THORACIC INJURY CHARACTERISTICS OF ELDERLY DRIVERS IN REAL WORLD CAR ACCIDENTS

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ABSTRACT

Recent research has indicated that elderly occupants are more vulnerable than other age groups in motor vehicle crashes while the elderly population has significantly grown worldwide. Based on the comprehensive claim data (2000-2008) from an automobile insurance company in South Korea, the survey showed that elderly drivers (65+) suffer thoracic injuries more compared to the other age groups. To show the significance of the age effect, this study investigates injuries among the different age groups involved in frontal, side and rear collisions based on real world crash data.

Real world crash analysis was statistically performed to analyze the elderly driver's accident pattern, and injury types in a variety of impact crashes. The result shows the thoracic injury risk of the elderly group is 2.6 times higher than that of the middle age group (24-54) in frontal crashes, 2.7 times in side crashes, and 4.8 times in rear crashes. In-depth study was conducted to compare the degree of injuries in detail between elderly drivers and non-elderly drivers. The medical records showed that elderly drivers have higher possibility of the thoracic injury. Diagnosis shows that most of thoracic injuries were caused by rib fractures. It has been demonstrated elderly drivers are likely to suffer more injuries at a chest region compared to the middle-aged group. Finally, thoracic injury analysis of two cases was done using CT images of injured elderly drivers. Using the reconstruction software, 3D model was built to analyze injury characteristics accurately. This model provided the detailed trace on rib fractures and showed the cause of injuries were safety devices such as seat belt and airbag. This research calls attention to the need for design improvement to make vehicles more protective for older drivers in car-to car frontal crashes.

INTRODUCTION

South Korea became an aging society in 2000 and has been changed to an aged society very fast. Therefore, it is natural that automotive accidents involving elderly occupants have also increased continuously. Consequently, the injuries of the elderly in motor vehicle crashes is a serious concern. According to the Traffic Accident Statistics in 2009, 1,735 people age 65 and older were killed in 2008, and these older individuals made up 29.6% of all traffic fatalities. Compared to 2007, all accidents increased by 2.0% but the accidents involving elderly people increased by 8.9%. Among people injured in this age group there was a 8.9% increase from 2007. Figure 1 shows the increase of the accidents involving the elderly from 2005 to 2010.

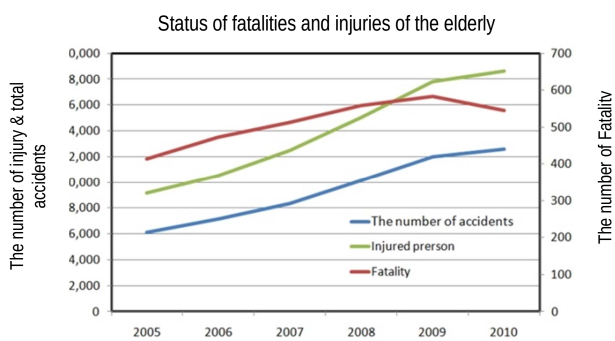

Figure1. The number of elderly drivers in traffic accidents in South Korea

Previous studies have shown that one of the most important factors that affect a person's risk of injury in a motor vehicle crash is the age of the occupant. Schmidt (1971) presented the difference of the degree of thoracic injuries by age performing crash tests at 40 km/h involving cadavers in twenties and sixties. Neathery (1974) and Marcus (1983) showed the result that AIS level of thoracic injury increases 0.31 and 0.25 respectively when people get old.

Zioupos (1998) concluded the aging induced the weakness of structure and mechanical property of bone and consequently, the elderly can be injured easily with the similar impulse. Carpo (1998) announced the rib cage of older people becomes harder. Kent (2005) analyzed the NASS-CDS and FARS concluded that 47.3% of the elderly group were killed due to the thoracic injury compared to 24.0% of mid-aged group. NHTSA (2007) followed the statistical data about frontal crashes in NASS-CDS from 1993 to 2004 and announced thoracic injuries of the elderly were doubled than that of the non-elderly that in frontal crash. Especially, among the cases with MAIS 4, thoracic injuries rank second to head injuries. Kent (2005) also reported that not only the thoracic shape but also the material property of bones is the major element by examining the reconstructed CT images. NHTSA (2009) continued to study thoracic injuries among older motor vehicle occupants. In this study, NASS-CDS for the years 1998 to 2007 was used to measure the relationship between occupant's age and the incidence of thoracic injuries. It demonstrated that the age group 75 and older (75+) had a higher percentage of AIS moderate or more sever (2+) thoracic injuries when driving or riding in any passenger vehicle type compared to three other age groups in a tow-away crash. Hong et al. showed the injury characteristics of the Korean elderly based on real world crash data in frontal, lateral, and rear impact, and reported thoracic injury is the most vulnerable to the elderly drivers. Stitzel (2010) attempted the first quantitatively estimated mortality age thresholds for common isolated thoracic injuries through the receiver-operator characteristic analysis based on the data of selected AIS 3+ thoracic injuries in NASS-CDS (2000-2008).

