VEHICLE FAR-SIDE IMPACT CRASHES

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ABSTRACT

This is a summary of a paper which first appeared in the International Journal of Crashworthiness under the title: "Side Impact Protection - Occupants in the Far-Side Seat", Vol. 3, No. 2, pp 93-122. Readers are directed to the full paper for a more comprehensive discussion of the issues presented here.

Much of the applied vehicle side impact occupant protection research to date has concentrated on occupants seated beside the struck side of vehicles. These occupants are defined as 'near-side' occupants. Real world crash evidence however has shown that occupants seated on the side away from the struck side, defined as 'far-side' occupants, are still subject to a risk of injury. This paper examines side impact epidemiology from an injury causation perspective, and endeavours to explain evidence indicating head injuries and seat belt related injuries constitute a significant proportion of all far-side impact injuries. Injury mechanisms and key dynamic parameters governing injury severity are detailed. Computer models simulating the dynamic motion of vehicle far-side occupants are described. Occupant kinematics and injury parameters from the models are then compared with real world crash case studies. The paper finally suggests vehicle design strategies which may reduce far-side injuries. Some alternative restraint systems are proposed as potential countermeasures to reduce occupant injuries.

INTRODUCTION

Vehicle occupants are particularly vulnerable in side crashes. Australian studies by Fildes et al [1,2] have revealed that side impact crashes accounted for 25 percent of all injury crashes and 40 percent of serious injury crashes where an occupant was either hospitalised or killed. Vehicle side impact occupant protection research has concentrated mostly on the occupants seated beside the struck side of the vehicle.

These occupants are defined as near-side occupants. All regulatory side impact test standards focus exclusively on this scenario and rely on an assessment provided by one test intended to represent one point in the spectrum of real world near-side impact crashes.

Real world crash evidence however has shown that far-side occupants as illustrated in Figure 1, are still subject to a risk of injury. The study by Fildes et al noted that around 40 percent of restrained side impact crash casualties were far-side occupants. Relatively little research literature is available that addresses protection of far-side occupants. The scope of this paper thus addresses far-side occupants where there may be opportunities for improved occupant protection.

Before any countermeasures to problems of vehicle far-side impact crashworthiness can be proposed however, it is first necessary to establish clear injury patterns which characterise the problem. It then becomes possible to identify the injury mechanisms and finally propose countermeasure strategies which can address these specific injury processes.
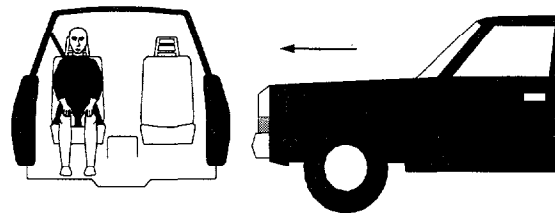

Figure 1. Far-Side Impact Crash Configuration

SIDE IMPACT STATISTICS

Ginpil et al [3], examined data relating to crashes occurring in Australia in 1990 where at least one occupant fatality resulted from an impact to the side of the vehicle. They reported that 79 percent of occupants in the sample were killed in near-side impacts compared to 36 percent of occupants killed in

far-side impacts. Further, this study reported that far-side fatalities were more likely to sustain serious head injuries than near-side fatalities. The report detailed 26 percent of far-side fatalities sustained severe injuries only to the head and no other region, compared with only 18 percent for near-side fatalities. Mackay et al [4] using UK field accident data discussed the relative importance of head injuries for restrained far-side occupants. The report highlighted the issue of torso restraint and detailed a frequent mechanism where far-side occupants can slip out of their chest restraint to make head contact with structures on the opposite side of the vehicle cabin. Based on a study sample of 51 head injury cases, 35 percent were judged to have come out of their seat belt. Mackay also reported frequent far-side occupant injuries to chest and abdominal body regions from excessive seat belt loads caused by the upper torso slipping from the shoulder belt. The reported mechanism of the upper torso flailing about in the cabin was considered a key element in the further investigation of far-side impact occupant injury.

Subsequent sections of this paper deal with a closer examination of Australian injured occupant cases. Mathematical computer modelling simulations of these cases have been developed which attempt to reconstruct the essential mechanisms and provide a basis for the selection of potential countermeasure designs.

