

Amongst the range of CRS available in Australia there are a variety of methods by which the adult seat belt is intended to be threaded through the CRS. Adding to the complication faced by carers is that "convertible" style CRS, that can be used facing rearwards or forwards, have separate belt paths and adjustment mechanisms. Partly as a result of this complication, about 12% of forward facing child seats in New South Wales had the seat belt threaded incorrectly (Paine and Vertsonis 1998). This was the dominant form of misuse of forward facing child seats. Many of these cases were confined to a few older designs of CRS where the belt could be threaded two ways and looked correct. In these cases the "incorrect" belt path still provided adequate restraint and, by itself, was generally not a serious safety hazard.

Harness adjustment

A loose harness increases the loads applied to the child, increases the forward excursion of the child and increases the likelihood of a child wriggling partially out of the harness.

The quality of harness adjustment can only be reliably assessed with a child in the CRS. This is difficult to achieve in the field and the assessment is likely to be subjective. Subject to this uncertainty, the proportion of loose harnesses in Australia is likely to have decreased as CRS designs have improved. The provision of a single point of adjustment of the harness has contributed to this improvement.

Consequences of misuse

Different types of misuse can have different effects on child restraint performance. The most common forms of misuse are relatively minor, resulting in sub-optimal levels of protection. While some extreme forms of misuse can in themselves lead to injury in a crash where otherwise no injury would have occurred (Weber, 2000). Misuse problems observed in the North American study cited above were mostly of the minor type. Likewise installation problems observed in the recent Australian study were found to be minor in nature, primarily related to the “tightness’ of both forms of anchorage. (i.e. the adult belts and top tether) and the child restraint harness (Paine, 1998).

Field studies investigating injury in restrained children have found that some form of misuse is commonly involved in cases where restrained children are injured. (Henderson, 1994; Gotschall C and others, 1997, Rattenbury & Gloyns, 1993 and Weinstein and others 1997).

Henderson (1994) highlighted the role of misuse in crashes included in his sample of children using forward facing child restraints in Australia. He reported that of the 38 children using forward-facing restraints, 5 were using their restraints incorrectly at the time of the crash. Four of this five were associated with injury or death. Even more important is the observation that in the children using rearward facing and forward facing restraints, only five received injuries with a MAIS greater than 2. Almost all of this serious injury was associated with some form of misuse.

The most comprehensive study to date of the role restraint misuse plays in injury to restrained children was presented by Gotschall and others in 1997. These authors studied the circumstances surrounding injury to all children 0 -12 years admitted to a major North American trauma centre following a motor vehicle crash. They found that 36% of the children admitted to the centre has been using their restraint incorrectly. And this incorrect use was associated with greater injury severity. Of particular interest was their observation that all fatal cases in their study involved incorrect use. Weinstein and others (1997) also reported similar findings. They found all but 1 of the 10 children fatally injured in their sample of 207 children, was using their restraint system incorrectly or inappropriately.

Inappropriate use is a subtle but widespread form of misuse. It involves the use of a restraint by children outside the age (or height and weight) range for which that type of restraint is designed. Gotschall and others (1997) found that more than 76% of their sample were 'inappropriately' restrained. (Although it should be noted that the definition of inappropriate use employed in this study included children using adult belts when they were still within the height/weight range for booster seats.) The effect of this form of misuse on injury severity was studied in detail by Weinstein and others (1997). They found a large number of children tended to move into the next stage of restraint before they had reached the appropriate size for that restraint system. A similar tendency was observed by Isaksson-Hellman and others (1997) in their Swedish sample. These authors noted that their sample included a significant number of children who would not have sustained injury if the most optimal child restraint system had been used. Of interest is their related finding that restrained children were more likely to be injured when they were at the youngest age for which the system they were using was recommended.

Reducing the incidence of misuse is one of the primary objectives driving the development of the universal or rigid CRS anchorage systems. Such a system has the potential to alleviate problems with installing restraints into vehicles. For installation problems with the current methods of anchorage, and problems with securing the child in a restraint, the International Standards organisations and a couple of other bodies have developed standardised methods of assessing an individual restraints potential for and consequences of misuse. To ensure dangerous misuse practices are minimised, Weber (2000) suggests such manufacturers should use such methods in the process of developing new restraints.

VEHICLES FACTORS AFFECTING CRS PERFORMANCE

In discussing the effectiveness of child restraint systems, it is clear that restraint type, seating position and crash characteristics all have some influence. However one particular factor has been poorly studied - the characteristics of the vehicle in which the restraint is fitted. Vehicle factors and their influence on restraint effectiveness are beginning to emerge as an area worthy of more detailed studies. This is particularly true in respect to the European move to include the performance of child restraints in individual vehicles as part as an overall rating of the safety of that vehicle. Vehicle factors influencing child restraint performance are discussed below.

Anchorage systems

As discussed in respect to laboratory child restraint work, the level of protection provided by child restraints depends greatly on how well the restraint is tied to the vehicle. Optimum performance therefore depends to some extent on the characteristics of the combination of restraint design and anchorage system design.

The fit of a restraint system in any vehicle will also be influenced by both the anchorage design and the characteristics of the vehicle seat.