The objective of this research is to provide the information on injury characteristics of Korean elderly drivers in real world car accidents through the analytical and integrated approach in Figure 2.

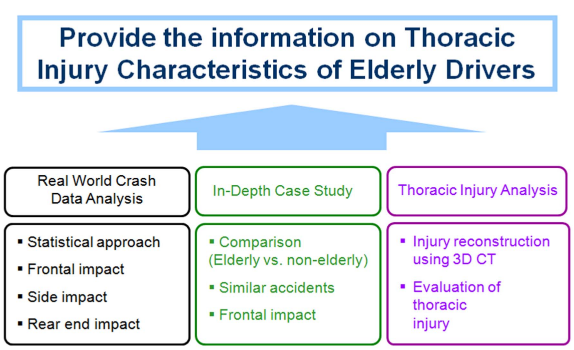

Figure2. Scope of this study

METHODS

While previous researches focus mainly on figuring out the differences of an occupant injuries by age, crash type, injury type, etc based on the database, this research focused on performing the in-depth study more in detail by comparing several pairs of similar real world accidents involving the elderly and the non-elderly drivers in the same accidents in terms of vehicle model, crash type, severity, and damage. Moreover, the examination of thoracic injury characteristics was made using CT images.
In this study, there are three progress made:

- Real world crash data analysis
- In-depth case study
- Thoracic injury analysis

Firstly, the claims from an automotive insurance company in South Korea for the years 2000 to 2008 were statistically investigated to analyze the relationship between occupant’s age and the incidence of the injuries in the different accident types such as frontal, side, and rear collisons. Secondly, several pairs of similar frontal impact accidents were extracted from the data source with respect to vehicle model, crash type, restraint device, and vehicle damage. The related medical treatment records were also reviewed and matched to severity and vehicle damage.
Finally, the thoracic injuries of the elderly driver were analyzed by reconstructing CT images to 3D model.

Real world crash data analysis

Based on the comprehensive claim data (2000- 2008) from an automobile insurance company in South Korea, the statistical analysis was conducted to investigate the injury trend on the elderly group compared to the other age group. Total 65,126 cases in three crash directions were included according to the following criteria from 2000 to 2008; frontal (26,057 cases, 2000-2007), side (5,583 cases, 2007-2008), and rear (33,486 cases, 2000-2008).

- car-to-car (except multiple crashes)
- sedan and sport utility vehicle
- not minor vehicle damage

Age groups under 24, 24 to 54, 55 to 64, and over 65 were compared by body region. Z-test was done to verify significance level.

In-depth case study

Among the database in the statistical analysis above, some cases were extracted with respect to vehicle model, damage type, and driver's age. And each case was collected by analyzing the accident reports. For the in-depth real world crash analysis, the specific cases were extracted from the previously collected dataset as following criteria;

- same target vehicle
- similarity of CDC code and delta-V
- comparative driver(elderly and non-elderly) in the same vehicle model

CDC (Collision Deformation Classification) and AIS (Abbreviated Injury Scale) were used as a measurement of the depth of vehicle damage and occupant's injury respectively.

Thoracic injury analysis

Generally, two-dimensional CT (Computer Tomography) images are used to analyze the injury of internal organs and hemorrhage, but are not accurate and limited to investigate bone fractures in detail. Therefore, three-dimensional reconstruction method is utilized to recreate 3D computer model from 2D CT images. By looking into the trace that rib fractures occurred, the cause of injury can be inferred.

In this study, the further investigation on injury characteristics was conducted using MIMICS (3D reconstruction software) with CT images of the elderly patients in car accidents as shown in Figure 3.

