Automobile Restraint Effectiveness

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Abstract – Restraint use has consistently been shown to influence the severity of injuries sustained by motor vehicle occupants during a crash event. In most cases, restraint use has been reported to reduce the severity of the injuries sustained, however circumstances do exist where if misused, restraints can cause additional injuries. This paper subsequently highlights the importance of restraint systems in protecting motor vehicle occupants during a crash. In particular, usage patterns and the effectiveness of seatbelts, airbags and child restraints have been reported for various vehicle occupants under a variety of crash configurations. Methods for improving these systems effectiveness have also been identified. This paper also highlights the importance of correct restraint use for each and every occupant in the vehicle.

Keywords: Seat belt, Air bag, restraints, Pretensioners, Load limiters, Effectiveness

1 Introduction

Restraints such as lap-shoulder belts, airbags and other systems are crucial when attempting to protect an occupant during a crash event. Either individually or combined as a system, they are designed to provide ride-down of the vehicle deceleration, containment on the seat, and distribution of forces on the bony structures of the body, such as the pelvis, shoulder and chest, avoiding concentrating loads on more compliant abdominal or thoracic regions [1].

Fig.1 Early generation seat belt designs [2]

Fig.2 Current design seat belts

Seatbelt restraints were first investigated in the 1950s to try and mitigate the large number of fatal injuries sustained by occupants during vehicle rollovers. In the mid to late 1960s the United States and Australian governments made seatbelts a mandatory device on all vehicles manufactured in their countries. This however did not compel or encourage their use. In 1967, Bohlin added the convenience of an inertial locking retractor to the lap-shoulder belt, claiming it would be worn in the

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field and would be effective as a means of injury reduction [3]. This was the case and now seatbelt restraints form the basis for most if not all occupant restraint systems.

Although seatbelt wearing rates escalated significantly after early interventions, there was still a need for a partner to this countermeasure. Those wearing seatbelts were now sustaining more thoracic injuries in addition to the possibility of still striking one's head on the vehicle interior. Furthermore, in regions such as the United States, seatbelt usage was and still remains relatively low, for a variety of reasons. In an attempt to try and mitigate the large number of injuries sustained by unrestrained occupants, the 1984 revision FMVSS 208 included the need for passive occupant restraints (require no action by the occupant). This lead to a number of automatic seatbelt systems being developed in addition to the re-emergence of the airbag.

Airbag technology was first developed and tested in automobiles in the late 1940s [2], however manufacturers and other bodies considered airbags to be more expensive and less effective than seatbelts. Commercialized implementation of airbags first occurred in 1971 when Ford Motor Company manufactured 831 Mercury models with driver-side frontal airbags. The 1984 FMVSS 208 ruling required manufacturers to install passive restraints (in 10% of 1987 models, 25% of 1988 models, 40% of 1989 models, and 100% of all 1990 and later models), unless two-thirds of the US population became subject to mandatory safety belt laws in April 1989 [4]. The decision was based on NHTSA analysis suggesting that passive restraints would save approximately 6000–9000 lives per year [5]. Although the airbag was initially designed to protect the unrestrained occupant, it has been shown more recently that when designed for coupling with seatbelts, there is a greater possibility for injury reduction [6].

The final type of restraint discussed in this paper is that designed specifically for children. Child restraints are designed for children from birth to 12 years of age. Many studies have highlighted that these young occupants require special consideration due to variations in anthropometrics and biomechanical characteristics compared to adults. For this paper, different child seat designs will be discussed along with their effectiveness in a variety of crash configurations.

2 Seatbelt Wearing

Despite early studies showing the benefit of seatbelt use, the public at large treated seatbelts with much skepticism. In light of this, governments saw that the best way to increase belt usage was through seatbelt wearing laws and primary enforcement. Hence in 1971, the state of Victoria in Australia became the first place in the world to implement mandatory seatbelt wearing laws. By the end of the same year, annual car occupant fatalities had fallen by 18%, and by 1975 a 26% reduction was achieved [7]. These results spurred other nations to adopt similar laws, most notably being the United Kingdom who had a seatbelt wearing rate of 37% prior to enforcement which later rose to 95% for a short period afterwards, with an accompanying fall of 35% in hospital admissions from road traffic injuries [8,9]. Seatbelt enforcement was also implemented in less western nations such as Kuwait, which in January 1994, introduced seatbelt laws, which resulted in dramatic increases in belt usage during the first week (2.8% to nearly 100%) [10]. Since then, levels of enforcement have decreased and currently approximately 50% of Kuwaitis and 65% of Non-Kuwaitis use seatbelts [11]. In late 2000, Korea was reported as having seatbelt wearing rates of just 28%, however after police enforcement, publicity and double the fine for non-use, belt usage rates rose to 98% by August 2001 [12].

2.1 Seatbelt Usage

To examine seatbelt use some twenty years after enforcement began, a large exposure survey conducted in Victoria in 1994 reported that approximately 97% of drivers wore seat belts, with front passengers having a slightly lower usage rate, and rear seat occupants belt usage being 85% [13]. A more recent exposure survey conducted by MUARC in metropolitan Melbourne in 2002 reported seatbelt wearing rates similar to that reported in the 1994 ARUP exposure survey, indicating little improvement in seat belt usage rates in the 1990's [14]. Amongst European nations, seatbelt usage rate varies dramatically, with much lower usage rates in the rear seat to that of the front (Table 1). Seatbelt usage is reported to be lower in less developed nations such as Argentina, where only 26% of people traveling in Buenos Aeries wear seatbelts, with 58% use on national highways [15]. A Kenyan survey found that among 200 crash survivors; only 1% reported seatbelt use 16].