Australian child restraints designed for use by children from birth to approximately 4 years must be anchored to a vehicle using the existing adult belt system and a mandatory top tether. The use of top tethers requires an appropriate anchorage location on the vehicle. In conjunction with the introduction of the mandatory top tether requirements in Australia (as discussed at the beginning of this paper), an amendment to the relevant Australian Design Rules was also introduced in the mid 1990s. This required the inclusion of at least one anchorage fitting (bolt and lug) in every car sold in Australia. Extra top tether anchorages, and all anchorage *fittings,* in vehicle manufactured prior to this time had to be installed either by the parent or some other appropriate party. This was one of the primary factors influencing the set up of a Restraint Fitting Station network in Australia.

Figure 12. Top tether components: straps, clip, lug and bolt

The mandatory requirement of a top tether anchorage with fittings made Australian child restraint practices relatively unique compared to elsewhere in the world.

This difference in anchorage system between Australia and most of the rest of the world also adds complexity to attempts at comparing effectiveness estimates from overseas with the Australian situation. Laboratory (and to some extent Australian field studies) have demonstrated that the greatest scope exists for improving the overall performance of restraints is in side impacts. In the laboratory one of the proven methods for achieving such an improvement is by modifying the current anchorage system. Since the geometry and rigidity of the two lower anchorages have been shown to have the most influence on the lateral stability of the child restraints in side impacts, side impact protection could be greatly enhance by the ISOFIX concept.

In terms of restraint effectiveness, laboratory testing of rigid (and semi rigid) ISOFIX type anchorage systems has been conducted both in Australia and elsewhere in the world. The main benefit of these systems is their ability to reduce sideways movement of child restrains in side impacts (Kelly and others 1995, Brown and others 1997). In frontal impacts it is expected that such systems will provide little additional protection to that already being provided by Australian child restraints and current anchorage systems (unlike overseas designs that rely solely on the adult seat belt). However where there are currently incompatibilities between CRS, seats and seat belts, the ISOFIX system has the potential to improve performance in frontal crashes.

Method of attachment to ISOFIX anchorages

The original ISOFIX concept was to require rigid attachment to lower anchorages. As indicated earlier, the USA has decided to allow flexible attachments to these lower anchorages. With respect to the rigid versus semi rigid attachment systems, an Australian study reported in 1997 (Brown and others) compared the performance of two point rigid lower anchorages with and without top tether with semi-rigid or webbing based lower anchorages with and without top tether. This work confirmed the ability of the rigid system to significantly improve the performance of Australian child restraints in side impact. Contact between the child restraints tested and a simulated side door structure was completely prevented by the rigid system in both 45º and 90º side impacts. The semi-rigid or webbing based system was found to provide some improvement over the current Australian system. In particular there was a slight reduction in the sideways movement of the child restraint system and contact with the door was prevented in 45º impact. The authors believed that for these reasons, such a system "may be useful as an interim measure in the move to introduce improved universal methods of anchorage". They did note however that the webbing based system allowed more sideways movement than the rigid system and to ensure optimum performance of webbing based systems careful consideration should be given to the characteristics of the flexible coupling. For example they suggest the flexible couplings should be kept as short as possible and be attached to the child restraint as low down and as far back as possible. They also believe the addition of self-adjusting retractors could assist the overall performance of such a system (Brown and others, 1997).

Currently there are a small number of vehicles available on the Australian market that have ISOFIX anchorages. However there are no child restraints available in Australia for use with such systems. In addition there is no Australian Design Rule or Standards Australia document available regarding these universal or rigid anchorage systems. This situation is currently under review. It is likely that any CRS that is designed to use ISOFIX lower anchorages will also need to have provision for attachment using the adult seat belt (plus top tether) to ensure the CRS can be used in any vehicle. This situation may change when ISOFIX anchorages become common or CRS are developed for specific vehicles (under the current Australian Standard they are required to be suitable for universal use).

Anchorage geometry

With respect to the current Australian anchorage system, the most important vehicle features influencing child restraint performance are the geometry of the tether anchorage points; the characteristics of the seat belt and the design of the vehicle seat itself. Performance issues related to the location (and length of the top tether strap) have been covered earlier in this paper. Potential problems in achieving tight coupling between the vehicle and child restraint exist when the location of the anchorage point is too close to the seat back. The influence of seat belts and seat back characteristics are discussed below.

Seat belt characteristics

Since the current method of anchorage relies on the existing seat belt systems, the geometry of seat belt anchorages has the potential to affect child restraint performance. In the mid 1990's it was noted by Australian researchers that in many cases seat belt geometry (presumably optimised for adults) was not amenable to good child restraint installation. Often the top anchorage (or shoulder strap anchorage) was forward of the front surface of the vehicle seat. Such geometry would allow unwanted additional forward motion of the child restraint. Lap belt geometry has also been found to be incompatible with good child restraint installation. This has recently been demonstrated in unpublished mathematical modelling work described in detail in earlier in this paper.

According to Griffiths and others (1994), lap belt geometry problems principally exists because child restraint manufacturers do not make sufficient allowance for the variability of lap belt geometry and buckle strap length in their design. Buckle size can also produce incompatibility issues (Griffith 1994, Weber 2000). A recommended practice related to these issues has been published by the Society of Automotive Engineers - J1819; Securing Child Restraint Systems in Motor Vehicles.

Insufficient seat belt length has also been found to be a problem in a number of vehicles in the past. The main problem being that belts were not always long enough to be routed around the restraint as directed by the child restraint manufacturer's instructions (Kelly and others, 1996).

Retractable seat belts can exacerbate seat belt geometry problems. One of the general problems with some retractable seat belt systems is that they sometimes allow slack or reel out to occur prior to loading. To overcome this problem a number of seat belt enhancements have become available. These include webbing clamps and pre-tensioners. While the advantages of these seat belt enhancement technologies for adult occupants has been well documented, little investigation of their influence on child restraint performance has been reported.