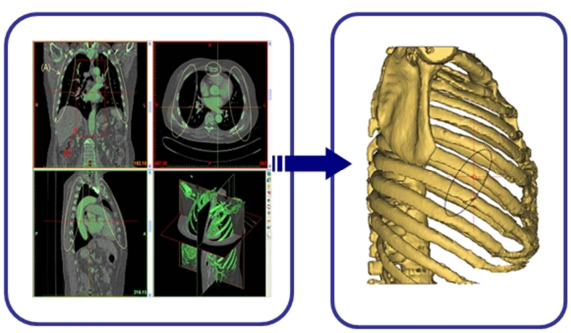

Figure3. 3D Reconstruction of rib fractures using CT images

RESULTS

Real world crash data analysis

Frontal collisions Figure 4 shows the distribution of the normalized injury incidence rate by body region. Assumed that the number of injuries of the middle age group between 24 and 54 is 1.0 as relative index, the numbers of injuries of the other age group were normalized. Distribution of normalized index in Figure 4 means the similar incidence rate in most of body parts except in thorax. The age effect caused about 2.6 times possibility of thoracic injury of elderly occupants.

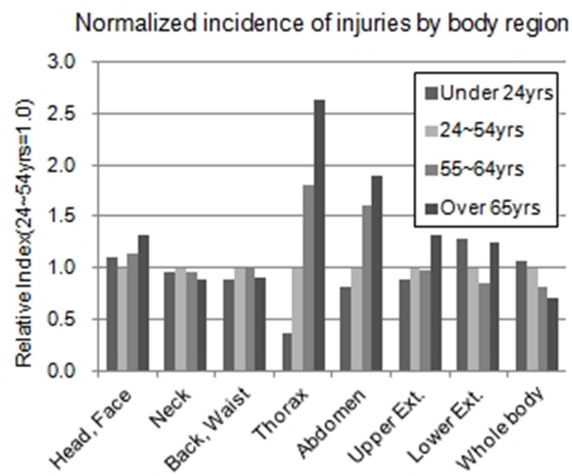

Figure4. Normalized incidence of injuries in frontal collisions

Injury severity of the thorax was also reviewed in Figure 5. Both MAIS2- and MAIS3+ injuries also increase as a driver gets old and the increase of the incident rate of MAIS3+ injuries is much higher than MAIS2- between 24-54 age group and 65+ age group.

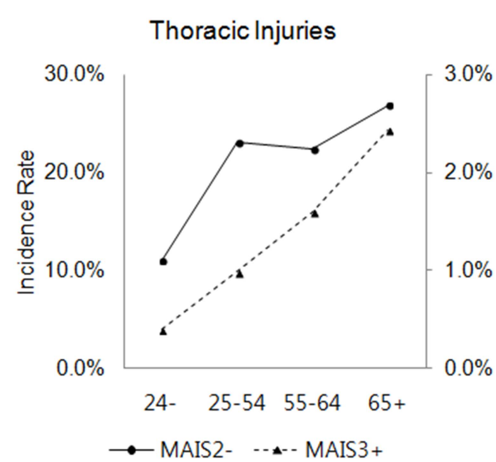

Figure5. Increase of thoracic injury severity in frontal crashes by age (p-value < 0.05)

Side collisions Similarly in frontal collisions, the incidence rate of thoracic injuries of elderly drivers is about 2.6 times than that of 24-54 year-old drivers as shown in Figure 6.

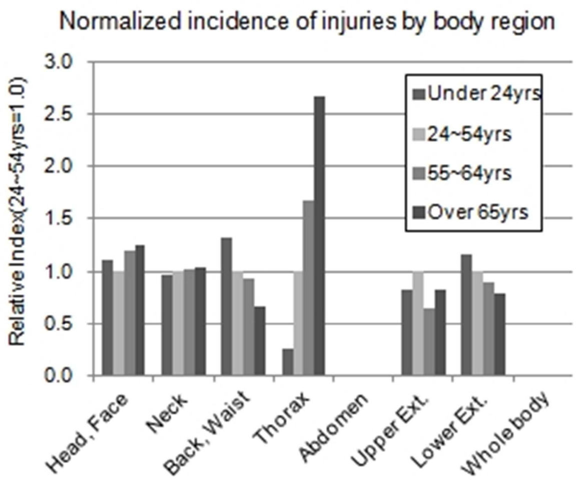

Figure6. Normalized incidence of injuries in side collisions

Different from the incidence rate in frontal crashes, MAIS3+ injuries has a significant increase from 17% to 50% while MAIS2- under 1.2%. This demonstrated when lateral crashes occur, the thoracic injury of the elderly driver become severe.