CRASHED VEHICLE CASE STUDIES

Crashed Vehicle File

Side impact case studies by Fildes et al [1] detailed vehicle crash parameters together with injury distributions for a sample of hospitalised and killed occupants in Australian crashes. These case studies were based on a sample of 198 side impact crashes of passenger vehicles. The study investigated 234 injured or killed occupants and formed part of the Monash University Accident Research Centre's (MUARC) crashed vehicle file collected for the Australian Federal Office of Road Safety (FORS). The whole FORS sample compiled at the time of writing included 134 restrained occupants in near-side impacts and 52 restrained occupants in far-side impacts.

Detailed information about the nature of each crash together with vehicle deformations and likely injury sources were recorded by MUARC researchers. Additionally, estimated vehicle delta-V values were derived using the Crash-3 computer program. Injuries to various body regions were coded according to the Abbreviated Injury Scale (AIS), documented by the American Association for Automotive Medicine, [5].

AIS is a "threat-to-life" scale ranging from AIS1 (minor severity) to AIS6 (non-survivable).

Far-Side Case Study Sample

The sample of occupants killed or injured in far-side cases collected by MUARC was examined to establish parameter patterns relevant to far-side impacts which typically lead to injury. The entry criterion for the far-side sample was based on primary impact damage on the side opposite where the injured or killed occupants were seated. To expedite this review, a subset of the overall MUARC crashed vehicle file published as one page summaries was analysed. As the prime interest of this study is on restrained occupants, cases where seat belts were judged not to have been used, were excluded. A sample of 45 restrained cases classified as far-side impacts by MUARC was thus used. The sample of injured and killed occupants comprised 26 males and 18 females. In the sample, 36 occupants were drivers and 9 were passengers (2 in rear seats). Further, 16 of these far-side occupants were seated beside adjacent (near-side) occupants, whereas 29 far-side occupants were not adjacent to any other occupant. The median occupant age in the far-side sample was around 30 years.

Case Study Vehicle Impact Data

The vehicle impact information from the case study sample was used to specify the significant impact conditions applied in subsequent computer modelling simulations. Figure 2 shows the sample's distribution of objects the car containing the subject far-side occupant impacted with, or was impacted by. Most cases involved impacts with other cars. Impacts with fixed objects such as trees and poles are notable as are impacts with heavier vehicles such as four wheel drives which are included in the light truck category. Most impacts occurred to the mid sections of the subject vehicles.

The sample of vehicles comprised almost equal proportions of vehicle size/weight categories. The numbers of small (under 900 kg), medium (900 to 1200 kg) and large (over 1200 kg) passenger cars in the sample were 14, 15 and 16 cases respectively. Figure 3 shows the distribution of vehicle mass ratios.
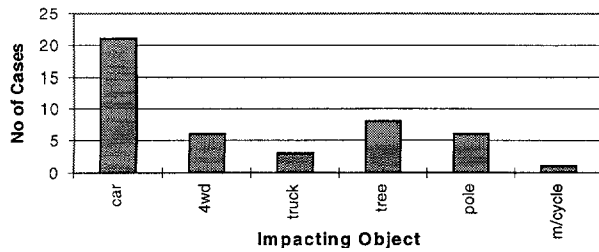
Figure 2. Histogram of Impacted/Impacting Objects, n = 45

The mass ratio in these cases was defined as the mass of the far-side occupant's vehicle divided by the mass of the impacting vehicle. Around half of the cases in the sample have vehicle mass ratios under 0.9.