One study reported by Czernakowski and Bell (1997) investigated the effect of seat belt pre-tensioners on child restraint performance. They found that on the whole pre-tensioners did improve the frontal impact performance of the child restraint systems tested. Belt pre-tensioners reduced head excursion and acceleration. The effect on neck loads was not monitored. The authors did note however that the effect of the pre-tensioners was different for different restraint systems with some showing little benefit. They believe that the influence the belt pre-tensioner depends on the design of the child restraint system with respect to the adult belt routing.

Although no studies regarding the influence of webbing grabbers or clamps have on child restraints have been reported, it is likely the overall influence would be similar. For these reasons it is probably important for child restraint manufacturers (and vehicle designers) to consider the potential for improving performance by designing seats compatible with such seat belt systems (Czernakowski & Bell, 1997).

So far seat belt pre-tensioners and webbing clamps are rare in the rear seats of Australian vehicles.

Vehicle seat characteristics

In addition to the properties of the anchorage system, how well a restraint fits into a vehicle will also depend on how snugly the contours of the child restraint match the contours of the vehicle seat. Both the vehicle seat cushion and vehicle seat back is important. The compatibility between any individual restraint system and the shape of the seat has its main influence in terms of stability. A poor match between child restraint and seat shape can also magnify any belt geometry inadequacies leading to poor performance in a crash. The major problem in trying to address this issue is that the compatibility will depend on the specific design of any child restraint and specific design of vehicle seat. A restraint that has been designed to match one vehicle seat well may not necessarily match as well with other seats. The move to include child restraint assessment in NCAP programs vehicle may work to overcome this problem to some extent. Since vehicle manufacturers will begin to look for those restraints most suited to their vehicles. Likewise rigid anchorage systems remove a lot of the interaction between the vehicle seat and the base of the child restraint and will therefore assist in overcoming this sort of problem.

Possibly more significant is the influence between the properties of the vehicle seat could have on the child restraint during an impact. Even in restraint system/vehicle seats with good compatibility, seat properties such as cushion stiffness can influence the overall performance of the restraint system. For this reason, the performance of restraint systems in standardised tests, which use a standardised test seat, should not be taken to be representative of how restraints will perform in all real vehicles. In particular it would be expected that child restraints in vehicles with seat properties on the extreme ranges of the 'average' seat used in standards tests would produce noticeably different results than that observed in the Standard test.

Fortunately the use of a top tether in Australia reduces the adverse influence of seat characteristics, compared with CRS with no top tether.

Child restraint interaction with airbags

In the USA serious problems have been reported in the interaction between rearward facing restraints and front passenger seat air bags. The problem arises due to airbag striking theses restraints during the airbag inflation process. The force involved in the inflation of the airbag is extremely large and accelerations have been measured in child dummy heads in these situations within the range of 100 to 200g. To date there have been 18 infants killed in the US in this manner, more than half were correctly restrained and the crashes have all be otherwise survivable. (Weber, 2000). This has not been a problem in Australia, mainly because child restraints are predominately used in the rear seat.

Weber (2000) reports that airbags in the front passenger position have the potential to cause serious and even fatal injuries to all children using this seating position regardless of type of restraint. She cites studies that have shown that the presence of an airbag in this position can increase the risk of fatal injury to a child using this position by about 34% -70%. The exact estimate depending on the type of analysis. Note, however, that there is no information about the type of restraints involved or the level of misuse. It could be expected that a CRS without a top tether or a misused CRS that allowed greater occupant excursion would expose that occupant to a much greater risk of injury.

There have been no reports of similar injuries and fatalities to children occupying the front passenger position of vehicles equipped with dual airbags in Australia. In a review of this problem presented by Griffiths (1997), he suggests that the Australian practice of not carrying children in child restraints in the front seats coupled with high restraint usage rates means that it is unlikely that this will become a problem in Australia.

Both Griffiths (1997) and Weber (2000) recommend that the way to overcome the problem is to never use a rearward facing restraint in the front seat of a vehicle equipped with dual air bags and to encourage all pre-teen children ito use the rear seat.

There is a potential problem in Australia with some styles of vehicle that do not have a rear seat, such as utilities ("pick-ups") because dual airbags might soon be introduced on these vehicles. However, the airbags used in Australia tend to be less aggressive than those in the USA which, by regulation, must protect unbelted occupants. This, combined with the firm restraint provided by a top tether and 6-point harness, will probably mean there is no danger from airbags to Australian children restrained in a forward facing child seat in such vehicles but research is needed to confirm this premise.

Side airbags are also becoming more common in modern vehicles. Although according to Weber (2000) less than 1% of these are in the rear seats. Weber (2000) also reports that there have been no studies reported to date that children properly restrained in child restraints of any type will be at any increased risk of injury. However she does cite studies that have shown unrestrained children and out of position children could be injured by these devices.