Despite Australia having one of the highest seat belt wearing rates in the world, approximately 30% of fatally injured car occupants are unbelted [17,18,19]. Studies from Scandinavia report similar findings in that 55% of drivers in fatal crashes were unrestrained in Finland, with 35% in Sweden [20,21]. Other studies have also shown that unrestrained motor vehicle occupants are three times more likely to be hospitalised in frontal crashes than those who were restrained [22] and up to seven times more likely to be killed [23]. In light of this, Bylund and Björnstig argued that if restraint wearing could be improved, the number of serious injuries or fatalities could drop dramatically [24]. Table 1 estimates the number of fatalities saved each year by increasing seat belt wearing rates to 95 percent in a number of European nations.

Table 1 Seatbelt wearing rates in Europe and estimated number of fatalities saved each year by increasing seat belt wearing rates to 95 percent (reproduced from [14])

Country	Wearing rate, front seats (%)	Potential lives saved	Country	Wearing rate, front seats (%)	Potential lives saved
Austria	70	236	Italy	50	1384
Belgium	55	351	Luxemburg	55	18
Denmark	70	76	Netherlands	75	173
Finland	87	63	Portugal	45	331
France	85	1456	Spain	61	978
Germany	95	1335	Sweden	85	87
Greece	45	256	UK	93	369
Ireland	53	61			

2.2 Seatbelt Effectiveness

Seatbelt effectiveness was also evaluated by Evans [25]. He noted that manual lap-shoulder belts were approximately more 45% effective in reducing fatalities in passenger cars over all crash configurations. Similarly, Kahane [26] observed that seatbelts were 60% more effective in reducing fatalities in light trucks, over all crash configurations. A more recent study reported that seat belts reduce the risk of moderate to critical injury in crashes by 50% for passenger vehicle occupants and by 65% for light truck occupants [27]. In a study by Cooper [28], seat belts were reported to be on average 49% effective in reducing fatalities and 35% for reducing serious injuries, 18% for moderate-injuries, and 11% for minor injuries. After comparing various literatures sources, the World Report on Road Traffic Injury Prevention claimed injury prevention effectiveness ranges for seatbelts to drivers and front seat passengers to be 40-65% in fatal collisions, 43-65% in moderate and severe injuries, and 40-50% over all severities [29]. It is well known however that seat belts are not equally effective in all crash configurations [30] as is shown in Table 2.

Table 2 Effectiveness of seatbelts by crash type [30]

Crash Type	Proportion of all crashes (%)	Driver seatbelt effectiveness (%)
Frontal	59	43
Struck Side	14	27
Non Struck Side	9	39

Rear	5	49
Rollover	14	77

It is also reported that unrestrained passengers pose a significant risk is posed to restrained occupants in a crash. Ichikawa reported on the threat posed to restrained drivers by unrestrained rear seat passengers [31] where he found that the risk of death increased by 5-fold by the presence of rear seat occupants. In a later examination of the UK and Japanese data, Broughton also estimated the risk to be elevated by three quarters, a much lower estimate than previous shown by Ichikawa [32].

2.2.1 Methods to Increase Seatbelt Usage

In light of the undisputed benefits of seatbelt usage, several methods aimed at increasing belt usage have been proposed and evaluated. Dinh-Zarr and colleagues [33] reviewed three such methods of increasing usage, namely seatbelt laws, primary enforcement laws, and enhanced enforcement. All methods investigated revealed benefits with increased belt usage. Russell et al [34] argued that primary enforcement is a preferred method for ensuring greater seat belt wearing, as secondary laws can often be difficult to enforce and seen as lower importance by legislators, judges and the general public.

Despite the undisputed benefits of wearing seatbelts, it is important the cost-benefit of enhanced seat belt enforcement be estimated. Harris and Olukoga performed one such study in South Africa [35]. They concluded that a program designed to enforce greater wearing of seat belts, estimated to cost 2 million rand in one year, could be reasonably expected to increase seat belt usage rates by 16 percentage points and reduce fatalities and injuries by 9.5%. They also concluded that it would result in saved social costs of 13.6 million rand in the following year or a net present value of 11.6 million rand in addition to favourable consequences for municipal finances.

A different approach towards increasing belt use is that of seatbelt reminder technology. Bylund and Björnstig [24] attempted to estimate the effectiveness of different seat belt reminder systems. It was observed that the seat belt non-usage rate in vehicles with a reminder system that had both a light and sound signal (12%) was significantly lower than the non-usage rate in vehicles without a reminder system (23%). In addition, the seat belt non-usage rate was the approximately the same for those in vehicles equipped with only a light reminder (22%) as those in vehicles without a reminder system (23%). In 2002, Ford and Insurance Institute for Highway Safety (IIHS) researchers reported that the new BeltMinderTM seat belt reminder system installed in late model Ford passenger vehicles had increased the drivers' seat belt wearing rate over a two month period [36]. Specifically, seat belt wearing rates were significantly higher for drivers of vehicles with the BeltMinderTM system (76%) than for drivers with vehicles without the BeltMinderTM (71%). Consistent with the findings of Bylund and Björnstig, Williams reported that female drivers tended to have higher seat belt wearing rates in both vehicles with and without a reminder (84% and 79% respectively) than male drivers (72% and 67% respectively). A recent Australian study has shown that even in countries with high seatbelt wearing, seatbelt reminders are likely to be cost-beneficial [37].