Figure 5 shows the distribution of the impacting object's directional angle α with the side of the subject occupants' car as defined in Figure 4. Most cases were classified as pure side impacts where the directional impact angle was around 90 degrees. The sample is however skewed towards angles less than 90 degrees where a rearward orientated velocity component relative to the occupant's car was present at the time of impact.
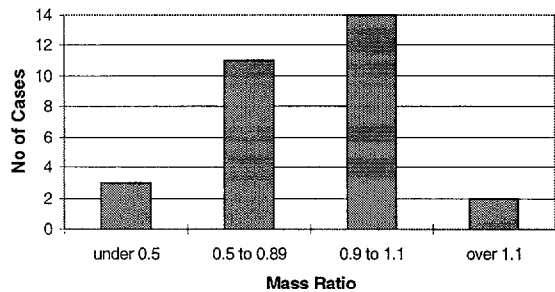

Figure 3. Histogram of Impacting Vehicle Mass Ratios, n = 30 (subject vehicle mass/impacting vehicle mass)

Figure 6 shows the cumulative distribution of the maximum cabin intrusion for all cases in the far-side injury sample. Intrusion exceeded 400 mm in around half of the cases. In around 20 percent of the cases, the maximum intrusion exceeded 625 mm which is equivalent to half of the cabin width of a typical small car. Interestingly, 20 percent of far-side injury cases were recorded where no intrusion was noted
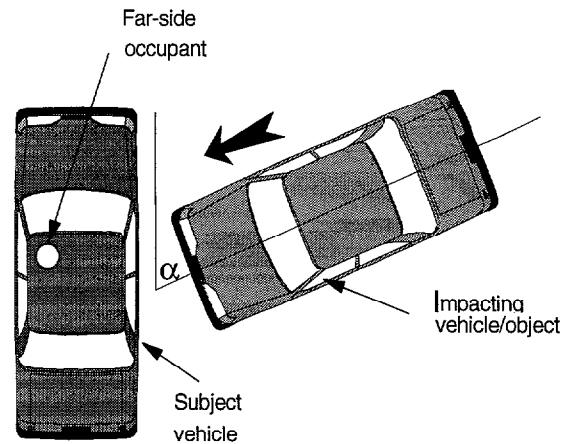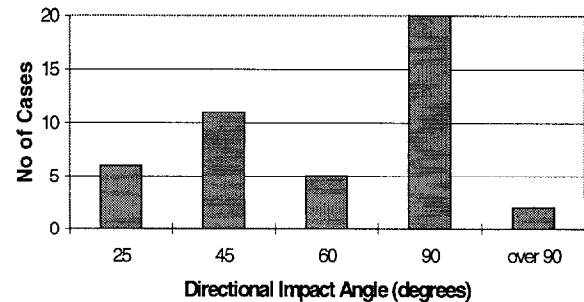

Figure 4. Definition of Impact Geometry

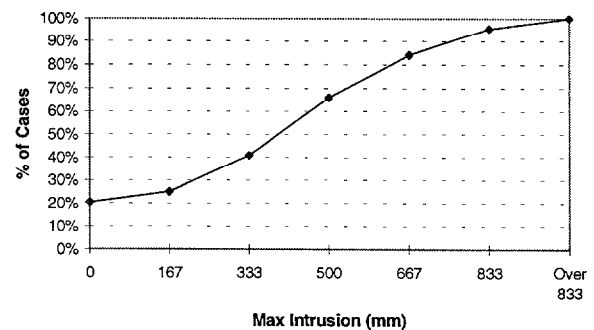**Figure 5. Histogram of Directional Impact Angle α, n = 45**

Figure 6. Cumulative Distribution of Max Intrusion for All Cases, n = 45

Figure 7 shows delta-V distributions for light truck or car into car impacts. These vehicle crash delta-V values were calculated by MUARC using the Crash-3 computer program. It was not possible to calculate estimates of delta-V in all cases, thus Figure 7 is based on data from 22 far-side impact cases. In the sample, 80 percent of cases have estimated delta-Vs

under 60 km/h, with half of the cases having delta-Vs estimated under 40 km/h.