Despite the apparent lack of incidents, there is clearly a need for more research into the interaction of CRS with side airbags

SUMMARY OF ISSUES

Australian experience with CRS

- Australia has had more than 25 years of experience with top tethers on CRS. In-depth crash studies, laboratory research and ongoing monitoring of serious crashes involving children have demonstrated the wisdom of the main features of Australian CRS: top tether, 6-point harness, single point of harness adjustment and exclusive use in the rear seat.
- The introduction of ISOFIX anchorages on many new vehicles provides an opportunity to address recognised deficiencies in CRS: misuse of the adult seat belts and inadequate restraint in side impacts. However, care will be needed to ensure that Australian CRS designed for ISOFIX will also be able to utilise the adult seat belts, where ISOFIX anchorages are not available. This would apply with older vehicles or newer vehicles where the centre rear seat is to be used.
- Despite their proven effectiveness in many types of crashes there are still improvements that can be made to Australian child restraints. These include:
  - Boosters with better sides for the sleeping child
  - Further development or addition of energy-absorbing side wings to all child restraints to protect the head in the event of a side impact.
  - Tight fitting of the base of the child restraint to the car seat, either through tensioned rear base straps or rigid base fittings. ISOFIX type fittings should enable this to be readily achieved.
  - Visual indicator systems which indicate when the child restraint is correctly fitted and all the straps are tensioned correctly.
  - Tighter restrictions on (regulated) zones for location of top tether anchorages for child restraints.
  - More biofidelic child test dummies and validated injury criteria.

- Encouraging carers to keep children under 12 months in rearward-facing for as long as possible (recognising that rearward facing CRS are best for very young children).
- Improved protection for the 3-10 year olds. There is scope for improving the level of protection available to those children through improved booster design.

The Kinetics of CRS

- Theoretical and modelling work confirms the soundness of the long-established principle of restraining children in Australia - they should "ride down" the crash with the vehicle and forward excursion should be minimised. Forward excursion that is not associated with absorption of kinetic energy is likely to be detrimental. This includes slack and elastic motion (ie with rebound). Even forward excursion that involves absorption of energy could be exposing the child to greater risk of injurious head contacts - this is of greater concern than injuries from deceleration forces alone. Australian experience is that children in forward facing child seats are not receiving serious injuries from deceleration forces, even in very severe crashes.
- A large range of laboratory tests of CRS have been conducted in Australia since the early 1970s. These have given a better understanding of the performance of CRS in real crashes and have contributed to the development and improvement of standards.
- In one series of crashes the same model of vehicle was subjected to progressively higher speed impacts with a crash barrier, from 40km/h to 100km/h. A key finding was that the deceleration of the rear parcel shelf, to which two CRFS were attached, tended to level off at speeds of 60km/h and higher. As a result the loads on the child dummies did not increase significantly at the higher speeds. Based on the child dummy injury measurements, the 100km/h crash was considered to be survival because the integrity of the rear occupant space was retained (unlike the front occupant space).
- At the current state of dummy development and knowledge about child injury tolerances, it would be inappropriate, and quite likely counter-productive, to base a CRS consumer rating program primarily on child dummy injury measurements. The dummies lack biofidelity and links between dummy injury measurements and risk of injury in real crashes has not been established. This is the main reason Australian researchers have serious concerns with the CRS assessment protocol proposed by EuroNCAP.

Effectiveness of CRS

- There are severe limitations in the use of mass crash data for assessing CRS effectiveness. Such analyses can be quite misleading.
- In general all types of CRS have been demonstrated to provide higher levels of protection for children than adult seat belts.

- The absolute level of protection of a child restraint will depend on a number of factors, including the type of restraint, its appropriateness for the child, seating position, the vehicle characteristics and crash characteristics.
- Rearward facing restraints have been shown to provide the highest level of protection for children. Adult belt systems provide the lowest level of protection for children but are still much better than no restraint.
- The practice of restraining children in the rear seat means that Australian child restraint effectiveness is likely to be higher than that reported for similar types of restraint in comparable overseas studies where front seats are used more often.
- Child restraints will provide different levels of protection in different types of impacts. Almost all studies have indicated that the rear seat provides more protection than the front seat.
- The effectiveness of child restraint has generally been found to be greater in frontal impacts than side impacts and as, might be expected, more effective in lower speed impacts than higher speed impacts.
- There have been no rigorous estimates of effectiveness of Australian child restraints. However it is likely that Australian child restraints are at least as effective as their overseas counterparts.

Injury studies

Some of most important issues relevant to the effectiveness of child restraints have been identified through in-depth crash investigations studying the injury patterns of child occupants. In summary, these include the following.

- Most injuries sustained by restrained children are minor in nature. The head and the face are the most commonly injured region. The head is also the site most frequently involved in serious and fatal injury to restrained children.
- Head injuries in frontal impacts mainly occur via contact with the vehicle interior.
- In side impact, head injuries most commonly occur from either contact with the vehicle interior and/or contact with the restraint.
- Head injury is the most serious form of injury sustained by both children restrained on the struck side and the non-struck side in side impact.

These issues suggest that in assessing the effectiveness of child occupant in the laboratory, and in program aimed at improving the level of child occupant protection, head protection should be the highest priority. In particular, limiting head excursion in frontal impact and head contact stiffness in side impact are the most crucial issues. Such findings confirm the experience of Australian researchers in laboratory studies.

Also of importance are findings related to the risk of injury to other regions of the body, These are summarised below.

- Age related differences can usually be explained by the type of restraint being used.
- In rearward facing restraints it is uncommon for children to suffer injury to any other region beside the head. In forward facing restraints the extremities, as well as the head region are also injured more frequently than other body regions but extremity injuries are usually fairly minor.
- Most injury risk (as reported in statistical evaluations of restraint effectiveness) is associated with the use of booster seats in conjunction with adult seat belts. Along with high frequency of head injuries in children using this form of restraint, the extremities, chest and the abdomen are also at some risk.
- Abdominal injuries are also common in children injured while using adult seat belts, especially lap only belts. It is likely that these injuries (and those suffered by children using boosters) occur from contact between the abdomen and the belt system. Likewise, chest injuries occur frequently in children injured while using adult belts.
- Spinal injuries are also relatively common in children injured while using adult seat belts. The region of the spine most commonly injured appears to be different for different age groups of children. The cervical region being the most common site in young children and the thoracic region being the most common in older children.

