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Children in Adult Seat Belts and Child Harnesses

Crash Sled Comparisons of Dummy Responses

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Abstract

Many children are still restrained in adult belts. A sled test program investigated the impact responses of three child dummies of 18 months, three years and six years, restrained in adult belts and child harness/belt systems. The lap/sash belt minimised dummy head and upper torso excursion, head acceleration and pelvic accelerations. Lap belt loads, head accelerations and excursion, HIC and chest accelerations were higher with the lap belt alone. The lap/harness system gave generally higher head and neck forces than the lap/sash belt.

Keywords

CHILD RESTRAINTS, SEAT BELTS, SLED TESTING

CONTENTS

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EXECUTIVE SUMMARY

Rationale for project

The effectiveness of adult belt systems when used by children has long been an issue of debate, because of the incompatibility of the size and shape of the typical child with the geometry of the typical seat-belt installation. Concerns centre on the crash protection offered by these systems and on the possibility of increased risk and severity of belt-induced injuries.

Many children are still restrained in adult belts alone, even though seat-belt restraint is not optimal for small occupants. Studies of the effects of adult belts on child injury reduction and injury patterns are rare. Until very recently there have not been available sufficiently biofidelic child dummies to attempt crash simulation studies. However, a 18-month-old CRABI dummy is now available, as is an early model of the new Hybrid III six-year-old dummy. Further, the developmental Hybrid III three-year-old dummy became available in Australia for a limited period in March 1996.

Accordingly, a test program was designed to supplement the field observations made during a recent Australian field study by investigating the responses of the above dummies when restrained in adult lap/sash, lap-only and child harness belt systems.

18-month CRABI dummy

Both the lap belt and the lap/sash belt allowed the 18-month CRABI dummy excessive excursion, and as might be expected the kinematics were far from satisfactory. Nevertheless, the CRABI 18-month dummy was restrained by the lap/sash adult belt surprisingly well, although the dummy still showed considerable forwards rotation despite the upper torso remaining constrained by the shoulder belt. Even the lap/sash belt allowed the dummy's head to contact the lower part of its legs.

When restrained by a lap belt, the dummy rotated much further forwards, so that the belt moved down on to the upper surface of the thighs. This allowed considerable excursion and the dummy's head impacted the front of the seat, including the wooden frame supporting the 156 mm deep cushion. The result was a high resultant head acceleration and HIC value.

These head contacts complicated the analysis of head and neck responses. In one lap-belted run, the head contact produced very high outputs for head acceleration, HIC, and neck moment. It is therefore difficult to determine any general difference, in terms of head accelerations and neck loads, between the two configurations of seat belt restraint. It was the head contact that determined the overall outcome.

Significant differences in terms of dummy response were apparent in the chest acceleration, lumbar load and pelvic acceleration responses. Lap-only belts produced higher lumbar loads and pelvic accelerations. Lap/sash belts produced greater chest accelerations.

Further, lap belt loads were much higher in the lap-only configuration, as would be expected. The lap-only belt showed lap belt webbing loads that were about double the loads in the lap portion of the lap/sash belt.

3-year old Hybrid III dummy

For the 3-year old Hybrid III dummy, the lap belt was the only restraint observed to allow definite head contact. As a result, the observed high head acceleration and neck loads may not be typical of the real world crash forces affecting these regions in the absence of head contact.

Except for axial tensile loads, which were highest in the lap belt, the lap/harness system produced the highest outputs for all neck force and moment measurements. The harness system also produced the greatest chest acceleration and higher pelvic accelerations than the lap/sash belt. The lap-only belt produced pelvic accelerations that were comparable to the harness system. The lap/sash system resulted in the lowest outputs generally.

All three restraints held the 3-year old Hybrid III in place during the entire crash sequence. The lap belt allowed excursion of the torso, although not to the extent observed with the 18-month CRABI. There was also some evidence of the 3 year old Hybrid III submarining to some extent under the lap belt, as in one test the lap belt ripped the "skin" of the dummy in the abdominal region.

6-year old Hybrid III dummy

All three restraint systems held the 6-year old Hybrid III dummy in place during the entire crash sequence. However, the lap belt did allow a large amount of forward excursion of the upper torso and head.

In general, the child harness system produced greater head accelerations, neck loads (in particular forward shear and compressive loads) and chest accelerations than the other restraint systems. However this restraint system produced the lowest pelvic accelerations.

Head accelerations and HIC were higher with the lap belt, because of head strike. Neck rearward shear was higher with the lap belt, and forward neck shear higher with the lap/sash belt. The average axial tensile loads were slightly higher with the lap belt than the lap/sash system, but contrary to the values for the three-year-old dummy the difference in this case is small.

As with the other dummies, loads in the lap-only belt were nearly twice as high in the lap portion of a lap/sash belt.

Discussion

The sled test data for the three dummies showed mixed results for neck shear, axial tension and bending moments. Except for axial tensile forces in the two larger dummies and neck moments in the 18-month CRABI, the tendency was for the lap/sash system to result in rather higher readings than the lap-only belt. However, the lap/sash system, as well as minimising dummy head and upper torso excursion, was effective in minimising head acceleration and pelvic accelerations.

Head accelerations, HIC, chest accelerations and lap belt loads were higher with the lap belt alone than with the lap/sash belt. The absence of upper torso restraint in the lap-only system allowed excessive excursion of the Hybrid III 3-year old and 6-year old, but it did minimise dummy neck and chest response.

There was a tendency for neck forces to be highest in runs with the lap/harness system. Even head accelerations and HIC were high in the lap/harness system, in the absence of the head contacts that affected the lap-belt runs. Probably because the shoulder straps load the centre of the lap belt in this configuration, lap belt loads were higher and submarining is more likely than in a lap/sash belt.

Generally, the values for force and bending moment in this sled test series were high in comparison with previous similar research. However, in the field data collected in the Australian field study there were 19 children aged two years to 14 who were restrained in lap/sash belts in generally frontal crashes at a calculated delta-V of 45 km/h or over. More than two-thirds of these children (13) were in frontal crashes of 65 km/h or over. It is probable, therefore, that all these children were exposed to forces of the same order of magnitude that we found in our series of sled runs, generally above the tolerance criteria suggested for guidance by other workers.

Yet, among these children in the real world there was only one neck injury that was not AIS 1 or 2. This AIS 6 (fatal) injury in a three-year-old directly resulted from a heavy head contact with the windshield. The other neck injuries were all soft tissue injuries commonly associated with bruising and abrasions from belt loading.

In European crash reconstructions, neck tensile (Fz) forces of over 2.5 kN have been recorded in laboratory reconstructions, yet no neck injuries had been sustained in the real crashes. This relationship - high loads measured in laboratory, yet little or no injury in a real crash of equivalent severity - is consistent with our observations.

Conclusions

In summary, accepting some inconsistencies in the results from dummy to dummy, the results are in accord with the field data: broadly, that in return for a greatly reduced risk of head and abdominal injury, a lap/sash belt may present a slightly higher risk than a lap belt of minor inertial neck injury, equivalent to AIS 1 or 2. However, there is nothing in this set of sled test results to indicate that adding a sash belt to a lap belt places a child at a higher risk of serious neck injury.

There are many more head injuries than neck injuries in the data from field studies. Lap-belt-induced injury of the abdominal organs and lumbar spine are also far more common than inertial injuries to the cervical spine. In the development of design or performance criteria, for the minimisation of the risk of cervical spine injury it is important not to unreasonably raise the risk of other serious injuries, such as those resulting from head and chest impact.

The results indicate that the simple addition of a harness system to a lap belt, although reducing excursion of the head and torso, may lead to neck forces that are much higher than those seen in the lap/sash belt configuration. There are therefore grounds for concern on the performance of the lap belt/child harness configuration. The comparatively high readings for head and neck forces and accelerations indicate the need for some attention to design. Unlike the configuration in a forward-facing child seat, the shoulder straps of the child harness when used with a lap belt are anchored directly to the vehicle structure. In a child seat, the harness is attached to the seat and the seat attachments are separate. The lap/harness configuration is therefore much stiffer in its reaction to crash forces, and this may be why the dummy neck loads were higher in these tests. This suggestion is supported by outputs for chest accelerations, which were also highest in the lap/harness configuration.

In addition, lap-belt loads were high in this configuration because the lap belt is loaded at its centre by the shoulder straps. This also raises the risk of "submarining" under the lap belt.

If a child is to use an adult seat belt, the best alternative is the lap/sash configuration. The case is very strong for encouraging, or compelling, the fitting of lap/sash seat belts in the centre seat positions of all passenger cars where practicable.

1 INTRODUCTION

1.1 Concerns about children in adult belts

Seat belt legislation in New South Wales requires all children to be restrained in an appropriate restraint. For children over the age of 12 months, the adult seat belt system is considered acceptable for the purpose of legislation.

However, the effectiveness of adult belt systems when used by children has long been an issue of debate, because of the incompatibility of the size and shape of the typical child with the geometry of the typical seat-belt installation. Concerns centre on the crash protection offered by these systems and on the possibility of increased risk and severity of belt-induced injuries.

The extent to which children may be placed at risk by using adult belts was investigated in an early study of restrained children by the Traffic Accident Research Unit in New South Wales (Vazey, 1977). A selection of reasonably severe crashes involving 65 case occupants was examined to provide evidence that would address the question posed by Snyder and O'Neill (1975): "*Are 1974/1975 automotive belt systems hazardous to children?*". At that time in the United States, and to a considerable extent even now in that country, few children were restrained in adult belts that had sash belts incorporated. In Australia, however, lap/sash belts had been required in outboard positions both front and rear since 1971, quite independently of mandatory-wearing requirements.