Based on the case study vehicle impact data, suitable test conditions to conduct subsequent dynamic simulation modelling evaluations of far-side impacts were established. These conditions were considered representative of important segments within the spectrum of real world crashes. Car to car simulation cases were initially investigated with a medium size 1000 kg car. An impacting vehicle mass higher than the far-side occupant's car was chosen, with a vehicle mass ratio of 0.9. Impact into the far-side occupant car's mid section at an angle of 90 degrees was considered representative. Delta-Vs below 60 km/h were also considered relevant for the investigation.
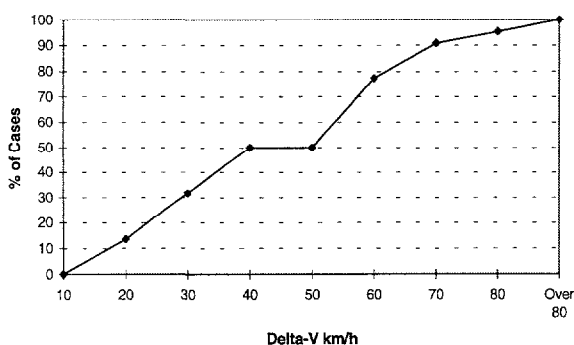

Figure 7. Cumulative Distribution of Delta-V for Light Truck or Car into Car Impact Cases, n = 22

Case Study Occupant Injury Data

Occupant injury data from the far-side study case study sample was used to verify whether simulation load measurements correctly predicted occupant injuries that would be expected in similar real-world situations. Details of injury severity outcomes and observed injury loading mechanisms from the sample of restrained far-side occupants are provided in Stolinski et al [6]. The following is a summary of the findings.

The typical motion of a relatively unrestrained upper torso pre-disposes far-side occupants to a risk of head injuries as the torso rotates across the cabin interior and the head contacts the vehicle's far side or instrument panel. Further, as the shoulder and chest slips out from under the sash part of a three point seat belt, belt loads can be concentrated on the body region impinged by the lap belt. Another mechanism observed in high severity impacts is direct contact with the intruding object. Where intrusion approaches half the width of the car cabin, direct contact with an intruding object may be unavoidable. An additional important mechanism is direct contact

with adjacent occupants. It is possible that an adjacent near-side occupant may shield the far-side occupant from intruding objects or the vehicle's far-side, however the impacts between occupants themselves would certainly involve some risk of injury.

FAR-SIDE OCCUPANT/VEHICLE DYNAMICS

Injury Tolerance

Questions arise as to what levels of the key dynamic measures of head velocity and lap seat belt load are critical. Kanianthra et al [7] and NHTSA [8] in the development of the US Upper Interior Head Protection Standard - FMVSS No. 201, selected a free motion headform impact test velocity of 15 mph (6.7 m/s) for the evaluation of interior padding materials. This test speed was established on the basis of US National Accident Sampling System (NASS) data, where it was noted to be the average occupant speed relative to the cabin interior at which the onset of serious injuries (between AIS 2 and AIS 3) are likely to occur. McIntosh et al [9] conducted studies on head impact tolerance in side impacts using cadaver tests and computer simulations. Findings indicated that at impact velocities in excess of *6 m/s*, head injuries of an AIS 3 level were likely. McIntosh et al proposed tolerance levels of maximum head acceleration of 150 g and HIC of 750. The authors suggested that even with padding, the likelihood of brain injury was not reduced at these higher velocities.

Leung et al [10] proposed lap belt injury tolerance loads. Using cadaver tests, injuries were observed for lap-belt tension loads higher than *3 kN*. Although this tolerance load was established with respect to frontal collision kinematics, it is considered that a lateral impact tolerance load may not differ too significantly. It is thought that during impact, the body rotates around its vertical axis so that the belt loads still primarily impinge on the forward portion of the abdomen. Nevertheless some fundamental research to better establish lateral impact tolerance loads still needs to be carried out.

Occupant Dynamics - Sled Test Computer Model

A model of a restrained occupant in a far-side impact sled test situation was developed using the TNO MADYMO occupant/vehicle crash simulation computer program. As previously noted, the mechanism of occupants slipping out of their seat belts is crucial to the realistic modelling of far-side occupant motion. It was therefore necessary to use a finite element seat belt model capable of simulating

seat belt slip. The occupant in the sled test was simulated using a multi-body 50th percentile Hybrid III ellipsoid model from the MADYMO dummy database [11]. The finite element seat belt was available as a MADYMO application and is detailed in the MADYMO Applications Manual [12]. The seat structure was simulated using plane elements with dummy-seat and dummy-belt contact interaction characteristics established experimentally by TNO [12].