The reports of misuse in a large proportion of the serious and fatal injury cases, in a number of in-depth studies, is real cause for concern. Not all forms of misuse carry the same risk. Further research is needed in this area.

Vehicle Factors

- The current anchorage system used in Australia comprises two lower anchorages formed by the existing seat belt and an upper anchorage using a top tether. Lower anchorage geometry will depend on how the child restraint has been designed in terms of seat belt routing and the actual geometry of the lower seat belt anchorage. Top tether geometry also depends on the restraint design, where the tether is mounted to the restraint and the location of the anchorage point in the vehicle.
- Anchorage system utilising top tethers have been found to be extremely beneficial in reducing head excursion in frontal impacts.
- Like other design features, it appears that there is some difference in how well the top tether limits head excursion depending on design features of the child restraint itself. The location of the anchorage point in the vehicle can also influence performance. In particular problems with the anchorage point being located too close to the seat back have been observed in Australia. Anchorage that are not readily accessible or are likely to be contacted by luggage are also a concern.

- Field and laboratory studies have demonstrated that the current form of anchorage employed in Australia is extremely effective in frontal impacts. There is however scope to improve anchorage in terms of how well sideways movement is controlled in side impact.
- A new concept of anchorage has been developed and is beginning to be introduced in many countries. This system makes use of rigid or semi rigid lower anchorages and a means to limit pitch rotation of the child restraint system. In North America and Canada authorities have adopted the rigid lower anchorages (with rigid or flexible attachments) in conjunction with a top tether. This concept has the potential to significantly reduce misuse and restraint/vehicle incompatibility problems. It also has potential to significantly improve the performance of child restraint systems in side impact.
- The optimum performance of child restraints relies greatly on how tightly the restraint is tied to the vehicle and how well the restraint 'fits' the vehicle. Vehicle features related to how well these two criterion are met are therefore have a bearing on how any particular restraint will perform in a specific vehicle.
- In terms of anchorages, the most important vehicle features are the location of the top tether anchorage and characteristics of seat belt system. For the seat belt system, the characteristics of particular importance include the anchorage geometry of the belts, the length of webbing available, the presence or not of seat belt enhancing technologies and the position of seat belt buckles.
- The 'match' between the general shape of the vehicle seat and any individual child restraint can also influence the performance of the restraint, particularly in terms of the restraint's stability. A poor 'match' could also exacerbate any potential problems with seatbelt geometry. Characteristics of the seat also have the potential to produce variations in the crash performance of any individual child restraint compared to that observed in Standard tests. This is mainly due differences between the actual vehicle seat (and seat anchorage geometry) compared with 'standard' test seat.
- Injury from the interaction of child restraint and airbags is unlikely to be a problem in frontal impacts in Australia because almost all children will be using restraints in the rear. The potential for injury from side impact air bags in the rear is largely unknown.

CONCLUSIONS

The child restraint designs used in Australia have been shown to provide exceptional protection to child occupants in severe crashes. Cases of serious injury are likely to involve misuse of the child restraint or gross intrusion.

Lessons learnt

- The number one priority in CRS design is to minimise excursion of the child's head. To achieve this the child should be coupled as tightly as possible to the structure of the vehicle.
- Top tethers, in combination with an adult seat belt, are a very effective way to firmly attach the CRS to the vehicle. Concerns about misuse (failure to attach top tethers) are unfounded.
- Six point harness distribute the crash forces to load-bearing parts of a child's body and eliminate the risk of ejection.
- No cases of serious neck injury to a child in a forward facing child seat with top tether and six point harness have ever come to the attention of Australian researchers, provided the CRS is correctly used and there is no gross intrusion into the child's survival space. On the contrary, there been numerous cases of children, some as young as 8 months old, surviving very severe crashes without injury.

Still room for improvement

The following issues need to be addressed.

- Injury measurements from the current generation of child dummies, when used in forward facing CRS, should be treated with caution and should certainly not be used as the primary means of rating performance of CRS. Even if the biofidelity of child dummies is improved considerable more research is needed in order to link such measurements with actual risk of injury to children. Therefore child dummy injury measurements cannot be used as a reliable indicator of real world performance.
- Compatibility between vehicle and CRS needs greater attention. Top tether anchorage location could be revised to improve dynamic performance, improve accessibility and eliminate the potential for interference from luggage. Seat back contours could be improved so that CRS fit better. A draft assessment protocol has been developed by ANCAP for this purpose (see Appendix).
- Rear seat design in cars needs greater attention - for adults as well as children..
- CRS should provide much better head protection in side impacts. Large "wings" with energy absorbing material would achieve this (also applies with booster seats that are used in conjunction with adult seat belts).
- The ease of use of various adjustments within CRS could be improved. Retractable top tethers and harnesses would eliminate slack. Shoulder height adjustment could be made simpler.
- To minimise excursion of the lower part of the CRS, the routing of the adult seat belt should be as low as possible.

- Designs of CRS that can easily utilise either adult seat belts or ISOFIX anchorages for lower restraint are needed, together with an education program about the use of such CRS. Tell-tale device that confirm the CRS is correctly installed should be considered.