Snyder and O'Neill had noted that in Australia the original legislation requiring the use of seat belts did not apply to children under eight years, but they wrongly concluded that the reason was concern for the safety of children using adult belts. In fact, at least in NSW it was for administrative reasons associated with the age of legal responsibility, and soon all passengers over the age of one year had to be restrained in a seat belt, including an adult lap/sash belt for children if that was the only restraint available.

The conclusion of the 1977 NSW study and those that succeeded it (Corben and Herbert, 1981) was that in practice children appeared to be afforded good protection by adult three-point lap/sash belts, even down to two years of age, as long as the restraint was properly adjusted. At that time few seat belts in the rear positions had automatically adjusting and locking retractors, whereas modern cars are now so equipped. When firmly restrained in well-adjusted belts, the children were found to withstand crash forces as well or better when wearing adult restraints than adults in the same car, even in crashes of 50 km/h change of velocity (delta-V).

However, it is now well accepted that any child riding in a passenger vehicle should be restrained in dedicated restraint equipment of a type appropriate to the child's size and age. Surveys indicate that until the child weighs more than 36 kg, or has a sitting height of about 760 mm (roughly equivalent to an age of 11 or 12 years), the seat belt will not fit in an ideal manner (Klinich *et al*, 1994). The importance of this issue has diminished over recent years with the ever-increasing availability and use of dedicated child restraints (including booster seats to be used with adult belts) that are much more appropriate for different ages and sizes of children.

Nevertheless, the fact is that countless children worldwide, much smaller than this, commonly do ride in motor vehicles while restrained only by adult seat belts. It is a reasonable expectation that from time to time vehicles with children thus restrained will crash. It would be a matter of great concern if this mismatching led to a commensurate increase in risk of injury to the restrained child.

Studies of the effects of adult belts on child injury reduction and injury patterns are rare. As it happens, available epidemiological data do not point to restrained children of at least ten years or so being at especial risk (Evans, 1988). However, predictions of injury risk (especially for smaller children) are based on a narrow knowledge base. This paper reports laboratory data that are intended to build on existing knowledge. The testing was performed in the context of recently completed field studies of real-world crashes, described briefly in the following section.

1.2 The CAPFA study of child passengers

To review issues of child occupant protection, a field crash investigation study undertaken through 1993 under the auspices of the Child Accident Prevention Foundation of Australia (NSW Division) was aimed at studying crashes involving vehicle passengers aged 14 years or under.[1] Some results of this study have previously been reported (Henderson, 1994; Henderson *et al*, 1994; Henderson *et al*, 1996).

A summary of the results of this study is shown in Table 1.

It can be seen that throughout the entire sample of children, in all kinds of crashes, dedicated child restraints generally performed the best, followed by adult lap/sash belts and then by lap-only belts. As would be expected, children without restraints fared badly. Although this was not a random sample of crashes, the difference in injury risk between restraint and no restraint is of the same order of magnitude as shown in studies based on comprehensive statistical data.

There were 121 children using adult three-point belts, ranging in age from one year to 14 (the maximum for the study), with a mean age of nine. Of the 121, 21 (17.4%) were aged five years

[1] The study was performed on behalf of the Child Accident Prevention Foundation of Australia (CAPFA), New South Wales Division, by personnel from Michael Henderson Research and the Roads and Traffic Authority of New South Wales. The study was sponsored by the Motor Accidents Authority of New South Wales.

or less. Six (5.0%) of the children using available lap/sash belts were killed, 21 (17.4%) suffered injuries with a maximum AIS of 2-4, and the majority (94, 77.7%) had injuries of AIS 1 or were uninjured.

There were also 35 children in the study who were restrained by lap-only seat belts. The results showed that although the use of lap-only belts prevented children in the sample from more serious injury, the lap belt is an incomplete restraint, to be used only when no better system is available. There was a significantly greater incidence of belt-induced abdominal injury among lap-belt wearers than lap/sash users, which confirms other Australian and overseas research.

Table 1. Summary of Results: NSW Study, All Restraints

	Child restraint		**Lap/sash belt**		**Lap-only belt**		**No restraint**	
MAIS	N	%	N	%	N	%	N	%
0	28	39.4	11	9.1	5	14.3	0	0.0
1	30	42.3	83	68.6	21	60.0	6	31.6
2	7	9.9	13	10.7	3	8.6	3	15.8
3	1	1.4	7	5.8	2	5.7	5	26.3
4/5	2	2.8	1	0.8	1	2.9	0	0.0
6	3	4.2	6	5.0	3	8.6	5	26.3
Total	71	100.0	121	100.0	35	100.0	19	100.0
MAIS 2+	13	**18.3**	27	**22.3**	9	**25.7**	13	**68.4**

The incidence of injury to the head and face was much the same among lap-belted and lap-sash belted children, but children using lap/sash belts in outboard positions received most of their head injuries by contact with the adjacent doors and window structures. Those wearing lap belts were using centre seats, and many of their head injuries should have been preventable because upper torso restraint would have minimised the forward excursion that allowed contact with structures in front of them, such as consoles and front seats.

Results from this field study indicated that while dedicated child restraints offer young children the best crash protection, adult lap/sash belts provide acceptable protection for children in most crashes. The most serious belt-induced injuries observed were minor superficial bruises and abrasions. The work confirmed earlier findings from Australia and elsewhere that children - even very small ones - can be well protected in severe crashes when using lap/sash seat belts, just as they can be by child restraints (Henderson *et al* 1994).

1.3 Rationale for the present sled study

The CAPFA study indicated that if a child has to use an adult belt, then the use of a lap/sash belt by a child would provide better protection overall than a lap-only belt. Lap-only belts are found in Australian cars these days only in the centre seating postions. It would follow that the fitment of a lap/sash seat belt in the centre rear seat is a desirable measure. However, some critics have suggested that to restrain the upper torso, especially that of a child, places the neck at greater risk than if the torso is allowed to swing unrestrained. Anatomical considerations (Burdi *et al*, 1969; Huelke *et al*, 1992), coupled with case reports of cervical spine injury to forward-facing children (Fuchs *et al*, 1989; Langwieder and Hummel, 1989) have caused considerable international attention to be drawn to the issue of cervical and high thoracic spinal cord injury to infants and young children in forward-facing restraint systems.

However, data searches in Australia have failed to show that the lap/sash seat belt poses a significant threat to a child's spine, and field studies have indicated that concerns about vulnerability based on purely anatomical considerations may be misplaced. In any event, serious spinal injury is rare. In the United States, after reviewing about 60,000 crashes for 1980 to 1989 in the National Accident Survey Study (NASS) files, Huelke *et al* (1992) found only nine children aged 10 years or less who had a cervical spine injury of AIS 3 or greater. None were in a child restraint, three were wearing lap belts in the rear seat, and the others were unrestrained.

On the other hand, over the years Australian case histories have included a high proportion of well documented crashes, at much higher changes of velocity than the 48 km/h barrier equivalent, that did not result in more than minor cervical spine injury to children restrained facing forwards in adult belts or child restraints.

In the USA, Kelleher-Walsh *et al* (1993) also found no injuries to the cervical spine in their retrospective case review of 198 children injured in forward-facing child restraints. Other studies have indicated that although the use of some kinds of restraint can increase the overall risk of neck injury, such injuries are generally minor while there is a decreased risk of injury overall for both children (Agran and Winn, 1987; Norin *et al*, 1984) and adults (Bourbeau *et al* 1993). In particular, torso restraint of any kind appears to increase the risk of minor (AIS 1) injuries to the cervical spine as a trade-off for improved protection from more severe injury (Yoganandan *et al* 1989).

Reporting a series of 66 deaths among children in the UK using adult lap/sash belts, Rattenbury and Gloyns (1993) found (while conceding the small number of cases) "little evidence of a major risk of life-threatening injuries being caused by the diagonal section of the adult belt, except perhaps for very young children . . . The authors' view is that direct belt induced neck injury for children in adult belts (with or without booster cushions) is not as great a problem as some people have feared".

In the CAPFA study outlined above, neck injury in children using adult lap/sash belts was not found to exceed very minor degrees of severity even when belt loadings had caused significant bruising of the soft tissues of the thorax and nearby neck. Although the field study did not on its own establish an upper limit of tolerance for cervical spine injury in restrained children facing forwards, it indicated that the limit may be higher than might be deduced from clinical studies of injured children. The field study included children who were not significantly injured despite the severity of the crash, and who would not therefore have been included in the typical trauma system databases. To study only those children who are injured can obscure the beneficial effect of safety equipment and give a false impression of vulnerability.

In summary, therefore, field studies in Europe, Australia and the United States have given quite consistent but rather inconclusive results because of small numbers and a scarcity of data on uninjured children. It is important, therefore, to build the knowledge base by widening the scope of the data. Until very recently there have not been available sufficiently biofidelic child dummies to attempt crash simulation studies. However, a 18-month-old CRABI dummy is now available, as is an early model of the new Hybrid III six-year-old dummy. Further, the developmental Hybrid III three-year-old dummy became available in Australia for a limited period in March 1996.