As a validation exercise, initial modelling was done to replicate a series of sled tests in a General Motors Research Laboratories program by Horsch et al [13]. Sled test response data from both Hybrid II dummies and cadavers was published by Horsch making comparisons possible with the computer model output data. As in the sled test program, *a 100 ms, 10g square acceleration pulse* was applied in the MADYMO model.

Figure 8 shows the computer model simulation kinematics that compared favourably with a sled test run using an unembalmed cadaver [6]. A comparison of responses from the Horsch test series [13] with the computer model simulation responses is summarised in Table 1. Head acceleration levels from the dynamic motion itself are well below published injury tolerance levels. However if the head were to contact an interior cabin structure at a velocity exceeding 6 m/s, as observed in the simulation, injury would be expected. It is noted that measured maximum lap belt loads are above the abdominal injury tolerance levels suggested by Leung.

Occupant Dynamics - Car Test Computer Model

A sled test scenario is somewhat limited as real vehicle lateral impacts also involve varying levels of rotational acceleration. A full car model also provides the opportunity to model more realistic acceleration pulses developed during the interaction of two colliding vehicles. Further, it was considered useful in subsequent studies, to develop the capability to model interactions between the far-side occupant and adjacent near-side occupants in the car. It was therefore decided to assemble a full car and occupant simulation model to further study far-side occupant dynamics in full vehicle side impact situations.

This model was developed [6] by integrating the sled test model, described in the previous section with a car side impact model originally developed to simulate an ECE R95 [14,15] side impact test at 50 km/h. Centre console and floor transmission tunnel surfaces were added to the model for far-side side occupant contact interaction as these structures are present in most cars and are considered important to modelling correct occupant dynamics.

Table 1.
Comparison of Sled Test and Computer Model Peak Responses

Dynamic Parameter	Sled Tests	Computer Simulation
Shoulder Belt Load (kN)	2.6 - 4.1	5.0
Inboard Lap Belt Load (kN)*	1.9 - 4.1	2.8
Outboard Lap Belt Load (kN)**	2.3 - 4.3	4.7
Upper Torso Acceleration (g)	19 - 23	20
Head Acceleration (g)	33 - 42	26
Head Velocity (m/s)	-	9.1

* Inboard Lap Belt Load - (adjacent dummy's right side)
**Outboard Lap Belt Load - (adjacent dummy's left side)

The full car and occupant computer model was run in a number of test cases and the results are detailed in Table 2. The model at this stage has only been run with the far-side occupant in the vehicle. A 1000 kg car with a 1111 kg impacting barrier (mass ratio = 0.9) was used. The subject car containing the far-side occupant was impacted mid section by the mobile barrier at 90 degrees.