Consumer test programs such as CREP and NCAP can provide incentive for improvements to CRS design and compatibility between CRS and vehicles. These programs also provide feedback for improvements to the Standard, by giving an indication of those products that perform much better than the minimum necessary to meet the Standard. However, at present, dummy injury measurements should not be used as the primary method of assessment in CRS evaluation programs.

There is an ongoing need to monitor crashes involving injury to children and to conduct in-depth crash studies from time to time. CRS usage surveys also provide feedback on CRS design problems and the need for educational programs.

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APPENDIX - Assessment of Child Restraint Installation and Use

DRAFT PREPARED FOR AUSTRALIAN NCAP, 2001

1. Introduction

This protocol sets out the procedures for testing and assessing the installation of child restraints in vehicles and the ease of putting a child dummy into the restraint.

This version applies only to child restraints that are suitable for children aged from 12 months to 3 years. In Australia it applies to Type B (forward facing child seat, Type A/B (convertible between rearward facing for infants and forward facing for toddlers) and Type D (rearward facing for toddlers - none on the market in Australia). It assumes that the child restraint:

- is provided with a top tether
- complies with the Australian Standard 1754 and
- is only installed in a rear seating position.

The Australian Standard has mandatory installation and ease of use requirements and checks of these are not covered by this protocol. In effect, it is a check of child restraint design features that go beyond the minimum set out in the Australian Standard, together with checks of compatibility with the vehicle.

The test may be conducted with one child restraint that is moved between the nearside and offside rear seating positions or with two child restraints in these seating positions. The TNO P1.5 dummy is tested in the nearside seating position and the TNO P3 dummy is tested in the offside seating position.

Only one person should carry out the installation, although others may observe and assist with scoring.

A default score applies to most clauses. Also listed are reasons for reduced scores - either half points or zero points. In some cases a bonus point can be earned for favourable design features.

2. Test equipment

- One or two child restraints as selected in accordance with the test protocol.
- Two test dummies: TNO P1.5 and TNO P3.
- Spring balance or similar device for measuring applied force
- Tape measure
- Device for measuring angle of inclination
- Device for measuring yaw rotation of child restraint

3. Preparation of vehicle

Front Seats

Both front seats should be adjusted to the test position specified in the EuroNCAP test procedure for the offset frontal test.

If the seats need to be moved in order to install the child restraint this should be noted (see clause XX).

Rear seats

If adjustable, the seat to be fitted with the child restraint should be adjusted so that the seat back angle is 25^{o} (+/-2^{o}) from the vertical or to the angle specified by the vehicle manufacturer, where this is clearly stated in user instructions.

If applicable, locate the top tether anchorage points and ISOFIX anchorage points. Ensure appropriate fittings are available for the anchorages.

4*. Installation of child restraint in vehicle*

4.1 Installation instructions

Locate the installation instructions attached to the child restraint. Read and assess the clarity of the installation instructions

(2 points)

Bonus point	Half Points	Zero Points
(a) Video of installation procedures provided	(a) Instructions are ambiguous or poorly illustrated	(a) No installation instructions provided on child restraint

4.2 Installing child restraint

If the child restraint is reclinable set it to its most upright position [check AS, ECE and EuroNCAP procedures].

Place the child restraint on the vehicle seat. Following the fitting instructions, pass the adult seat belt through or around the child restraint. Buckle up the seat belt and remove any slack. Note the ease of doing this and the likelihood and consequences of misuse.

(4 points)

Bonus point	Half Points	Zero Points
(a) Correct path is clearly colour coded (dual colour system used for convertible restraints)	(a) Difficult to feed the seat belt through the correct path (b) Child restraint needs to be moved or rotated substantially to gain access to path (c) Seat belt buckle difficult to do up due to its location or interference from CR components (d) Child restraint does not mate with the geometry of the seat so that there could be confusion about the correct installation position	(a) Possible to incorrectly feed the seat belt so that it fails to provide restraint (but looks correct). (b) Seat belt buckle strap not under tension when tongue is latched (insufficient distance provided between anchorage and child restraint)

If applicable, apply and adjust any seat belt locking device associated with the child restraint. Note the ease of doing this and the likelihood and consequences of misuse.

(1 point if a guide/device is not required or the locking device is provided as an integral part of the child restraint. (Gated buckles are not eligible))

Bonus point	Half Points	Zero Points
(a) -	(a) Guide/device provided but if not used is unlikely to compromise security of child restraint	(a) Guide/device provided and, if not used, is likely to compromise security of child restraint

Connect the top tether strap to the appropriate anchorage fitting. If necessary use an extension strap. Note the ease of doing this and the likelihood and consequences of misuse or inappropriate use, including:

- having to fold-down a seat or seats behind the seating position in which the child restraint is installed in order to access the anchor fitting;
- the incorrect use of alternative anchorage points (such as those for a third row of seats):
- the risk of the top tether slipping between split seats.

- whether it was necessary for the installer to move to a different position to attach the top tether, including moving outside to open the rear hatch.

(4 points)

Bonus point	Half Points	Zero Points
(a) -	(a) Installer needs to move to a different part of the vehicle in order to attach the top tether. (b) Extension strap required* (c) Difficult to clip tether into anchorage due to limited access, proximity of objects or angle of attack	(a) Having to fold-down a seat or seats behind the seating position in which the child restraint is installed in order to access the anchor fitting. (b) A child restraint anchorage for another seat might be confused for the correct one (where the other anchorage does not comply with location requirements). (c) Tether strap likely to slip between split seats or another location that will compromise security of restraint.