Accordingly, the unique opportunity arose to generate some new and directly relevant data on dummy loadings and dummy kinematics. Support was obtained from the Roads and Traffic Authority of New South Wales and the Federal Office of Road Safety. In summary, the test program was designed to supplement the field observations made during the CAPFA field study by investigating the responses of the 18 month CRABI, three-year-old Hybrid III, and six-year-old Hybrid III when restrained in adult lap/sash, lap-only and child harness belt systems. The dummies were made by First Technology Safety Systems.

In summary, the project was undertaken for the following reasons:

- a comparison of the effects of lap/sash and lap-only seat belts on child dummies in sled tests had never been done before;

- sled test results could be directly compared with field data for crashes of known delta-V;

- the results could be used for public education about the use of adult belts for children;

- the results might support moves by the Federal Office of Road Safety to mandate the fitting of lap/sash belts in rear centre seats and encourage the use of child harness in these seats;

- the work would aid in the international cooperative development of the new Hybrid III (First Technology Inc) "three-year-old" dummy.

This report documents the data from these comparative series of laboratory sled tests.

2 METHODOLOGY

The sled tests were all conducted in the *Crashlab* facility of the Roads and Traffic Authority of New South Wales on an MTS Monterey "Impac" rebound sled at a nominal change of velocity (delta-V) of 48 to 49 km/h (30 miles/hr).[2] The configuration of this sled gives rise to a short-duration, near-sinusoidal pulse, with a rapid rise of acceleration. For the given delta-V, therefore, these tests represent a violent and rather "stiff" crash. The peak sled acceleration for all runs was within the range 26.8 g to 27.5 g, typically peaking at 40 ms after first contact with the decelerator piston.

Table 2. Basic Dimensions, Child Dummies

Dummy	**Weight**		**Erect sitting height**	
	kg	pounds	mm	inches
CRABI 18-month Old	11.2	24.7	505	19.9
Hybrid III Three-year-old	14.5	32.0	546	21.5
Hybrid III Six-year-old	22.8	50.2	640	25.2

Three anthropomorphic dummies were employed, representing for the desired age ranges the most biofidelic examples currently available. All were manufactured by First Technology Safety Systems Inc, of Plymouth, Michigan. They were as follows.

- CRABI ("Child Restraint Airbag Interaction") Eighteen-month Old Infant Dummy (Version 1).
- Hybrid III Three-year-old Dummy (prototype status, in verification testing stage, especially made available for this research by First Technology Safety Systems).
- Hybrid III Six-year-old Dummy (Model 127-0000).

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2 The original protocol required runs at 56 km/h, but calibration tests revealed the probability of damage to the dummies in the lap-belted configuration at this delta-V.

Their basic dimensions are shown in Table 2.

Following calibration sled runs, each of the three dummies was tested with a lap/sash belt and a lap-only belt. A child harness in conjunction with a lap-only belt was tested with the 3-year old and 6-year old dummies. The child harness system was not included in the 18-month CRABI program.

There were two sled runs for each configuration. The test matrix is shown in Table 3.

Table 3. Test matrix for sled tests

Dummy	Restraint system	Velocity change	Peak g	Number of tests
CRABI 18 months	Lap/sash	49 km/hr	approx 27	2
CRABI 18 months	Lap only	49 km/hr	approx 27	2
Hybrid III 3 years	Lap/sash	49 km/hr	approx 27	2
Hybrid III 3 years	Lap only	49 km/hr	approx 27	2
Hybrid III 3 years	Harness/lap belt	49 km/hr	approx 27	2
Hybrid III 6 years	Lap/sash	49 km/hr	approx 27	2
Hybrid III 6 years	Lap only	49 km/hr	approx 27	2
Hybrid III 6 years	Harness/lap belt	49 km/hr	approx 27	2

The seat belt or harness was replaced by a new one after each run. The acceleration/time characteristics of each run were measured by accelerometers mounted on the sled.

The lap/sash belt in each case was of running-loop configuration, with a dual inertia-locking and webbing-sensitive emergency-locking retractor (as required in Australian cars) mounted at the upper end of the sash belt. The positioning of the belt anchor points was in accordance with the requirements of Australian Standard 3629.1-1991, *Methods of testing child restraints; Part 1: Dynamic testing* (Standards Australia, 1991). This positioning is consistent with the Australian Design Rules covering seat-belt anchorage geometry.

The seat used for the tests was a stylised generic rear passenger-vehicle seat, also in accordance with the requirements of Australian Standard 3629.1-1991. The required base of this seat is a polyurethane slab, density 28-29 kg/m^3, 156 mm thick, on a rectangular frame. The seat back is 70 mm thick.

All three dummies were instrumented as follows:

- head acceleration: 3-axis accelerometers;
- upper neck forces and moments: 6-axis transducers;
- chest acceleration: 3-axis accelerometer:
- pelvis acceleration: 3-axis accelerometer.

In addition, the lumbar region of the 18-month CRABI carried a 6-axis transducer for forces and moments. Belt force transducers were mounted on the webbing straps and buckle mounts. A summary of dummy instrumentation is shown in Table 4.

Table 4. Child dummy instrumentation

Body region	**Response**	**CRABI 18 months**	**Hybrid III 3yrs**	**Hybrid III 6yrs**
Head	Tri-axial acceleration (g)	YES	YES	YES
Neck	Tri-axial load (kN)	YES	YES	YES
Neck	Tri-axial moment (Nm)	YES	YES	YES
Chest	Tri axial acceleration (g)	YES	YES	YES
Lumbar	Tri-axial load (kN)	YES	NO	NO
Lumbar	Tri-axial moment (Nm)	YES	NO	NO
Pelvis	Tri-axial acceleration (g)	YES	YES	YES
Webbing Lap	Load (kN)	YES	YES	YES
Webbing Buckle	Load (kN)	YES	YES	YES
Webbing Sash	Load (kN)	where applicable YES	where applicable YES	where applicable YES

Sign conventions, head acceleration coordinates and data filter classes were as specified in SAE J211 (Society of Automotive Engineers, 1988). The condition of the dummies was monitored after each test by visual inspection and instrument checks. Faces were painted to detect contact points.

All runs were filmed by a stationary high-speed camera positioned to the side of the sled. The cameras were operated at 1000 frames per second.

3 RESULTS

3.1 Overview

A selection of data on accelerations and loads is shown in Table 5. These data were selected on the basis of their most probable direct relationship to injury risk. Photographs of the configurations for each run, including post-impact positioning, are shown in Appendix 1. A complete set of the responses obtained from each dummy in each test is given in Appendix 2.

3.2 CRABI 18-month dummy

3.2.1 Head Accelerations

The head acceleration responses obtained from the CRABI 18-month dummy were complicated by the occurrence of head contacts. In the lap belt tests, observations from the high speed film revealed that the dummy torso rotated forwards, taking the lower abdominal region upwards and over the lap belt, with extensive excursion of the dummy head. This allowed the dummy's head to contact the front of the test seat. In the lap/sash test, the dummy's head contacted its legs.

The results show no significant difference between lap belts and lap/sash belts in terms of resultant head acceleration, except that a head contact for one of the lap-belted dummies produced high a peak acceleration (377 g) of very short duration.

3.2.2 Head Injury Criterion (HIC 36)

The Head Injury Criterion (HIC) is a calculation based on the resultant head acceleration. Therefore, the occurrence of head contacts also confuses the comparative HIC results.

Taking all the the HIC results together, there was no significant difference shown between the lap belt and the lap/sash belt for the 18-month CRABI dummy. However, in one of the lap-belt runs the head contact resulted in a very high HIC (2567).

3.2.3 Neck forces

The peak resultant neck forces were slightly higher in the runs using the lap/sash belts, being 2.2 and 2.3 kN at about 75 ms for the lap/sash belt runs, and 1.8 and 2.1 kN at about 80 ms for the lap-belt runs. However, the difference is not significant, being within the range of variation associated with sled test runs, but is also indicative of the difference in neck loading with the two different belt systems.

Table 5. Summary of Principal Results, Lap/sash, Lap-only and Lap/harness Configurations: Two Runs for Each Configuration

	18-month-old CRABI		Three-year-old Hybrid III			Six-year-old Hybrid III		
	Lap/Sash	Lap	Lap/Sash	Lap	L/Harness	Lap/Sash	Lap	L/harness
Head								
Resultant acceleration (g)	87 84	83 94	70 76	151 153	81 91	83 83	82 87	103 106
HIC	1004 1056	866 2567	822 869	2196 2160	978 1011	1488 1163	2753 3604	1617 1685
Neck								
Forwards shear -Fx (kN)	-0.90 -0.95	-0.76 -0.79	-0.68 -0.79	-0.41 -0.55	-1.33 -1.25	-1.43 -1.29	-0.56 -0.68	-2.00 -1.56
Axial tension +Fz (kN)	2.17 2.23	1.81 2.15	1.66 1.79	2.13 2.25	1.58 1.95	3.09 2.62	2.50 3.91	3.36 3.41
Forwards moment +My (Nm)	26 22	67 94	53 57	23 41	78 90	75 60	20 33	69 57
Resultant Moment (Nm)	29 32	59 83	52 55	29 39	75 88	72 59	47 49	74 70
Chest								
-Gx (g)	-53 -51	-56 -78	-54 -55	-66 -63	-65 -72	-59 -54	-41 -65	-74 -66
Belts								
Lap (kN)	1.04 1.08	1.94 1.92	2.11 2.07	3.94 4.06	2.94 3.65	3.80 3.12	5.51 5.98	3.70 3.93
Buckle (kN)	3.38 3.34	2.09 2.06	4.36 4.36	3.24 3.26	3.23 3.66	0.72 1.89	5.18 5.22	3.63 3.86
Sash/tether (kN)	2.68 2.76		2.59 2.77		3.84 3.96	4.54 4.39		5.13 5.53

The responses obtained for forward neck shear (-Fx) mimic the resultant peak forces. That is, the forward shear loads were about 15% higher in the lap/sash tests than with lap belts. This is not a significant difference.
Only the lap belt tests produced any significant rearward neck shear (+Fx) response. This occurred as a short-duration peak at about 100 ms, coincidentally with high peak head accelerations, and is therefore associated with the head contacts experienced during the lap-belt runs.