Table 3 Preferred Benefit-Cost-Ratios for the three seat belt reminder systems used in this analysis, assuming a 15 year fleet life and a 5% discount rate [37]

Seating Position	SIMPLE 1	SIMPLE 2	COMPLEX	COMPLEX 40%
<u>Driver only</u>				
Unit Harm Benefit	\$36.37	\$72.75	\$109.12	\$145.50
Economic Cost	\$9.09	\$36.36	\$40.91	\$40.91
Benefit-Cost-Ratio	4.0:1	2.0:1	2.7:1	3.6:1
Annual Harm Saved	0.45%	0.9%	1.35%	1.8%
<u>Front seat occupants</u>				
Unit Harm Benefit	\$46.92	\$93.84	\$140.76	\$187.68

Economic Cost	$22.73	$59.09	$68.18	$68.18
Benefit-Cost-Ratio	2.1:1	1.6:1	2.1:1	2.8:1
Annual Harm Saved	0.6%	1.2%	1.75%	2.3%
All occupants				
Unit Harm Benefit	$53.81	$107.61	$161.42	$215.23
Economic Cost	$63.64	$127.27	$150.00	$150.00
Benefit-Cost-Ratio	0.8:1	0.8:1	1.1:1	1.4:1
Annual Harm Saved	0.65%	1.3%	2.0%	2.7%

2.3 Seatbelt Pretensioners

In modern vehicles, there are a variety of devices designed to address some of the shortcomings of early seatbelt systems. More commonly, lap-shoulder belts are coupled with webbing grabbers, seatbelt pretensioners and load limiting devices, all aimed at increasing the effectiveness of seatbelts in a crash event. Early improvement centered on controlling the large amount of webbing within the belt system to enable retractable seatbelts. This excess webbing delayed the ability of the seatbelt to apply significant restraint forces. To control this, retractors now generally have two sensors that work independently on the locking mechanism. The vehicle sensor detects sudden deceleration of the vehicle, while the webbing sensor detects violent pullouts of webbing from the retractor. A supplement to retractors is webbing grabbers that prevent the so-called "film spool effect" - a payout of the belt as loading tightens the stowed webbing.

Pretensioners are designed to retract belts rapidly, removing any slack and coupling the occupant to the vehicle sooner than a standard belt system [38]. These devices are generally triggered by typical airbag sensors and can tighten belts up to 15cm. This is done using small amounts of pyrotechnic propellents, which pull the seat belt buckle towards the floor or operate the retractor. Pretensioners subsequently manage to maximize the time and distance over which, the belt forces are applied. In addition, this has the benefit of being able to apply greater restraint forces earlier in the crash event, therefore affording greater energy extraction [39]. Seatbelt pretensioners have also been shown to reduce the risk of submarining, caused by incorrect positioning of the lap belt over the abdomen, either due to neglect or varying anthropometry.

Load limiters are designed to be used in combination with airbags and commonly consist of a torsion bar built into the retractor shaft. When a predefined belt force is achieved (commonly 4kN), the torsion bar starts to bend, keeping belt tension below this specified value. They are designed such that the remainder of the energy in the system can be absorbed by the airbag in a gentler manner than without. The simplest and earliest load limiters were a fold or series of folds sewn into the belt webbing. The stitches holding the folds in place are designed to break when a certain amount of belt force is achieved. When the stitches come apart, the webbing unfolds, allowing the belt to extend a little bit more, thereby limiting the force transmitted to the occupant. Today, load limiters are being introduced that work in two steps. In the initial onset of the crash, when a belt alone restrains the occupant, the force of the seat belt is held at a relatively high, constant level. As the occupant moves forward and into the airbag, the seat belt's load limiter switches to "the second gear" – a lower restraining force – that will prevent the risk of peak load that could occur if the restraining forces of the two safety systems were added to each other. The 2-stage system therefore gives a high and relatively even load on the occupant's chest during the whole crash [40].

A 2003 NHTSA set out to determine what effect, if any, pretensioners and load limiters have on injury prevention [41] It reported that the combination of pretensioners and load limiters is estimated to reduce the Head Injury Criterion (HIC) by 232, chest acceleration by an average of 6.6 g's, and chest deflection (displacement) by 10.6 mm, for drivers and right front passengers. The same report studied the individual influences of each device, showing that pretensioners are more effective in reducing HIC scores for both drivers and right front passengers, as well as chest acceleration and chest deflection scores for drivers. They reported greater reductions in chest acceleration and chest deflection scores for right front passengers with load limiters.

Further evidence for the benefits of pretensioners is seen in Czernakowski [42] where their influence on various child restraints was investigated using the ECE44.03 dynamic test. It was shown that in general, lower HIC and head excursion was seen for infant capsules and forward facing toddler seats. A reduced HIC was also seen for forward facing impact shield boosters and belt positioning boosters. Foret-Bruno and co-workers [43] reported on the importance of load limiting devices and observed that 4 kN load limitation results in a very important reduction of thoracic injury risk for all AIS levels, compared to others samples. Overall, a 50 to 60% reduction for AIS 2+ injuries was observed, as well as 75 to 85% for AIS 3+. They claimed a complete absence of AIS 4+ injuries with a 4 kN load limiters were installed, although it must be stressed that controls (no limiter and 6 kN limiter) only had 8% of AIS 4+ injuries.

2.4 Supplementary Seatbelt Designs

More recently, studies have investigated the concept of changing from a three-point belt to a four-point or three-plus-two point belt [44,45] Initial work from these studies suggests that there are benefits of using such a design, most importantly, distributing the seatbelt load over more of the bodies bony structures, which may be beneficial for older more frail people. In addition, such devices are estimated to be beneficial in non-struck side impacts where lateral excursion is excessive and can lead to serious head and chest injury. Bostrom and Haland [45] showed that such a device used in combination with an inboard torso side support will help restrain the occupant laterally (Figure 1). More research is currently being undertaken to ensure that these new restraints cause little or no disbenefit to groups of users such as occupants of small stature and those who are pregnant.

Fig.3 Current design 5-point cross belt
(courtesy of Autoliv Reseach, Sweden)

Fig. 4 Cross belt under test [45]

3 Frontal & Side Airbags

In modern vehicles, airbags are now almost a standard item, with new car market saturation of approximately 100%. Most common is frontal airbags for both driver and front seat passenger, however more frequently we are now seeing front seat occupants also having side thorax and head airbag restraints. Some luxury vehicles have also implemented side airbags for rear seat occupants. One benefit of airbags compared to seatbelts is that they are passively activated, which almost ensures that when a severe crash event occurs, they are deployed.