* Note: If top tether is required but cannot be attached, even with an extension strap, then assess the location of the anchorage point against the relevant ADR. If non-compliance is established, then the assessment should be abandoned.

Adjust the top tether so that it is firm. Note the ease of doing this. Note whether the child restraint tends to tilt backwards so that the front lifts off the seat cushion.

(2 points)

Bonus point	Half Points	Zero Points
(a) -	(a) A force of more than 50N is required to move the webbing through the adjuster, once static friction has been overcome, or awkward manual manipulation is needed to adjust top tether. (b) When top tether is tightened firmly the front of the child restraint lifts substantially off the seat cushion (gap more than 60mm) so that the installer may be tempted to loosen the tether.	(a) Top tether runs out of adjustment before it is tight. (b) With the top tether firmly tightened the child restraint tilts back excessively (seat back angle more than 35^o from the vertical for forward facing restraints or less than 15^o for rearward facing restraints) (c) The top tether anchorage clip is loaded in bending because it fouls a component and is unable to align with the webbing.

Observe whether the top tether is likely to be in the way of luggage or rearward passengers. For this purpose "luggage" may regarded as a 400mm cube placed anywhere on the floor of the cargo area.

(2 points if no obstruction)

Bonus point	Half Points	Zero Points
1. -	(a) The top tether or extension strap passes through the sitting space of an occupant to the rear (where that seat is a fold down seat that is not normally used) (b) The top tether or extension strap passes through the luggage space and would be in the way of luggage (less than 400mm above cargo space floor at any point)	(a) The top tether or extension strap passes through the sitting space of an occupant to the rear (permanent seats only) or interferes with access to a seat. (b) The top tether or extension strap is vulnerable to damage from unsecured luggage in the event of a crash (webbing is in the forward part of the cargo space and is unprotected between the floor and 400mm above the floor).

For the portion of the top tether rearward of the seat top or the CR (whichever the top tether last contacts) measure the angle extended rearward [diagram - excessive angle introduces slack].

Bonus point	Half Points	Zero Points
(a) -	(a) For a roof mounting, the angle of the top tether is between 30^0 and 45^0 above the horizontal	(a) For a roof mounting, the angle of the top tether is more than 45^0 above the horizontal

For the portion of the top tether between its point of attachment to the child restraint and the seat top, measure the angle from the horizontal with the child restraint in its installed position [diagram - excessive angle introduces slack].

(4 points)

Bonus point	Half Points	Zero Points
(a) -	(a) Angle is between 30^o and 45^o.	(a) Angle is more than 45^o.

Determine the first sturdy point of contact between the lap portion of the adult seat belt and the lower part of the child restraint (the effective lower attachment point). Measure the angle from the horizontal of a line between this point and the seat belt anchorage point [excessive angle introduces too much slack into lower part of child restraint]. If there is a large deflection of the webbing due to the seat cushion, note the increase in seat belt length that would result were the cushion not present. [diagram - including estimation belt lengthening]. If the geometry on either side is not symmetrical then measure the angle on both sides and use the worst case. If there is more than one path for the seat belt use the worst case. For rigid ISOFIX systems assume the angle is zero degrees.

(4 points)

Bonus point	Half Points	Zero Points
(a) The child restraint provides for *rigid attachment* to an ISOFIX style anchorage (b) The child restraint provides for *flexible attachment* to an ISOFIX style anchorage *and* the length of the attachments adjusts automatically.	(a) Angle is between 45^o and 60^o	(a) Seat belt angle is more than 60^o or is rearwards (seat belt anchorage point is forward of point of attachment to child restraint) (b) Belt lengthening due to cushion or other non-structural component is more than 50mm. (c) The seat belt passes through slots in the back of the child restraint that have a opening with a gap larger than 50mm in a vertical direction (not applicable if there is a device to prevent the webbing sliding out of position).

4.3 Measuring slack, under steady load, between child restraint and vehicle

Measure yaw rotation in either direction when a lateral force of 100kN is applied to the foremost structural point of the child restraint. Use the largest angle for assessment [diagram - reduce rotation of child restraint in side impacts]

(1 point)

Bonus point	Half Points	Zero Points
(a)	(a) Angle is between 20^o and 30^o	(a) Angle is more than 30^o.

5. Child Restraint Use - Checks with dummy in child restraint

5.1 Preparation of child restraint

Read and assess the clarity of usage instructions.

(2 points)

Bonus point	Half Points	Zero Points
(b) Video of installation procedures provided	(b) Instructions are ambiguous or poorly illustrated	(b) No instructions for adjusting harnesses to suit the child are provided on child restraint

Briefly place the child restraint on the vehicle seat and the dummy in the child seat - do not attach tethers, adult seat belts or harnesses at this stage. Determine the appropriate harness slot height (in accordance with the child restraint instructions or otherwise, where possible, the lowest position that is above shoulder height).

Remove the dummy and child restraint from the vehicle.

Relocate the shoulder straps to the shoulder strap slots as determined in Section 5.1.2. Note the ease of adjustment of harness slot height and the likelihood of serious misuse

(2 points)

Bonus point	Half Points	Zero Points
(a) Height can be readily adjusted without removing webbing or disassembling any component (height adjusting device provided).	(a) Adjustment method is straightforward but tedious so that users may but reluctant to adjust harness.	(a) High risk of incorrectly reassembling harness after changing slot height.