It was observed that for far-side occupants where the upper torso is relatively unrestrained, head velocities were closely related to the car delta-Vs. The simulation results show that at an impact speed of 40 km/h, neither the head velocity nor the lap belt load exceeded previously established tolerance values. At 50 km/h, the head velocity exceeded the tolerance value. At 60 km/h, *both* the head velocity and the lap belt loads exceeded the tolerance values. The 60 km/h test speed resulted in only a 31 km/h delta-V of the impacted car. Delta-Vs up to this level in the MUARC far-side injury sample, as detailed in Figure 7, accounted for less than half of the injured occupants. Accordingly, the majority of injured cases occurred beyond this level of delta-V. This is consistent with the simulation findings that injury tolerance levels are certainly exceeded beyond this level of crash severity.
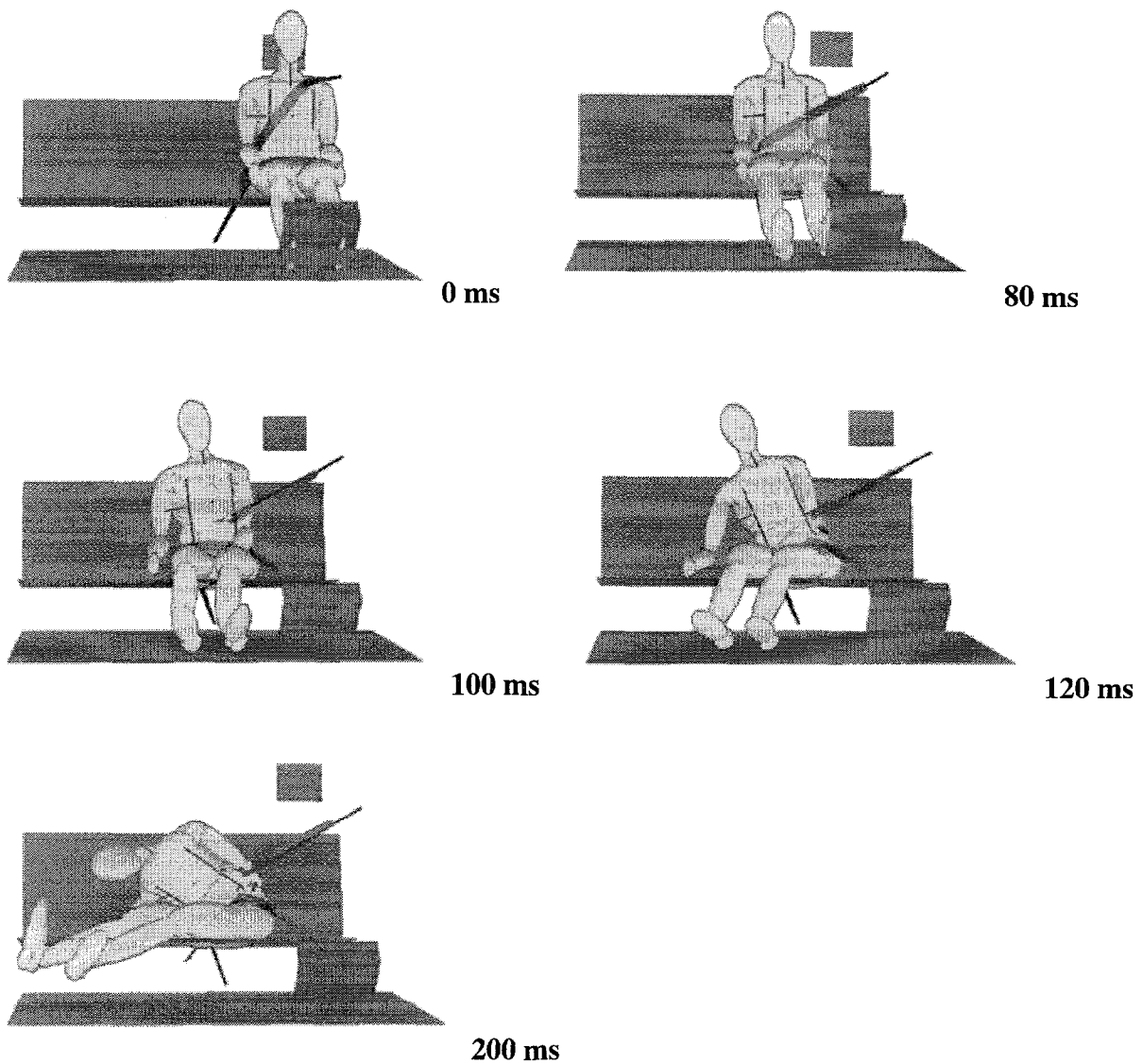
0 ms

80 ms

100 ms

120 ms

200 ms

Figure 8. Dynamic Motion in Far-Sided Impact Sled Test from MADYMO Simulation of Hybrid III Dummy During 10g Side Impact Pulse.

Table 2.
Peak Responses of Far-Side Occupant in the Car Test Computer Model

Impact Speed (km/h	Head Velocity (m/s)*	Lap Belt Load (kN)**	Car Acceleration (g)***	Car Delta-V (km/h, m/s)
40	5.3	1.4	10.5	20.4, 5.7
50	7.3	2.3	12.6	25.9, 7.2
60	9.1	3.5	14.6	31.1, 8.6

* head velocity relative to the car interior, ** outboard lap belt load, *** lateral acceleration measured at the car's centre of gravity

FAR-SIDE INJURY COUNTERMEASURES

Seat Belt Pretensioners

If better upper torso lateral restraint could be provided, the level of torso swing could be reduced, causing either fewer head impacts to occur with the cabin interior or at least at lower impact velocities. Seat belt pretensioning of the sash belt that is activated during lateral impacts may be effective in delaying or reducing the extent of seat belt slip.