The pattern of neck tensile forces (+Fz) was similar to that for the resultant forces. The lap/sash restraints produced slightly higher axial tensile forces than the lap-only belt.

The only significant compressive forces (-Fz) registered in the CRABI neck occurred in the second lap-only belt run. These were probably caused by the dummy's head contact with the seat.

3.2.4 Neck moments

The resultant neck moments were much higher in the lap-only belt runs: lap sash belts, 29.5 and 31.7 Nm, and lap belts 58.6 and 83.5 Nm. The best lap belt run resulted in a resultant moment about double the lap/sash tests, and the worst lap-only test produced loads almost three times higher than the lap/sash belt.

However, the results for the lap-belt runs were overwhelmed by moments recorded after 100 ms, and were thus probably associated with head and neck contacts. If moments after 100 ms are disregarded, the moments recorded in lap-only belts are still slightly greater than for lap/sash belts but the difference is not significant This illustrates the general principle that head contacts may confuse the assessment of neck responses and that the time history of the test runs must be taken into account.

Dummy responses for forward bending moments (+My, flexion) showed a similar pattern of differences between belt configurations as for the resultant moments described above.

3.2.5 Chest Acceleration

The peak resultant chest accelerations produced by the lap-only belt and the lap/sash belt showed little difference between the restraints. Only one of the lap-only belt tests produced a significantly higher resultant chest acceleration than the other tests.

However, the acceleration/time graphs obtained for these runs show that there were a series of significant peaks in chest acceleration. The first was in association with the maximum forward movement of the dummy. The second probably corresponded with the dummy rebounding into the back of the test seat in association with rearward movement of the dummy. If the response during the forward movement of the dummy is taken in isolation by analysing only the first 100 ms of the crash sequence, lap/sash belts showed higher (more than double) the chest accelerations produced by the lap-only belt.

However, dummies in lap belts showed a third response, at 100 to 110 ms, with short-duration peak accelerations of around 56 g and 76 g. These appear to have been in association with chest impacts on the lower limbs, as the legs kicked up on rebound from the seat.

3.2.6 Lumbar forces

The 18-month CRABI was the only one of the three dummies that could be instrumented for obervation of lumbar load and moments.

The lap-only restraints gave rise to resultant lumbar spinal forces more than double than the resultant lumbar forces produced by the lap/sash restraints (2.2 and 2.6 kN, as opposed to 0.9 and 1.2 kN). The lap/sash belts produced a double peak, probably associated with rebound into the seat back, whereas the lap belt runs produced a single peak only.

3.2.7 Lumbar moments

No significant differences in lumbar moments were observed between the lap-only and lap/sash restraint tests. Again, a double peak was demonstrated for the lap/sash belt runs, with the second peak - at rebound - being slightly higher but of shorter duration than the first peak.

3.2.8 Pelvic acceleration

Although the acceleration time histories for pelvic acceleration were similar for lap/sash and lap-only seat belts, peak accelerations were much higher in the lap-only belt tests. Peak resultant accelerations for lap/sash belts were 53.3 and 57.8 g, and for lap belts 72.5 and 75.4 g.

3.2.9 Belt loads

Loads produced in the lap-only belt were almost twice as heavy as those produced in the lap portion of the lap/sash belt.

Loads recorded at the buckle strap were higher in the lap/sash belt than those recorded in the lap-only belt, because the dummy loads the buckle portion through both the sash and lap belts.

3.2.10 Dummy kinematics

The lap belt when used alone by the 18-month CRABI allowed an undesirable rotation forwards of the whole dummy, raising the lower abdominal region and bringing it over the lap belt, together with excessive forward movement of the upper torso. This resulted in secondary impacts between the head/torso region and the lower limbs and seat base.

The upper torso of this dummy was also not well restrained by the lap/sash system, being allowed to move out of the sash portion of the belt. This also allowed undesirable forward excursion of the upper torso, although not as extreme as for the lap belt. This occurred at the end of the crash sequence, but may be an issue in real-world situations where there are often secondary impacts.

3.2.11 Summary

Both the lap belt and the lap/sash belt allowed the 18-month CRABI dummy excessive excursion, and as might be expected the kinematics were far from satisfactory. Nevertheless, the CRABI 18-month dummy was restrained by the lap/sash adult belt surprisingly well, although the dummy still showed considerable forwards rotation despite the upper torso remaining constrained by the shoulder belt. Even the lap/sash belt allowed the dummy's head to contact the lower part of its legs.

When restrained by a lap belt, the dummy rotated much further forwards, so that the belt moved down on to the upper surface of the thighs. This allowed considerable excursion and the dummy's head impacted the front of the seat, including the wooden frame supporting the 156 mm deep cushion. The result was a high resultant head acceleration and HIC value.

These head contacts complicate the analysis of head and neck responses. In one lap-belted run, the head contact produced very high outputs for head acceleration, HIC, and neck moment. It is therefore difficult to determine any general difference, in terms of head accelerations and neck loads, between the two configurations of seat belt restraint. It was the head contact that determined the overall outcome.

Significant differences in terms of dummy response were apparent in the chest acceleration, lumbar load and pelvic acceleration responses. Lap-only belts produced higher lumbar loads and pelvic accelerations. Lap/sash belts produced greater chest accelerations.

Further, lap belt loads were much higher in the lap-only configuration, as would be expected. The lap-only belt showed lap belt webbing loads that were about double the loads in the lap portion of the lap/sash belt.

3.3 Hybrid III 3-year-old dummy

3.3.1 Head accelerations

The peak resultant head accelerations for lap/sash, lap-only and lap/harness runs showed similar results for the lap/sash and lap/harness (70 to 91 g), but higher peak figures for the lap-only runs (just over 150 g). The reasons for these differences can to a large extent be found in the acceleration/time traces.

In the case of the lap-only belt, head accelerations were low (30 g) until 100 ms, when the head accelerations (-Gx) reached a short-duration peak of over 150 g. This was almost certainly in association with head contact against the forward side of the test seat base. Similarly high peaks were observed at the same time for lateral accelerations (Gy). Vertical (+Gz) accelerations reached between 80 and 90 g before 80 ms and before there was any head contact.

Adding a child harness to the lap belt produced head accelerations of around 60 g at 60 ms and vertical accelerations of about 70 g.

The lap/sash belt resulted in head accelerations of 40 to 50 g (-Gx) and vertical accelerations peaking at 60 to 65 g.

It was difficult to determine whether any head contact occurred in the lap/sash and harness system tests. Very short-duration, low-level lateral acceleration peaks were observed at 90 to 100 ms, which would indicate some light contact. The movement of the dummy in these restraint systems was such that if there was head contact it would be with the legs in the lap/sash tests and the chest in the harness tests.

Overall, therefore, it seems that it was the head contact with the seat that resulted in the very high resultant accelerations for the lap belt alone. However, even when head/seat contact was not included in the analysis, with the exception of horizontal acceleration in the early stages head accelerations were generally lower in the presence of torso restraint by a sash belt or harness when comparing the lap/shoulder and lap/harness systems.

The harness system produced slightly higher resultant head accelerations than the lap/sash belt.

3.3.2 Head Injury Criterion (HIC 36)

Because of the close relationship between HIC and head acceleration, differences between dummy responses for the Head Injury Criterion were essentially the same as for accelerations described above.

The validity of the HIC for child head injury is debatable, but the HIC of over 2000 observed for both the lap belt runs - resulting almost certainly from head/seat contacts - indicates a high risk of injury if head contact with a similarly solid object were to occur in a real-world crash of equivalent severity. The lap/sash runs resulted in HIC readings of 822 and 869, and lap/harness runs of 978 and 1011. A HIC of 1000 is regarded as being on the margin of "acceptable" for adults, but its relevance for childhood head injury is not clear.

It should also be remembered that the physical structure of the sled and the sled seat is not the same as in real-world passenger vehicles.

3.3.3 Neck forces

The lap-only belt (2.1 and 2.3 kN) and child lap/harness restraint systems (1.9 and 2.0 kN) gave rise to higher peak resultant neck forces than the lap/sash restraint (1.7 and 1.8 kN).

For the lap-only belt, the responses obtained for forward neck shear (-Fx) showed a peak of 0.41 to 0.55 kN at around 75 ms, followed by a sharp peak of 0.9 to 1.1 kN just after 100 ms, almost certainly the result of head contact with the seat.

Adding a harness to the lap belt resulted in high forward shear forces, peaking at -1.3 kN at 75 ms. Forward shear forces were half these figures with a lap/sash belt, at -0.7 to -0.8 kN.

The pattern of neck tensile forces (+Fz) was that although differences were not large, the highest figures were recorded for the lap-only belt system, with lap/sash and lap/harness responses being of the same order of magnitude.