3.1 Frontal Airbag Effectiveness

Many studies have set out to determine the effectiveness of airbags, however their results have varied considerably in part due to the type of airbag used and the country where it was evaluated. Most investigations focused on the airbag's ability to prevent fatal injuries. Initial estimates of the percentage reduction in fatalities due to airbags plus safety belts, based on expert judgment or experimental data or both, ranged from 18% to 55% [46]. A 1996 NHTSA reported that the overall airbag effectiveness of airbags only in fatal crashes is 13% whereas when used in combination with a seatbelt the effectiveness increases to 50% [47]. Studies investigating the effectiveness of airbags at reducing fatalities for belted and unbelted drivers and front seat passengers over the age of 12 showed that airbags were 14% effective for unbelted occupants and 9% effective for belted occupants [48,49,50]. The same studies also show that airbags appear to have a lower net effectiveness for the elderly compared to younger adults. It was also observed that since airbags cause so many fatal injuries to children, they have an overall negative impact on them with estimates extending from -21 to -88%.

More recent studies have indicated that airbags are slightly less effective than earlier identified. Specifically, NHTSA updated their estimate from an earlier report by Kahane [48] claiming the effectiveness in reducing fatality risk for was 11% for belted occupants and 14% for unbelted occupants, leading to an overall benefit of 12% [51]. In 2002, Cummings et al. [52] reported even lower effectiveness rates; 7% for belted, 9% unbelted, leading to an overall effectiveness of 8%. Both studies indicated an overall higher benefit for unbelted occupants over those belted, however neither study found this result to be significant.

Using data from NHTSA and Cummings et al., Evans [53] estimated the cost effectiveness of driver and front seat passenger airbags, claiming that net annual benefits of airbags of $1.14 billion produced by airbags that cost their original purchasers $30.0 billion. Hence over a 10 year vehicle life the cost exceeds the $1.14 benefit by almost a factor of three, indicating that the driver airbag falls short of being cost effective. Evans also showed that for passengers the $0.47 billion annual cost of replacing deployed airbags exceeds the injury reducing benefits of $0.34 billion.

Fig. 5 Supplementary Restraint Airbag

Body Region	Airbags	Controls
Head	2%	7%
Face	0%	2%
Neck	1%	4%
Chest	4%	11%
Abdo/pelvis	2%	2%
Spine	1%	2%
Upper limb	6%	3%
Lower limb	5%	4%

Fig. 6 AIS 2+ injury savings [54]

In Australia, Fildes and his colleagues [54] revealed the benefits of using the airbag in conjunction with the seat belt, the so-called Supplementary Restraint System (SRS). They were the first to analyse the effectiveness of the airbag outside the USA using a different design (a supplementary airbag fires at a higher threshold and is less aggressive to the primary restraint airbags used in the USA). Their results showed a considerable reduction in occupant Harm with major benefits to the head, chest, face and abdomen, the regions expected to benefit from the airbag.

3.2 Side Airbag Effectiveness

The majority of studies investigating airbag effectiveness have focused on frontal airbags. Side airbags on the other hand, have very little field evidence outlining their effectiveness despite them being fitted in a large proportion of new vehicles. Much of the evidence related to their benefit has come from sled tests and full-scale crash tests using dummies and cadavers. From the field investigations, most separated side airbags into those that offer head and thorax protection and those which offer only thorax protection. Thus it is not possible to evaluate which form of head airbag such as tubular, seat mounted head-thorax or curtain bag is most effective.

However, it hypothesised that curtain airbags may offer more complete protection for most occupants and from all impact directions, due to the larger airbag surface offered. Figures 7 and 8 show the two designs for airbags that offer head protection in a side impact collision.

Fig.7 Head & Chest design airbag
(courtesy of General Motors)

Fig. 8 Air Curtain design

McGwin et al. presented a journal article to evaluate whether side airbags were effective at reducing injury when compared to non-side airbag equipped vehicles [55]. Using the US General Estimates Systems (GES), 757,852 weighted (6,223 unweighted) near side impacts cases where evaluated. Due to a lack of data, all vehicles categorised as containing side airbags were presumed to have deployed during the accident. Following this, they derived injuries from data that Braver and Kyrychenko claimed was often incorrectly coded [56]. Thus it was not surprising that McGwin et al. failed to show a statistically significant benefit from the inclusion of side airbags into vehicles.

In contrast, the paper presented by Braver and Kyrychenko from the Insurance Institute for Highway Safety (IIHS) saw significant gains from the inclusion of side airbags into vehicles [56]. Using data from GES and Fatality Analysis Reporting System (FARS), vehicles were identified as being side airbag equipped through Vehicle Identification Number (VIN) tracking via manufacturers records. Weighting factors were then applied to take into consideration the higher socio-economic and driver behaviour characteristics of the typically more wealthy driver of vehicles equipped with side airbags. Similar to the McGwin et al. study, there appeared to be no entry criterion as to whether the airbag was deployed or not, which may be an ongoing problem with GES data. Interestingly, Braver and Kyrychenko did claim that the inclusion of head-thorax side airbags reduced the chance of driver death by up to 45% over non-equipped vehicles. Thorax side airbags also offered significant reduction in risk of death at 11%, although they show nowhere near as impressive benefits as those offered by head-thorax side airbags.

Braver and Kyrychenko separated out information as to age and gender. Not surprisingly male and drivers under the age of 65 years old, showed clear risk of death reductions when side airbags where in the vehicle. Females and drivers over the age of 65 tended to not see reductions, and could be placing the occupants at greater risk. However Braver and Kyrychenko concluded that more data is needed to statistically support this trend.

3.3 Increasing the Effectiveness of Airbags

Even though seatbelts and airbags are effective in reducing impact severity for most vehicle occupants, it should be highlighted that these devices are also potential sources of injury. Those injured are most likely of small stature, elderly, infants, children, out of position occupants, or those with disabilities. Their risk of injury is considered higher as these occupants are thought to be seated in close proximity to the airbag device upon its deployment. It is generally accepted that the region of highest danger is within 250mm of the airbag device. Ensuring each occupant uses the correct seatbelt in the correct seat can subsequently lower the risk of injury. However, many short people, despite being correctly restrained, may need pedal extenders to stay out of this 250mm zone [58].