Adjust harness to its maximum length. Note the ease of lengthening the harness.

(1 point)

Bonus point	Half Points	Zero Points
(a) -	(a) -	a) between 50N and 75N force needed to lengthen harness. b) Harness can only be lengthened by manipulating it in some way other than by pulling on the shoulder straps.

If the child restraint is fitted with a crotch strap or leg straps that have fore and aft positions, determine the ease or difficulty with which the positions can be changed.

(1 point - in effect, a bonus for having adjustable straps)

Bonus point	Half Points	Zero Points
(a)	(a) Adjustment method is straightforward but tedious so that users may but reluctant to adjust the straps.	(a) Easy to incorrectly reassemble straps after changing repositioning them.

5.2 Placing dummy in restraint

If necessary, disconnect the top tether and note the ease of doing this

(1point if top tether does not need to be disconnected).

Bonus point	Half Points	Zero Points
(a)	(a) Top tether can be disconnected without unclipping it from the anchor fitting (quick release buckle is provided)	(a) Top tether needs to be detached from the anchor fitting.

Place the dummy in the child restraint. Place the harness on the dummy and secure the buckle. Note the ease of doing this and the likelihood and consequences of misuse. Note that the harness should still be at its maximum length in accordance with clause 5.1.5.

(4 points)

Bonus point	Half Points	Zero Points
(a)	(a) Dummy limbs need to be placed in an awkward position in order to fit harness (this may be due to insufficient spare length in the harness straps).	Difficult to engage the tongues in the buckle. (e.g. buckle design requires both tongues to be manipulated to obtain a specific configuration before inserting them simultaneously into the buckle.) (a) Potential for buckle to be incorrectly latched

If necessary, adjust the harness to remove slack. Note the ease of doing this and the likelihood and consequences of misuse.

(4 points)

Bonus point	Half Points	Zero Points
(a) Harness is designed to adjust automatically and works as intended.	(a) -	(a) A force of more than 50N is needed to adjust the harness, once static friction has been overcome.

Observe whether the shoulder straps are likely to slip off the shoulders or rub the neck of the dummy [diagram].

(2 points)

Bonus point	Half Points	Zero Points
(a) Lateral adjustment of shoulder slots available and simple to operate.	(a) Harness shoulder straps rub the neck of the dummy.	(a) Harness shoulder straps are likely to slip off the shoulders of the dummy (the centreline of the webbing is further outboard than the mid-point of the dummy's shoulder).

If necessary, reconnect the top tether (no assessment).

5.3 Checking clearance within vehicle

Forward facing restraints (see 5.3.2 for rearward facing). Measure the horizontal distance from the child restraint harness buckle to the rear surface of the seat in front (or other object, if applicable). [diagram - note front seat at mid-point of travel]
(4 points)

2 Bonus points	Half Points	Zero Points
(a) -With the front seat in its rearmost position the clearance is at least 700mm	(a) Clearance is between 550mm and 700mm	(a) Clearance is less than 550mm or part of the dummy touches the seat

Rearward facing restraints. With the front seats in the position specified in Section 3.1, note whether there is sufficient space between the front and rear seats to install the child restraint. [diagram - note front seat at mid-point of travel]

(4 points)

2 Bonus points	Half Points	Zero Points
c) With the front seat in its rearmost position there is room for the child restraint (no contact between seat and child restraint).	(a) The child restraint can be installed, but touches the back of the front seat	(a) Child restraint cannot be accommodated.

Check if the dummy's face be seen by the driver (either by turning around, looking in a mirror or looking at a visual aid)

(2 points)

Bonus point	Half Points	Zero Points
(a) A visual aid, such as a camera and monitor, is provided	(a) The driver needs to turn around in order to see the face of the dummy	(a) The dummy's face cannot be seen by the driver

5.4 Removing dummy from child restraint

If necessary, disconnect the top tether (see next clause).

Undo the harness buckle. Release the dummy from the harness straps and remove the dummy from the child restraint. Note the ease of doing this.

(2 points)

Bonus point	Half Points	Zero Points
(a) In an emergency the child restraint, together with occupant, can be quickly removed from the vehicle. (check the effectiveness of such a facility)	(a) More than one hand is needed to release the harness 1. Dummy limbs need to be placed in an awkward position in order to remove harness. 2. It is necessary to undo the top tether in order to remove the dummy but a quick release device available so the top tether does not need to be unclipped from the anchor fitting.	(a) It is necessary to undo the top tether in order to remove the dummy from the restraint but no quick release device is available.

Disconnect the child restraint and remove it from the vehicle. Note the ease of doing this.

(1 point)

Bonus point	Half Points	Zero Points
(a) -	(a) Installer needs to move to a different part of the vehicle in order to remove the child restraint. (b) Difficult to remove adult seat belt from child restraint.	(a) Potential for child restraint to be disassembled during removal from vehicle.

6. Maintenance of child restraint

Follow manufacturer's instructions for removing covers, inserts and other washable items from the child restraint. Reassemble the components.

(2 points)

Bonus point	Half Points	Zero Points
(a) -	(a) Difficult to remove or reassemble washable items (b) Poor instructions.	(a) Potential for incorrect reassembly of child restraint after cleaning.

7. Calculation of score

For each clause in sections 4 to 6, take the worst score (that is, zero points, half points, full points or full points plus bonus).

Add the resulting scores for each clause to obtain a total score for the child restraint installation. The maximum score is XX points, irrespective of bonus points scored.