Some low-level compressive forces were measured for all restraints late in the crash sequence, probably in association with rebound into the seat back.

3.3.4 Neck Moments

The child harness system produced significantly higher resultant neck moments (75/88 Nm) than the lap/sash (52/55 Nm) and lap-only (29/39) systems.

The lap-only system produced the lowest resultant moment. Flexion of the neck with this restraint, as might be expected, occurred quite late in the crash sequence, and followed contact between the torso and the upper limbs.

Identified separately, the forward bending moment (flexion) responses for the three restraint system were similar to the resultant responses.

3.3.5 Chest accelerations

The harness system produced the greatest chest resultant and forward (-Gx) accelerations, in the order of 65 to 72 g. These occurred early in the crash sequence, at about 50 ms.

Chest accelerations were lower with lap/sash belts, at around 50 g.

Resultant chest accelerations for lap-only belts were higher than for lap/sash belts, at 62 g, but the resultants were influenced by high, short peaks occurring later than 100 ms into the crash sequence. These probably reflected chest-to-lower limb contacts. Peak accelerations at around 75 ms were similar to lap/sash belts, at 45 to 50 g. There was a later, lower peak at the time of rebound into the seat back.

3.3.6 Pelvic accelerations

The lowest pelvic accelerations were observed in the lap/sash belt runs, around 50 g at 60 ms. At 130 ms, however, there was a high, very short duration peak as the pelvic region rebounded into the seat back. This raised the resultant acceleration levels.

With the lap-only belt, pelvic accelerations before 100 ms were much higher, at -70 to -80 g, followed also by a short-duration peak on rebound. Very similar readings were shown for the lap/harness system, although without the sharp rebound.

3.3.7 Belt loads

The highest loads recorded in the lap portion of the restraint system occurred in the lap belt tests. In both the lap-belt only runs, the force in the lap belt reached 4 kN at around 75 ms.

The loads in the lap belt used with the child harness belt were slightly lower, at about 3 and 3.5 kN.

Loads in the lap portion of the lap/sash seat belt were lower again, at about 2 kN for each run, about half the loads in the lap belt used alone.

Naturally, in the lap/sash system some loads were taken through the sash portion, where they reached 2.6-2.8 kN.

The top tether attaching the child harness to the sled structure was also quite heavily loaded, at nearly 4.0 kN.

Buckle loads on the lap belt buckle were greatest in the lap/sash system, with forces transmitted through both the sash and lap belts. The loads on the buckle of the lap belt in the harness system and the lap-only belt were very similar and about 1.0 kN lower than in the lap/sash belt.

3.3.8 Dummy kinematics

The Hybrid III 3-year-old dummy was much better restrained by the adult belt than the smaller CRABI dummy. There was submarining to the extent that the lap portion of the belt rode over the rudimentary pelvic structure, but otherwise the dummy's motion was driven by its high centre of gravity (consistent with a child of an equivalent age). The top mounting of the shoulder belt was high in relation to the sitting height of the dummy (as it is in passenger cars), and the shoulder belt allowed considerable downwards motion of the dummy's torso as it moved forwards within it. However, the net excursion of the dummy head was within acceptable levels, and did not extend beyond the front of the seat base (410 mm from its angle with the seat back).

The Hybrid III three-year-old flexed sharply over the lap-only belt. In the first of the two runs in this configuration, the lap belt ruptured the dummy's vinyl "skin" on the abdominal region, between the pelvic and rib structures. In both the lap-belt runs the head of the dummy impacted the forward side of the seat and its base. As noted above, these contacts had an adverse influence on head and neck accelerations and forces.

3.3.9 Summary

For the 3-year old Hybrid III dummy, the lap belt was the only restraint observed to allow definite head contact. As a result, the observed high head acceleration and neck loads may not be typical of the real world crash forces affecting these regions in the absence of head contact.

Except for axial tensile loads, which were highest in the lap belt, the lap/harness system produced the highest outputs for all neck force and moment measurements. The harness system also produced the greatest chest acceleration and higher pelvic accelerations than the lap/sash belt. The lap-only belt produced pelvic accelerations that were comparable to the harness system. The lap/sash system resulted in the lowest outputs generally.

All three restraints held the 3-year old Hybrid III in place during the entire crash sequence. The lap belt allowed excursion of the torso, although not to the extent observed with the 18-month CRABI. There was also some evidence of the 3 year old Hybrid III submarining to some extent under the lap belt, as in one test the lap belt ripped the "skin" of the dummy in the abdominal region.

3.4 Hybrid III 6-year-old dummy

3.4.1 Head accelerations

Peak resultant head accelerations for the lap/sash system were around 83 g. These were much lower than the resultants for the lap/harness system (103.1 and 106.1), but about the same as for the lap-only system (81.9 and 87.5 g). Vertical (Gz) accelerations were higher with the lap belt than the lap/sash belt.

Observations from the lap-belt runs showed a high (340/440 g) short-duration (about 2 ms) peak occurring at 90 ms into the crash sequence, which could well have resulted from head impact.

A similar but much lower short-duration peak of opposite sign occurred in the lap/sash runs between 200 and 300 ms, indicating head rebound into the seat back. A similar rebound occurred with the lap/harness system.

3.4.2 Head Injury Criterion (HIC 36)

Head Injury Criterion figures for the lap/harness system were higher (1617 and 1685) than for the lap/sash system (1488 and 1163). The HIC figures for the lap-only system were very high (2753 and 3604), being influenced by the head strike at 90 ms.

3.4.3 Neck forces

Peak resultant neck forces for the lap/sash system were 3.3 and 2.6 kN. These figures were of the same order of magnitude as for the lap-only system, at 2.6 and 2.9 kN, and for the lap/harness system at 3.4 kN for both runs.

The child lap/harness system produced about the same forwards neck shear force (-Fx), at -1.6 and -2.0 kN, as the lap/sash system, at -1.3 and -1.4 kN. The equivalent figures for the lap-only belt were lower, at -0.5 and -0.7 kN. As for the smaller dummy, there was a rearwards shear force on the neck of the 6-year old in the lap-only system that was associated wth head contact.

The lap/sash systems produced neck tensile forces (+Fz) of 2.6 and 3.0 kN. There was a large difference between the responses obtained from the two lap-only runs. One lap-only run produced the greatest response, approximately 3.9 kN, and the other showed 2.5 kN. During the 30 ms or so that neck tensile forces were peaking, in both lap-belt runs short sharp over-riding peaks (both positive and negative) were observed. This is probably in part due to different head contact locations and indicates the vulnerability of the neck to head contact when under full tensile loads.

Tensile neck loads shown by this dummy in the lap/harness system were higher than in the lap/sash belt, at 3.4 kN.

3.4.4 Neck moments

The neck moments produced in the tests using the child harness system and the lap/sash system were very similar. Typically, neck moments occurred as a consequence first of flexion then of extension of the neck: a kind of "whiplash" phenomenon. There were variations in response from test to test, with peak resultants ranging from 58.5 to 72.2 Nm in lap/sash belts, and 70.2 to 74.4 Nm for the lap/harness runs.

Neck moments for the lap-only system were lower, at peak resultants of 47 and 49 ms. The most severe flexion moments occurred late in the crash sequence, indicating that the flexion occurred over the lower limbs or the seat base.

3.4.5 Chest accelerations

Resultant chest accelerations for the lap/sash system were 50.8 and 57.4 g. There were similar responses for the lap/harness system, at 55.7 and 58.8 g.

The resultant chest accelerations for the lap belt were 36.9 and 52.9 g. In this latter case there were two peaks, at 50 ms during the middle of the crash sequence and at near 100 ms probably in association with chest contact with the lower limbs. There was a substantial component of vertical acceleration (+38 g) during this second contact. The highest -Gx accelerations were shown in the lap/harness system.

3.4.6 *Pelvic accelerations*

Pelvic accelerations peaked at 46 and 53 g for runs in the lap/sash configuration. The resultant for one of these runs was 63.1 g, but was not available for the other because of instrumentation problems. The peak resultant for the lap/harness configuration was 56 g and 62.7 g.

Peak resultant pelvic acceleration responses for the lap-only belt system were much higher, at 80.9 and 78.8 g. This was to a large extent a function of a vigorous rebound into the seat back, as the -Gx accelerations were nearer the average for all the systems, at 66 to 68 g.

3.4.7 *Belt loads*

Loads in the lap portion of the lap/sash belts were 3.1 and 3.8 kN. The lap-only belt loads were higher, as in the tests with the smaller dummies: 5.5 kN and 6.0 kN.

Sash belt loads in the lap/sash belt systems peaked at 4.5 and 4.4 kN.

In the lap belt/child harness systems, the loads in the lap belts were 3.7 and 3.9 kN, and the loads at the top tethers 5.1 and 5.5 kN.

3.4.8 *Dummy kinematics*

The Hybrid III 6-year-old was well restrained by the adult lap/sash belt, with acceptable excursion and kinematics generally. The rotation forward seen in the smaller dummies, with their relatively high centres of gravity, was not apparent.

It was doubtful whether any head contact occurred in the lap/sash and lap/harness tests. If head contacts did occur they were against the legs in the case of the lap/sash tests and the chest in the case of the child harness.

With the lap-only belt, as with the other dummies, there was sharp flexion and excessive head excursion. The dummy head struck the forward face of the rigid base of the seat with high resultant head accelerations and HIC values. In one run the lap belt became wedged between the ribs and the abdominal insert.