Occupants are also more likely to be injured by the airbag if the inflatable device is not designed as a supplementary restraint. Primary restraint airbags are generally more aggressive than supplementary restraint systems (SRS) or depowered airbags, which are designed for use in combination with a three-point belt. These aggressive airbags are required to inflate at over 200mph to restrain the unbelted 50th percentile male, and as such, also require a low trigger threshold. The use of depowered airbags (like those in Europe, Australia and more recently the USA) is made possible when seatbelt wearing rates are relatively high. However during 1984, the United States had belt usage rates of approximately 20%, which required that airbags be designed to primarily restrain the 80% of people who were unbelted. More recently, seatbelt usage has risen to over 70%, which prompted NHTSA in March 1997 to issue a final rule permitting manufacturer's to depower airbags by 20-35%. This de-powering was initially estimated to increase the number of deaths and injuries sustained by unbelted occupants, however little data has shown this to be the case.

In recent times, manufacturers have shifted away from depowered airbags to advanced airbags. Advanced frontal air bag systems are designed to be even more effective than depowered airbags in saving lives, while at the same time reducing the potential of causing an airbag-induced serious injury or death. The new system reduces the risk of airbag injury by either suppressing the frontal air bag, or deploying the frontal air bag with less inflation force. Advanced frontal airbags began phasing into the marketplace on September 1, 2003, where 20% of each manufacturer's vehicles intended for sale in the United States were required to meet NHTSA's advanced frontal air bag requirements. NHTSA’s rules require all passenger cars and light trucks produced after September 1, 2006 to be fitted with advanced frontal air bags.

Airbags are also observed to be particularly dangerous for children restrained in the front of the vehicle. A study by Weber [58] highlighted 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 [55]. Drawing from several studies, Weber claimed that the presence of a front passenger airbag can elevate the risk of fatal injury to a child in this seat by approximately 34% - 70%. Despite this elevated risk, Griffiths [59] claimed that there had been no reports of similar injuries and fatalities to children occupying the front passenger position of vehicles equipped with dual airbags in Australia. He suggested that the Australian practice of not carrying children in child restraints in the front seat coupled with high restraint usage rates means that it is unlikely such events will become a problem in Australia.

4 Child Restraint Usage and Effectiveness

As previously mentioned, children are not adequately protected using restraints designed for adults. The primary explanation is due to their smaller overall size in addition to quite different ratios of body segments compared to adults, most notably a larger head. Despite this, legislation in Australia only enforces that children under the age of 12 months use a specific child restraint. Those over 12 months old are required as a minimum to use adult seatbelts. However child restraints are available for use by children from birth to an average age of about 10 years. In Australia, child restraints are roughly grouped into those for infants, toddlers/preschoolers and young children. Some examples of the three groups can be seen in Figures 9 to 11.

Fig. 9 Infant capsule

Fig. 10 Child seat

Fig. 11 Child booster seat

For children under 9kg or 70cm (usually < 6months old), the recommended method of restraint is using a rearward facing infant capsule. Rearwards facing infant restraints are designed to uniformly distribute crash forces over the whole of the child's chest and head. In frontal impacts, the crash forces shift from the back of the restraint to the infant's back. This design subsequently provides support for the child's head and prevents unwanted relative motion between the head and the torso thereby eliminating undesirable neck loads [59, 60].

It is recommended that children aged 6 months to 4 years (8 – 18kg or 70 – 100cm) should be restrained using a forward facing child seat. These restraints are designed to be situated in the rear seat of the vehicle and tethered at the top to the vehicle. Otherwise, this restraint is coupled to the vehicle using existing adult seatbelts. For the child restraint to provide optimum protection for the child, the fit of the internal harness must be as snug as possible, and the child seat must be anchored to the vehicle as tightly as possible [60]. The internal harness systems of forward facing child restraints work to distribute impact loads over the body's bony structures such as the shoulders, hard thorax and pelvis.

Booster seats are recommended for use by children who are up to 12 years old or over 100cm. The main function of a booster seat is to facilitate a better seatbelt fit by raising the seated height of the child occupant. Doing so improves the compatibility between the child and the adult three-point seat belt, subsequently assisting in the transition between child restraint and the in-vehicle occupant protection systems [59,60]. It should be highlighted however, that several booster seat design features have the potential to impact the level of protection provided to the child in a crash. Firstly, is ensuring that correct belt routing is achieved over the body of the child. Henderson and Charlton [60] reported that some booster seats still place the adult belt system too far away from the child's body. Secondly, are the implications of a backless booster seat. In side impact, there is very little lateral support provided to the child by the seat, which may lead to the child's body flailing. The third implication relates to the possibility of submarining due to boosters that are manufactured using soft compressible seating surfaces. The issue is brought about by the soft seat surface being compressed, allowing the children to either fall sideways or slip under the belt, thereby increasing the risk of self-strangulation.

Despite the existence of a variety of child restraints, a major problem exists in ensuring that the child is restrained in the correct type of seat for their size. In 1994, the state of NSW in Australia observed usage rates to be in the vicinity of 80-90% depending on where the child was seated. Restraint use by children in the front seats was found to be slightly higher than for rear seating positions[61]. In the United States, Winston et al observed that 93% of children were restrained during a crash [62]. Children under 5 wore belts 97% of the time, with children aged 5-9 and 10-15 showing restraint use to be 95% and 88% respectively. Similar results were also observed by Edwards and Sullivan [63], using NASS data from 1988-95. Winston et al also observed that of those restrained, 72% wore seatbelt and 28% used specific child restraint devices [62]. It was shown that the majority of children under 2 were restrained in a CRS, whereas 43% of 3-4 year olds used seatbelts. Of those wearing seatbelts, 81% used a 3-point belt and 19% used only a lap belt. In Germany, Langweider et al. reported 1990-91 data observing that 54% of children aged 6-12 are only restrained by a three-point belt or lap belt [64]. Upon closer inspection it was shown that for children aged 0-11, 32% wore either a three-point or lap belt, whereas children aged 0-5 used the same belts in 14.5% of cases. Despite this, Langweider and his colleagues claimed that in 1998 in Germany, belt usage for children aged 6-11 was 56% with those aged 0-5 wearing adult belts in only 2% of cases.