Reduction of sash belt slip would also be expected to reduce the concentration of lap belt loading by maintaining more belt loading on the upper torso.

Lateral Wing Seat Bolsters

Another countermeasure could be the provision of highly defined lateral 'wing' torso restraints that are built into seat structures. This design configuration is common in motor sport. Together with a full harness, this design provides a high level of lateral occupant restraint for racing drivers. It appears likely however that comfort issues could lead to serious difficulties in consumer acceptance of this configuration. Careful design of inboard lateral bolsters would be needed to ensure their acceptability in passenger vehicle applications.

As such designs provide more torso restraint, further research is needed to establish whether unacceptable inertial loads are transferred to the unrestrained head/neck of far-side occupants. The human neck model developed by de Jager [16] may be useful in this regard. It will also be important to ensure that thoracic loads on far-side occupants do not exceed tolerance levels.

Reverse Geometry Seat Belts

Another potentially effective countermeasure against far-side head impacts worth considering may be the provision of reverse geometry integrated seat belts. This design configuration has been implemented in the rear seats of some BMW passenger vehicles. Some tests have shown however that belt/neck loads could be excessive with this seat belt configuration. Horsch et al [13], who conducted cadaver sled tests, indicated that serious C5-C6-C7 cervical spine injuries could occur. Conversely, Kallieris et al [17], using cadavers in full vehicle side impact tests, concluded that application of reverse geometry seat belts did not cause neck injuries beyond AIS level 1. It appears therefore that more research is still needed into the biomechanical effects of reverse geometry seat belts and potential benefits for far-side occupants. Reverse geometry integrated seat belts would however incur cost and weight penalties for vehicles because more complex seat and re-inforced floor structures would need to be designed.

Inflatable Restraint Systems

Alternative solutions, involving inflatable airbag restraint systems using existing technology may be possible. This way, existing consumer expectations of comfort and space would not need to be compromised. A basic problem with inflatable systems is the need to provide surfaces or supports for an airbag to react against whilst restraining an occupant. It is possible that an inflatable curtain devices originally intended for protection of near-side occupants could also provide protection for far-side occupants by providing a buffer against head impacts with far-side structures.

CONCLUSIONS

In far-side impact situations, a key mechanism leading to injury is the upper torso slipping out of the shoulder belt. As a result, excessive head velocities can develop in the car together with excessive lap belt loads. This process is considered responsible for many of the head and abdominal injuries observed in far-side impact occupant injury case studies. Head velocities relative to the car interior exceeding 6 m/s and lap belt loads higher than 3 kN have been shown to be critical values, above which, head or abdominal injuries are likely. Other important loading mechanisms include direct contact with intruding objects and contact with adjacent occupants.

The simulation studies described in this paper have shown that with impact velocities at or above 60 km/h (with delta-Vs exceeding 31 km/h), critical values of head velocity relative to the car interior or lap belt load can be exceeded in some crash situations. This is consistent with real world case studies, where most injury cases in the sample were noted to occur above this level of crash severity.

Some alternative restraint systems have been proposed as potential countermeasures to reduce far-side impact injuries. These include seat belt pretensioners which are activated by lateral acceleration, lateral wing seat bolsters, reverse geometry seat belts and inflatable devices. Further research is recommended to investigate the usefulness of these countermeasures, particularly to ensure that neck injury tolerance loads are not exceeded.

Further research work is also recommended to examine:

- larger sample sizes of real world far-side injury cases;
- abdominal injury mechanisms from the lap belt under lateral impact loading;
- injury mechanisms during adjacent occupant interactions and contact with intruding structures;
- issues of eccentric and angled vehicle impact geometry;
- effects of pole and tree impacts.

Consideration should be given to the inclusion of a far-side occupant dummy in future side impact design rule test standards.

Finally, it has been shown that opportunities exist for the development of new and innovative restraint systems.

ACKNOWLEDGMENTS

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