3.4.9 *Summary*

All three restraint systems held the 6-year old Hybrid III dummy in place during the entire crash sequence. However, the lap belt did allow a large amount of forward excursion of the upper torso and head.

In general, the child harness system produced greater head accelerations, neck loads, (in particular forward shear and compressive loads) and chest accelerations than the other restraint systems. However, this restraint system produced the lowest pelvic accelerations.

Head accelerations and HIC were higher with the lap belt, because of head strike. Neck forwards (+Fx) shear was higher with the lap belt, and rearwards (-Fx) shear higher with the lap/sash belt. The average axial tensile loads were slightly higher with the lap belt than the lap/sash system, but contrary to the values for the three-year-old dummy the difference in this case is small.

As with the other dummies, loads in the lap-only belt were nearly twice as high in the lap portion of a lap/sash belt.

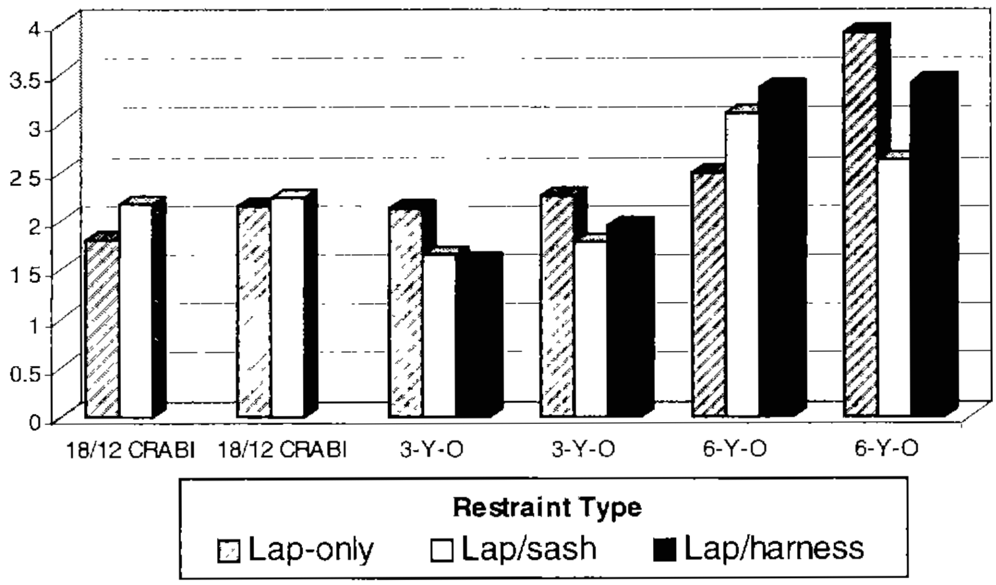
4 DISCUSSION

4.1 Sled test data for three dummies

To support and build upon existing field data, the objective of the sled study was to assess the effects of using three-point lap/sash seat belts for the restraint of a selection of child anthropomorphic test dummies, in comparison with the effects under the same test conditions but using lap-only seat belts. Another series of runs compared these results with the effects of using a child harness. Particular attention was paid to head and neck forces and seat-belt loads. This appears to be the first time that such direct comparisons have been undertaken in a systematic manner.

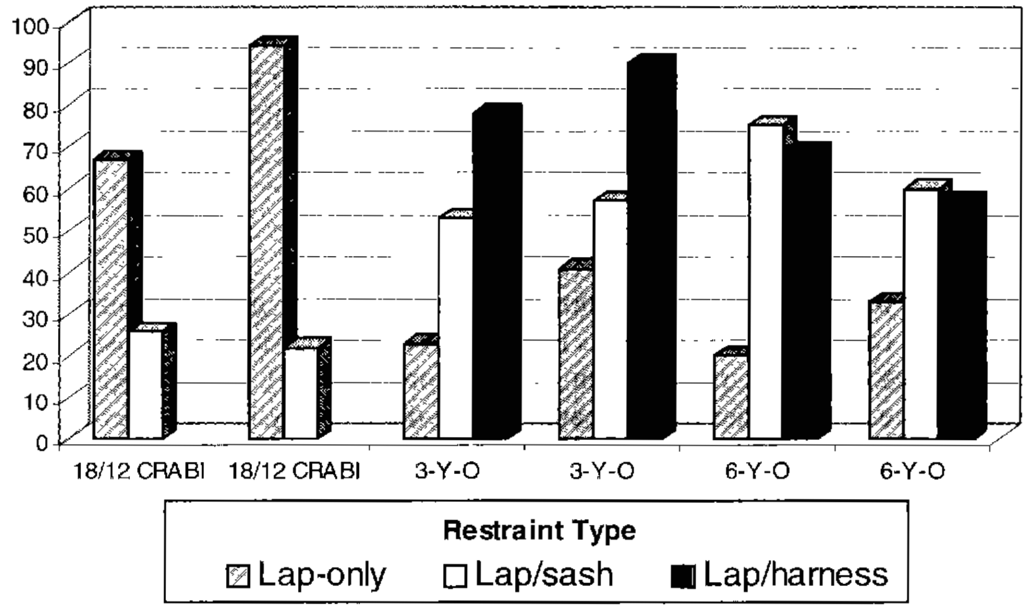
The sled test data for the three dummies showed mixed results for neck responses: shear, axial tension (see Figure 1) and bending moments (see Figure 2). Except for axial tensile forces in the two larger dummies and neck moments in the 18-month CRABI, the tendency was for the lap/sash system to result in rather higher readings than the lap-only belt. However, the lap/sash system, as well as minimising dummy head and upper torso excursion, was effective in minimising head acceleration and pelvic accelerations.

Figure 1 - Neck axial tension +Fz (kN)



Head accelerations, HIC (see Figure 3), chest accelerations and lap belt loads were consistently higher with the lap belt alone than with the lap/sash belt. The absence of upper torso restraint in the lap-only system allowed excessive excursion of the Hybrid III 3-year old and 6-year old, but it did minimise dummy neck and chest response.

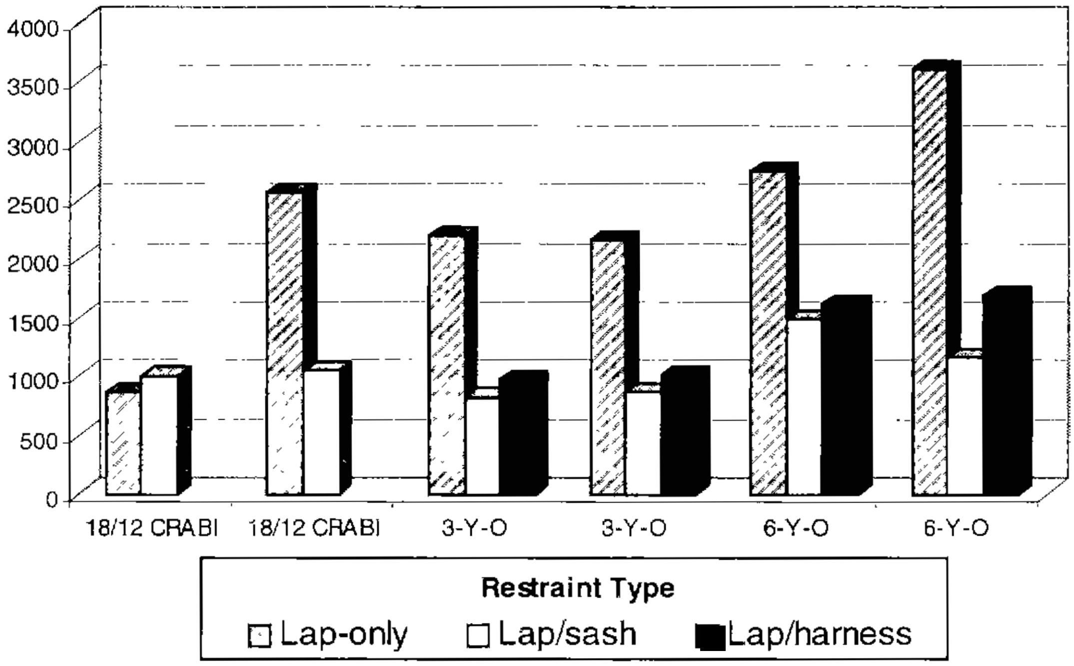
Figure 2 - Neck forwards moment +My (Nm)



Of all the dummies, only the 18-month CRABI was not correctly held in place by either restraint during the entire crash sequence. In the lap belt tests, the dummy torso rotated forwards, pulling the lower abdominal region upwards. In the lap/sash tests, the dummy's upper torso "fell out" of the sash portion of the restraint at the end of the crash sequence. It is possible that this is a factor of a difference in biofidelity between the CRABI and Hybrid III dummy range. It is more likely to be a reflection of the different weights, segment length and mass distribution between dummies representing the anthropometric difference between toddler and young children, and is therefore possibly relevant to the real world.

For the CRABI 18-month dummy the results suggest that the lap/sash system minimises head acceleration and therefore HIC and forward bending moment of the neck. The lap-only belt minimised neck loads, chest and pelvic accelerations. These results directly relate to the lack of upper torso restraint. Although the absence of an upper torso restraint reduces loads on the dummy, it allows excessive excursion of the upper torso and head.