The ability of child restraints to effectively reduce the risk of death and serious injury to those children who wear them is almost undeniable. Most studies investigating their effectiveness have come from North America and Europe, where overall effectiveness is estimated at approximately 70% [58,65-69]. However, as mentioned earlier, there exist various designs of child restraints, each with varying levels of effectiveness. For rearward facing restraints, most studies estimate injury reduction effectiveness to be approximately 80-90%, however a recent Swedish study reported the effectiveness to be as high as 96% [66,67,69]. Forward facing child seats on the other hand have been shown to be slightly less effective, with effectiveness estimates closer to 70% [57, 66]. The third group of child restraints, booster seats (in addition to belt positioning boosters) have been reported to reduce the risk of injury by anywhere between 30% and 77% [65-67].

Fig. 12 Child correctly fitted to CRS

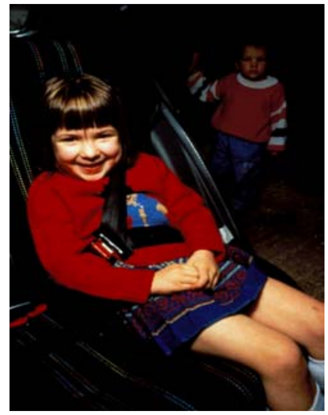

Fig. 13 Child too large for the CRS

Despite the recommendation to restrain children in specific child restraint where possible, it is important to understand the implication of children being restrained by adult belts. By in large, adult seat belts are reported to have protective effects for children, with estimates of effectiveness varying widely between 30% and 60%. The primary factor influencing the effectiveness of these adult belts has been shown to be the age of the child [65,66,70]. On the other hand, the use of a lap belt compared to a three-point belt has been estimated to lower the level of protection by approximately 20% [71,72].

The effectiveness of child restraint systems has also not surprisingly shown to vary depending on the crash severity and configuration. Studies by Braver et al. [56] and Cuny et al. [66] showed that restraint effectiveness is reduced during crashes of higher severity. In Cuny's case, a 70-80% in MAIS 2 plus injuries was observed for children restrained in booster seats and forward facing child seats during impacts occurring at less than 40km/h. At speeds above 40km/h, the injury reduction was reduced to 23% and 65% respectively. For various crash configurations, Braver et al. observed that 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 [46]. Side impacts in particular have been identified by several sources to place child occupants at higher risk of serious and fatal injuries compared to frontal impacts [49,73,74].

5 Conclusion

This paper has highlighted the importance of a range of restraint systems available for the protection of passenger car occupants during a crash. In particular, usage patterns and the effectiveness of seatbelts, airbags and child restraints have been reported for various occupants, under a variety of crash configurations. Methods for improving these systems effectiveness have also been identified. This paper also highlighted the importance of correct use of the restraint for every occupant in the vehicle, as dangers do exist if the restraint is not fitted correctly or misused.

6 References

1. Crandall, J, Kent, R, Viano, D, Bass, C. (2003) The Biomechanics of Inflatable restraints – Occupant Protection and Induced Injury, in Air Bag Development and Performance: New Perspectives from Industry, Government and Academia, R. Kent (ed.), PT-88, Society of Automotive Engineers.

2. Andréasson R & Bächström C-G. The Seat Belt; Swedish Research and Development for Global Automotive Safety; EO Print AB, Stockholm, April 2000.

3. Bohlin, N., (1967) Statistical analysis of 28,000 vehicle accident cases, with emphasis on occupant restraint value. SAE 670925, 11th Stapp Car Crash Conference, Society of Automotive Engineers, Inc., Warrendale, Pennsylvania, USA.

4. National Highway Traffic Safety Authority (1984) Amendment to FMVSS 208. Passenger Car Front Seat Occupant Protection, Federal Regulatory Impact Analysis. Washington DC

5. National Highway Traffic Safety Authority (1984) Traffic Safety Facts 1983. Washington DC.

6. MUARC, Feasibility of Occupant Protection Measures, Report CR100, Australian Transport Safety Authority (formerly, the Federal Office of Road Safety), Canberra, Australia, 1992.

7. Heiman L. *Vehicle occupant protection in Australia*. Australian Transport Safety Authority (formerly, the Federal Office of Road Safety), Canberra, Australia, 1988.

8. Ashton SJ, Mackay GM, Camm S. Seat belt use in Britain under voluntary and mandatory conditions. In: *Proceedings of the 27th Conference of the American Association for Automotive Medicine (AAAM)*. Chicago, IL, American Association for Automotive Medicine, 1983:65–75.

9. Rutherford W et al. *The medical effects of seat belt legislation in the United Kingdom*. London, Department of Health and Social Security, Office of the Chief Scientist, 1985 (Research Report No. 13).

10. Koushki, P.A., 1996. The seat belt law in Kuwait: observed and reported compliance and impacts on road safety. Transportation Research Record, TRR 1485, Washington, DC, pp. 13–18.

11. Koushki, P.A., Al-Anezi, S., 1998. Seat-belt use trend in Kuwait. Research Report No. CE-499, Department of Civil Engineering, Kuwait University.

12. Yang B, Kim J. Road traf. c accidents and policy interventions in Korea. *Injury Control and Safety Promotion*, 2003, 10:89–94.

13. ARUP Transportation Planning (1995). The 1994 Exposure Survey, Final Report. Prepared for VicRoads by ARUP Transportation Planning.

14. Whelan, M., Diamantopoulou, K., Senserrick, T., & Cameron, M. (2003). Establishing a benchmark of safety on Melbourne roads, Report 198. Monash University Accident Research Centre.