Figure 3 - HIC by dummy and restraint



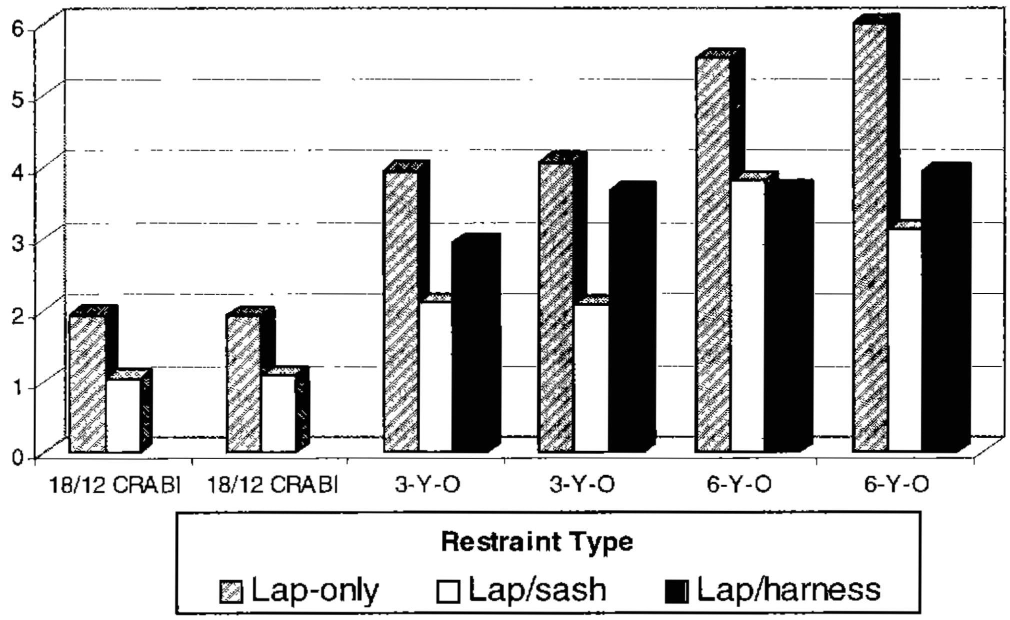
There was a consistent tendency for neck forces to be highest in runs with the lap/harness system. Head accelerations and HIC were also high in the lap/harness system, even in the absence of the head contacts that affected results from the lap-belt runs. This indicates the need for some attention to the design of the lap/harness system. Unlike the configuration in a forward-facing child seat, the shoulder straps of the child harness when used with a lap belt are anchored directly to the vehicle structure. In a child seat, the harness is attached to the seat and the seat attachments are separate. The lap/harness configuration is therefore comparatively stiff in its reaction to crash forces, and this may be why the dummy neck loads were high in these tests. This suggestion is supported by outputs for chest accelerations, which were also highest in the lap/harness configuration.

Lap belt loads were by far the highest with the lap-only system in all runs. This is not surprising, but more unexpected were generally higher loads in the lap belt in conjunction with a harness than with a shoulder belt (see Figure 4).

There is a logical explanation for this observation. The accessory harness has two loops at each of the bottom parts of the shoulder straps through which the lap belt is threaded.When the shoulder straps are loaded in a crash, they pull upwards on the lap part of the seat belt, making it even more likely that "submarining" will occur as the lap belt is pulled off the pelvis and into the abdomen. Also, when the centre of the lap belt is loaded by the shoulder straps, which are in turn being loaded by the upper torso, the tension in the lap part may be higher than in the shoulder belts. An analogy is a cable under tension, in which the tension can be much increased by pulling upwards at a point near its centre.

This effect is in contrast to the situation with a lap/sash seat belt. In the lap/sash system there is a loop of webbing running relatively freely through a slot in the latch plate. If friction between the latch plate and the webbing were zero, then the tensions in the sash and lap parts of the belt would be the same.

Figure 4 - Lap belt loads (kN)



Because of limited data on biomechanical tolerance data and anthropomorphic child dummy biofidelity, the absolute dummy responses should be assessed cautiously in relation to their validity for the real world. The relevance of the laboratory to the real world is further discussed in the following section.

In summary, accepting some inconsistencies in the results from dummy to dummy, the results are in accord with the field data: broadly, that in return for a greatly reduced risk of head and abdominal injury, a lap/sash belt may present a slightly higher risk than a lap belt of minor inertial neck injury, equivalent to AIS 1 or 2. However, there is nothing in this set of sled test results to indicate that adding a sash belt to a lap belt places a child at a higher risk of serious neck injury.

The results also indicate, however, that the simple addition of a harness system to a lap belt, although reducing excursion of the head and torso, may lead to neck forces that are much higher than those seen in the lap/sash belt configuration. In addition, this configuration of accessory harness may also lead to increases in lap-belt loads and the risk of abdominal injury through loading and submarining.

4.1 Relating laboratory data to field data for neck injuries in children

Most of the existing work relating sled tests to the real world have been in association with the use of dedicated child safety seats and with dummies representing smaller children than in the work reported in this paper.

Planath *et al* (1992) reported data following reconstruction on sled runs of crashes involving two children sustaining fatal head/neck injuries in forwards-facing child seats. The forwards-facing sled tests were performed with a Type P572C (Hybrid II) three-year-old dummy with a replacement neck that could be instrumented at the craniocervical junction (upper neck). Runs were at 40 km/h and 50 km/h, but sled acceleration levels were not reported. The 50 km/h runs reproduced a crash with a 15-month-old child in a forwards-facing child seat, in which the child sustained fatal brain contusion without skull fracture but no neck injury. The average figures for the tests were for HIC 809, shear (Fx) 280 N, tension (Fz) 2570 N, and flexion (forward bending moment, My) 33 Nm. These compare with the average figures reported in this paper for a Hybrid III three-year-old in a lap/sash belt as follows: HIC 845; shear 730 N, tension 1720 N, and flexion 55 Nm.

Planath *et al* also brought together data from sled tests with rearwards-facing seats, plus data from scaling down data for adults. In addition, they noted the work on child/airbag interactions of Prasad and Daniel (1984) and Mertz and Weber (1982) with matched sets of tests with a three-year-old "airbag dummy" and piglet child surrogates.

The synthesis of all these data led them to conclude that the following values could be used as guidelines for neck protection criteria for assessment of the risk of neck injury for a child of about four years of age: tensile axial force, 1000 kN; shear force, 300 N; forward bending moment, 30 Nm. These figures may be compared with those from our own work, summarised in Table 5. However, it is stressed that comparisons between results from different centres should be interpreted with caution.

Janssen *et al* (1993) used similar reconstruction and scaling techniques, and employed a TNO 3/4 (9-month-old, 9 kg) dummy for their series of sled runs. The neck of the standard TNO dummy cannot be instrumented, and it was modified for this research. The restraint system was a four-point child harness in a child seat in all cases. They proposed maximum shear and tension forces as guidelines for protection criteria for children through all age ranges. For a three-year-old, the suggested maxima for neck tension and shear would be about 1000 N, and for bending moment about 30 Nm.

Weber *et al* (1993) used a six-month-old CRABI dummy (7.8 kg) in reproducing a crash of 50 km/h delta-V in which a six-month-old child had sustained a spinal cord contusion at T2. The child seat had been used without an effective top tether. They recorded a resultant force in the upper neck of 1260 N and in the lower neck 1160 N. The resultant moments were -6 Nm in the upper neck and 45 Nm in the lower neck.
Trosseille and Tarriere (1993), again using crash reconstruction techniques (four crashes, including one also used by Weber in her work), found for six-month-old children no injury under Fx 950 N and My 41 Nm, but injury over Fz 1200 kN. They note the importance of obtaining data from *uninjured* children, which we also stress. They agree with Planath's (1992) suggestion of a limit of Fx of 0.30 kN for three-year-old children, but note the substantial and rapidly-changing influence of age: there were children of 4.5 years who sustained no injury with Fx of 750 N. They also found a case of no real-world injury when the sled reproduction led to an axial tensile force of Fz of 2500 N for this age group, and suggest further work to explain what they perceived to be an anomalous finding.

Planath *et al* (1992) cautiously suggest that their figures might be unduly conservative. Further, Janssen *et al* point to the fact that measures taken to reduce neck forces might increase excursion of the restraint and the child and thus the risk of head injury.

All the research groups noted above stress the dangers in comparing results from different dummies, and variations in design could explain some of the differences between dummies that we found. None of the proposed tolerance data that exist in international literature were derived using the CRABI 18-month or the Hybrid III child dummies that we used in the present series.

There is also the matter of time dependency. There is general agreement in the literature that there will be a higher tolerance to forces of very short duration, usually published as "peak" forces, whereas forces applied over 30 msec or more would have a better association with injury tolerance. We support all the above cautions.

Generally, the values for force and bending moment in our sled test series were high in comparison with previous similar research, as reviewed above. This may have been related to the type of the sled we used and the acceleration pulses it generated. Nevertheless, in the field data collected in the CAPFA study (see section 1.2) there were 19 children aged two years to 14 who were restrained in lap/sash belts in generally frontal crashes at a calculated delta-V of 45 km/h or over. (See Table 6.) More than two-thirds of these children (13) were in frontal crashes of 65 km/h or over, which gives some allowance for errors in delta-V calculations. It is probable, therefore, that all these children were exposed to forces of the same order of magnitude that we found in our series of sled runs, generally above the tolerance criteria suggested for guidance by Planath *et al* (1992) and other workers.

Yet, among these children in the real world there was only one neck injury that was not AIS 1 or 2. This AIS 6 (fatal) injury in a three-year-old directly resulted from a heavy head contact with the windshield. The other neck injuries were all soft tissue injuries commonly associated with bruising and abrasions from belt loading.

Table 6. Lap/sash belts, frontal crashes with delta-V of 45 km/h or more

Age (years)	**Maximum AIS**		
	0 - 2	3 - 6	Total
< 3	1	1	2
4 - 6	2	0	2
7 - 9	4	1	5
10 - 14	8	2	10
Total	15	4	19

In their crash reconstructions, both Planath *et al* (1992) and Trosseille and Tarriere (1993) recorded neck tensile (Fz) forces of over 2.5 kN, yet no neck injuries had been sustained in the real crashes. This relationship - high loads measured in laboratory, yet little or no injury in a real crash of equivalent severity - is consistent with our observations.[3]

This is not, of course, to suggest that children's necks are immune from inertial injury in high-speed frontal impacts. This is manifestly not the case. But much larger studies, including *uninjured* children, are required properly to assess the degree of risk. It may well be the case that some of the crash reconstruction studies in the literature, being based on children whose spines were known to have been severely injured, are consequently based on outlier cases involving crash-related or child-related factors not typically representative.

[3] Some efforts to relate instrumented real-world crashes with dummy responses for adults have also produced neck forces that have been regarded as above previously-accepted tolerance levels. For example, Melvin *et al* (1994) have shown neck tension loads of well over 3.3 kN and up to 7.7 kN in dummies representing race-car drivers, yet, as the authors comment, ". . . the lack of head/neck injury in Indy car frontal crashes of this severity is remarkable considering the magnitude of the neck tension loads generated in these tests . . . ". They suggest that head contacts reduce neck tension forces in the real world.

After analysing a selection of cases of real-world spinal cord injuries in children, Stalnaker (1993) concluded that as long as the injuries are not caused by external forces applied to the head, spinal column tension is by far the most important parameter for limiting distraction injuries for children of the age group he analysed, up to five years. Trosseille and Tarriere (1993) correctly complicate the issue by pointing out that different forces in different crashes involving children of different ages produce different injuries and thus lead to the definition of different tolerances. Nevertheless, although the relative importance of shear, compression and tensile forces in bringing about injuries to children's necks is yet to be fully elucidated, much contemporary work stresses the importance of axial tensile forces.

The spine and the head together make up an exceedingly complex system, and spinal injury mechanisms are sensitive to countless variations in the way that potentially injurious loads are applied. There is a very great deal of work yet to be done before tolerance levels for the cervical spine can be firmly established, and in respect to children this work is at a very early stage. Children, by definition, are growing up quickly and tolerances may be expected to change year by year for each child, yet vary from child to child at a given age. The problems are compounded by the difficulties in performing cadaver experimentation with children, and there have only recently been improvements in the biofidelity of test dummies. Animal models are generally inappropriate, and now rarely used. Thus, field and epidemiological research has a particularly important part to play.

There are many more head injuries than neck injuries in the data from field studies. Lap-belt-induced injury of the abdominal organs and lumbar spine are also far more common than inertial injuries to the cervical spine. In the development of design or performance criteria, for the minimisation of the risk of cervical spine injury it is important not to unreasonably raise the risk of other serious injuries.

4.2 Other studies of neck injury in adults

There have of course been several previous studies of neck loads on impact, intended at least in the early stages to develop neck tolerances for adults. The work with adult volunteers and cadavers by Mertz and Patrick (1971) indicated a risk of injury with a bending moment in flexion of 189 Nm, with a possibility of muscular injury at lower levels. For tensile loading these authors suggested a tolerance of 1160 N during postero-anterior acceleration of the torso, in rough accordance with the conclusions of Sances *et al* (1982). Shea *et al* (1991) reported a tensile load to failure of about 500 N in the absence of muscle tone. Mertz has summarised tolerance levels for several neck values in order to evaluate the responses of the Hybrid III (adult) dummy (Mertz, 1984).

Unfortunately, the neck of the Hybrid III dummy - having been designed very much with flexion and extension as priorities (Deng, 1989) - is poorly biofidelic in regard to axial forces (Pintar *et al*, 1990). Essentially, it is too stiff. That could be one explanation for the rather similar and non-discriminatory values for +Fz tensile forces for all the sled tests for all three child dummies (which are constructed along the lines of others in the Hybrid III range) reported in the present paper.

5 CONCLUSIONS

In summary, accepting some inconsistencies in the results from dummy to dummy, the results are in accord with the field data: broadly, that in return for a greatly reduced risk of head and abdominal injury, a lap/sash belt may present a slightly higher risk than a lap belt of minor inertial neck injury, equivalent to AIS 1 or 2. However, there is nothing in this set of sled test results to indicate that adding a sash belt to a lap belt places a child at a higher risk of serious neck injury. Taking account of the whole range of results, the lap/sash configuration generally gave the most favourable dummy responses.

Although many of the dummy responses were of a higher magnitude than have been suggested as criteria by other authors, when related to field studies in Australia it appears that children are surviving real-world crashes while wearing adult lap/sash belts at severities equivalent to the sled runs, without more than trivial injuries. That suggests that criteria based on field studies of *injured* children may be too low, and lead to the design of restraints that allow too much excursion while aiming to reduce dummy responses.

We are also cautious at the present stage of dummy design about relying on dummy outputs in simulated impacts as the sole determinants of injury criteria. The overall response of the restraint system is at least as important in assessing the best means to protect children.

There are many more head injuries than neck injuries in the data from field studies. Lap-belt-induced injury of the abdominal organs and lumbar spine are also far more common than inertial injuries to the cervical spine. In the development of design or performance criteria, for the minimisation of the risk of cervical spine injury it is important not to unreasonably raise the risk of other serious injuries, such as those resulting from head and chest impact.

The results also indicate, however, that the simple addition of a harness system to a lap belt, although reducing excursion of the head and torso, may lead to neck forces that are much higher than those seen in the lap/sash belt configuration.

There are therefore grounds for concern on the performance of the lap belt/child harness configuration. The comparatively high readings for head and neck forces and accelerations indicate the need for some attention to design. The main need appears to be to lessen the stiffness of the system's response to crash forces, without increasing excursion more than necessary. The results also indicate that this configuration of accessory harness may also lead to increases in lap-belt loads and the risk of abdominal injury through loading and submarining.

Most of the dummy responses in the lap/sash configuration were more favourable than in the lap/harness configuration, which is an unsatisfactory situation because not only are harnesses commonly used on their own, they are also used in association with booster seats, especially in the centre rear seating position.

The 18-month old CRABI dummy was not well restrained in either of the adult belt systems. The use of dedicated child restraints should be strongly encouraged up to at least the age of two years.

The best adult restraint system overall, as indicated by the present series of sled tests, is the lap/sash system if an adult belt has to be used by a child. The lap belt offers too much of a threat of abdominal and head injury, and the lap/harness system appears to raise neck and lap-belt loadings to a level in excess of the lap/sash system. The case is therefore very strong for encouraging, or compelling, the fitting of lap/sash seat belts in the centre seat positions of all passenger cars where practicable.

6 SUMMARY

Many children are still restrained in adult belts alone, even though seat-belt restraint is not optimal for small occupants. Therefore, a test program was designed to supplement the field observations made during a recent Australian field study by investigating child dummy responses of the above dummies when restrained in adult lap/sash, lap-only and child harness belt systems.

The sled test data for the three dummies showed mixed results for neck shear, axial tension and bending moments. The tendency was for the lap/sash system to result in rather higher readings than the lap-only belt. However, the lap/sash system, as well as minimising dummy head and upper torso excursion, was effective in minimising head acceleration and pelvic accelerations.

Head accelerations, HIC, chest accelerations and lap belt loads were higher with the lap belt alone than with the lap/sash belt. The absence of upper torso restraint in the lap-only system allowed excessive excursion of the Hybrid III 3-year old and 6-year old, but it did minimise dummy neck and chest response.

There was a tendency for neck forces to be highest in runs with the lap/harness system. Even head accelerations and HIC were high in the lap/harness system, in the absence of the head contacts that affected the lap-belt runs.

The general conclusion in regard to neck injury is that in return for a greatly reduced risk of head and abdominal injury, a lap/sash belt may present a slightly higher risk than a lap belt of minor inertial neck injury, equivalent to AIS 1 or 2. However, the results do not suggest that placing a child in a lap/sash belt places it at more danger of neck injury than in a lap belt.

The results also indicate, however, that the simple addition of a harness system to a lap belt, although reducing excursion of the head and torso, may lead to neck forces that are much higher than those seen in the lap/sash belt configuration. In addition, this configuration of accessory harness may also lead to increases in lap-belt loads and the risk of abdominal injury through loading and submarining. The comparatively high readings for head and neck forces and accelerations indicate the need for some attention to the design of these restraints, as it appears that the performance of the lap belt/child harness configuration should be improved.

There are many more head injuries than neck injuries in the data from field studies. Lap-belt-induced injury of the abdominal organs and lumbar spine are also far more common than inertial injuries to the cervical spine. Lap belts, it appears from these data, are more likely than other restraint configurations to be associated with belt-induced abdominal and pelvic injury, and head injury secondary to torso excursion. In the development of design or performance criteria, for the minimisation of the risk of cervical spine injury it is important not to unreasonably raise the risk of other serious injuries, such as those resulting from head and chest impact.

If a child is to use an adult seat belt, the best alternative is the lap/sash configuration.

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