15. Silveira AJ. Seat belt use in Argentina: a 10-year struggle. *Traf. c Injury Prevention*, 2003, 4:173–175.

16. Nantulya VM, Muli-Musiime F. Uncovering the social determinants of road traf.c acci-dents in Kenya. In: Evans T et al., eds. *Challeng-ing inequities: from ethics to action*. Oxford, Oxford University Press, 2001:211–225.

17. Fildes B.N., Fitzharris M., Koppel S. & Vulcan A.P. (2002) Benefits of seat belt reminder systems. CR Report 211a. Australian Transport Safety Bureau.

18. ATSB (2002). Road crash statistics, 1996. http://www.atsb.gov.au/roads/stats/timefatl.cfm Accessed May, 2002.

19. Regan, M.A., Oxley, J.A., Godley, S.T., & Tingvall, C. (2001). Intelligent Transport Systems: Safety and Human Factors Issues (Report number 01/01). RACV Ltd Melbourne.

20. Valtonen J. The use of safety belts and their effect in accidents. Helsinki, Central Organization for Traffic Safety, 1991.

21. Kamrèn B. *Seat belt use among fatally injured in the county of Stockholm 1991–1992*. Stockholm, Folksam, 1992.

22. Fildes, B. N.; Lane, J. C.; Lenard, J.; Vulcan, A. P. Passenger cars and occupant protection. Report CR 95. Camberra, Australia: Federal Office of Road Safety, Department of Transport and Communications; 1991.

23 McLean, A.J., Aust, H.S., Brewer, N.D., & Sandow, B.L. (1979). Adelaide in-depth accident study – 1975-1979: Part 6; car accidents. NHMRC, Road Accident Research Unit, The University of Adelaide, Adelaide, Australia.

24 Bylund, P-O. & Björnstig, U. (2001). Use of seat belts in cars with different seat belt reminder systems. A study of injured car drivers. AAAM 45th Annual Conference, September 24-26, 2001.

25 Evans, L. (1986) The effectiveness of safety belts in preventing fatalities. Accident Analysis and Prevention 18:229-241.

26 Kahane, C. J. 2000. *Fatality Reduction by Safety Belts for Front-Seat Occupants of Cars and Light Trucks.* DOT-HS-809-199. National Highway Traffic Safety Administration, U.S. Department of Transportation, Dec.

27 NHTSA. 2002. *Traffic Safety Facts 2001: Occupant Protection.* DOT-HS-809-474. U.S. Department of Transportation.

28 Cooper, P.J., 1994. Estimating over involvement of seat belt non-wearers increases and the effect of lap/shoulder restraint use on different crash severity consequences. Acc. Anal. Prev. 26, 263–275.

29 World Report on Road Traffic Injury Prevention (WHO, 2004)

30 Evans L. Restraint effectiveness, occupant ejection from cars and fatality reductions. *Accident Analysis and Prevention*, 1990, 22:167–175.

31 Ichikawa, M., Nakahara, S., Wakai, S., 2002. Mortality of front-seat occupants attributable to unbelted rear-seat passengers in car crashes.

32 Broughton J (2004) The actual threat posed by unrestrained rear seat car passengers Accident Analysis and Prevention 36 (2004) 627–629

33 Dinh-Zarr, T.B, Sleet, D.A Shults, R.A, Zaza, S, Elder, R.W, Nichols J.L, Thompson R.S. Sosin D.M Reviews of Evidence Regarding Interventions to Increase the Use of Safety Belts Am J Prev Med 2001;21(4S) Published by Elsevier Science Inc.

34 Russell N, Dreyfuss M, Cosgrove M, Low & Associates. Legislative history of recent primary safety belt laws. Washington, DC: U.S. Department of Transportation, 1999; publication no. DOTHS808-833.

35 Harris GT, Olukoga IA A cost benefit analysis of an enhanced seat belt enforcement program in South Africa 2005;11;102-105 *Inj. Prev.*

36 Williams, A. (2002). Status Report, Vol. 37 No. 2. Insurance Institute for Highway Safety.

37 Fildes B, Fitzharris M, Koppel S & Vulcan AP, Benefits of Seat Belt Reminder Systems, Report CR 211a, Australian Transport Safety Authority (formerly, the Federal Office of Road Safety), Canberra, Australia, 2002.

38 Eppinger R. (1993) in: Nahum, A. and Melvin, J. (editors) Accidental Injury: Biomechanics and Prevention. Springer-Verlag, New York, NY.

39 Autoliv (2005) Taken from website: http://www.autoliv.com/appl_alv/Autoliv.nsf/pages/seat_belts. Accessed 17/08/2005.

40 Walz M.C. (2003) NCAP Test Improvements with Pretensioners and Load Limiters.

41 Department of Transportation. National Highway Traffic Safety Administration Washington, DC 20590

42 Czernakowski W & Bell R (1997) The effects of belt pretensioners on various child restraint designs in frontal impacts (SAE 973310), *Child Occupant Protection 2nd Symposium,* Society of Automotive Engineers, Warrendale, PA.

43 Foret-Bruno, J-Y., Trosseille, X., Page, Y., Huere, J-F, Le Coz, J-Y., Bendjellal, F., Diboine, A., Phalempin, T., Villeforceix, D., Baudrit, P., Guillemot, H., Coltat, J-C (2001) Comparison of thoracic injury risk in frontal car crashes for occupants restrained without belt load limiters and those restrained with 6 kN and 4 kN belt load limiters. Stapp Car Crash Journal 45:205-224.

44 Rouhana, S. W.; Bedewi, P. G.; Kankanala, S. V.; Prasad, P.; Zwolinski, J. J.; Meduvsky, A. G.; Rupp, J. D.; Jeffreys, T. A.; Schneider, L. W. (2003) Biomechanics of 4-point seat belt systems in frontal impacts. Stapp car crash journal. Vol. 47 (Oct. 2003) p. 367-399. Report No.: SAE 2003-22-0017

45 Bostrom O, Haland Y (2003). Benefits Of A 3+2 Point Belt System And An Inboard Torso Side Support In Frontal, Far-Side And Rollover Crashes. *Enhanced Safety of Vehicles Conference,* Nagoya

46 Segui-Gomez, M. (2000) Driver air bag effectiveness by severity of the crash. American Journal of Public Health 90:1575-1581.

47 National Highway Traffic Safety Administration: Third Report to Congress: Effectiveness of Occupant Protection Systems and Their Use. U.S. Department of Transportation, December, 1996.

48 Kahane, C.J., 1996. Fatality Reduction by Air Bags; Analyses of Accident Data Through Early 1996. Technical Report DOT HS808 470. US National Highway Traffic Safety Administration, Washington DC, August.

49 Braver ER, Whitfield R, Ferguson SA. *Risk of Death Among Child Passengers in Front and Rear Seating Positions*. Arlington, VA: Insurance Institute for Highway Safety; 1997

50 Braver, E. R., S. A. Ferguson, M. A. Greene, and A. K. Lund, “Reductions in Deaths in Frontal Crashes among Right Front Passengers in Vehicles Equipped with Passenger Air Bags,” *JAMA* 278:17(1997), 1437–1439.

51 National Highway Traffic Safety Administration. Fifth/Sixth Report to Congress: Effectiveness of occupant protection systems and their use, NHTSA Report DOT HS 809 442, November 2001.

52 Cummings P et al. Association of driver air bags with driver fatality: a matched cohort study. *British Medical Journal*, 2002, 324:119–122.

53 Evans L. (2004) Traffic Safety ISBN 0-9754871-0-8

54 Fildes et al. Effectiveness of airbags in Australia, Paper 96-S5-O-17 presented at the 15th International Technical conference on the Enhanced Safety of Vehicles, Melbourne, 13-17 May 1996.

55 McGwin G, Metzger J, Porterfield JR, et al. Association between side air bags and risk of injury in motor vehicle collisions with near-side impact. J Trauma 2003;55:430–6.

56 Braver E.R, Kyrychenko S.Y. Efficacy of Side Air Bags in Reducing Driver Deaths in Driver-Side Collisions. In American Journal of Epidemiology Vol. 159, No. 6

57 Griffiths M (1997) Airbags - Children and adults in airbags: Effectiveness and Safety*, Proceedings of National Panel for the Biomechanics of Impact Injury Institution of Engineers*, Melbourne, Australia.

58 Weber K (2000) Crash protection for child passengers: A review of best practice*, UMTRI Research Review*, 31, 3.

59 Griffiths M, Brown J & Kelly P (1994) Child restraint system development in Australia (Paper No. 94510 015), *Fourteenth Enhanced Safety of Vehicles Conference,* Munich, Germany.

60 Henderson M, Charlton J (2005) Internal MUARC Report

61 Roads and Traffic Authority (1994) *Child Restraint and Seat Belt Usage Survey,* Road Safety Bureau, NSW Roads and Traffic Authority.

62 Winston F, Durbin D, Bhatia E, Werner J, Sorenson W. Patterns of appropriate restraint for children in crashes. In, Child occupant protection in motor vehicle crashes. Joint session organised European vehicle passive safety network, AAAM and IRCOBI

63 Edwards J & Sullivan K (1997) Where are all the children seated and when are they restrained? (SAE971550), *Child Occupant Protection 2nd Symposium*, Society of Automotive Engineers, Warrendale, PA.

64 Langweider K, Hummel T, Finkbeiner F. (1999) Injury risks for children in cars depending on the type of restraint. In, Child occupant protection in motor vehicle crashes. Joint session organised European vehicle passive safety network, AAAM and IRCOBI

65 Isaksson-Hellman I, Jakobsson L, Gustafsson C & Norin H (1997) Trends & effects of child restraint systems based on Volvo's Swedish accident database (SAE 973 229), *Child Occupant Protection 2nd Symposium*, Society of Automotive Engineers, Warrendale, PA.

66 Cuny S, Got C, Foret-Bruno J, LeCoz J, Brun-Cassan F & Brutel G (1997) The effectiveness of child restraint systems in France, *Child Occupant Protection 2nd Symposium,* Society of Automotive Engineers, Warrendale, PA.

67 Carlsson G, Norin H & Ysander L (1991) Rearward-facing child seat: The safest car restraint for children? *Accident Analysis and Prevention,* 23, 213.

68 Partyka SC (1990) Lives saved by Child Safety Seats from 1982 through 1987*, 12th International Technical Conference on Experimented Safety Vehicles*, National Highway Traffic Safety Administration, Washington, DC

69 Tingvall C (1987) Children in cars, some aspects of the safety of children as car passengers in road traffic accidents, *Acta Paediatrica Scandinavica*, Supplement 339.

70 Partyka SC (1988) *Belt effectiveness in fatal accidents: Papers on adult seat belts – effectiveness and use* (DOT HS 807 285), National Highway Traffic Safety Administration, Washington, DC.

71 Malliaris A & Digges K (1987) Crash protection offered by safety belts, *11th International Technical Conference on Experimental Safety Vehicles*, National Highway Traffic Safety Administration, Washington DC.

72 Lundell B, Carlsson G, Nilsson P, Persson M & Rygaard C (1991) Improving rear seat safety - a continuing process (Paper No. S9-W-35), *Thirteenth International Technical Conference on Experimental Safety Vehicles*, National Highway Traffic Safety Administration, Washington, DC.

73 Rattenbury S & Gloyns P (1993) A population study of UK car accidents in which restrained children were killed*, Child Occupant Protection Symposium*, San Antonio

74 Langweider K, Hell W, Lowne R & Huijskens C (1996) Side impact to children in cars: Experience from international accident analysis and safety tests (Paper 96-S7-0-02), *Fifteenth International Technical Conference on the Enhanced Safety of Vehicles*, National Highway Traffic Safety Administration, Washington, DC.