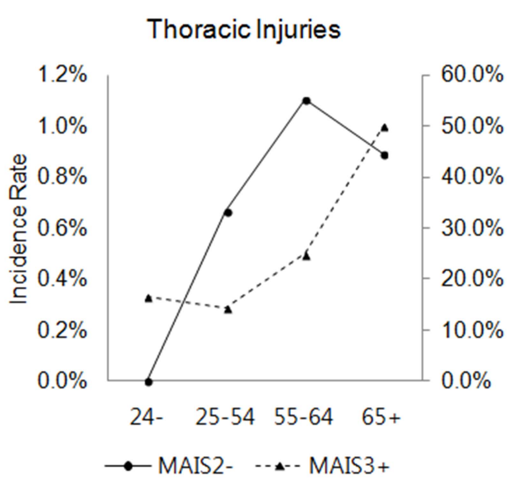

Figure7. Change of thoracic injury severity in side crashes by age (p-value < 0.05)

Rear collisions In rear collisions, the age effect doesn't show the significance except thorax. Relative index shows most of injuries in other body parts are similar while thoracic injuries get much higher by 4.7 times. Over 55 year-old drivers is much vulnerable to the thoracic injuries.

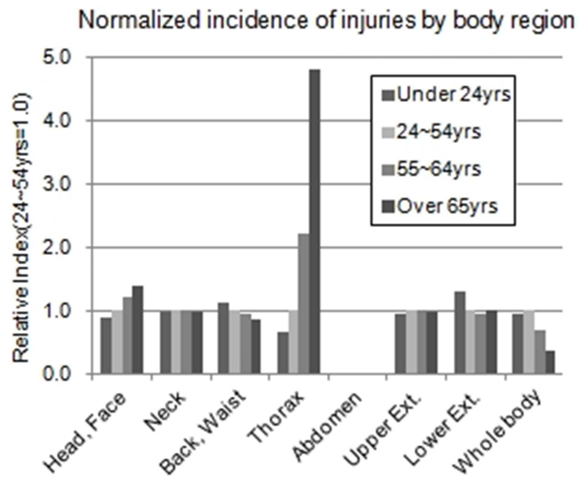

Figure8. Normalized incidence of injuries in rear collisions

In Figure 9, the incidence rate of MAIS2- thoracic injuries is very low (under 1%), however, that of MAIS3+ thoracic injuries go up to 22% from 7%.

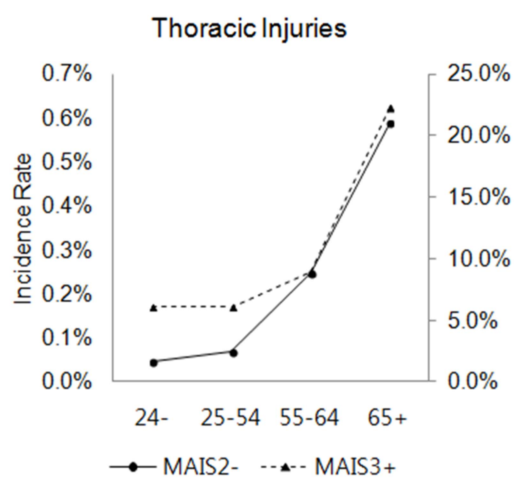

Figure9. Change of thoracic injury severity in rear crashes by age (p-value < 0.05)

In-depth case study

In this step, thoracic injuries in frontal collisions were considered. Table 1 presents the general information of vehicles (vehicle type, vehicle damage type) and drivers (age, sex, airbag deployment, major injured body region, maximum AIS, hospitalization period). Overall, the most severe injury of 5 elderly drivers was thoracic injuries with rib fractures (MAIS3+) in all cases while other drivers suffer minor neck injuries or no injury. All occupants wore seat belts and airbag was deployed in only case 4.

Table1.
Information of vehicles and drivers used in the in-depth case study

No	Type	CDC	Age	Sex	Airbag	Body	MAIS	Period*
1	Sedan	12FDEW3	65	M	×	Thorax	3	43
			42	M	×	Neck	1	25
2	Sedan	01FREW2	65	M	×	Thorax	3	45
			57	M	×	Neck	1	6
3	SUV	12FDEW2	67	M	×	Thorax	3	107
			33	M	×	None	0	0
4	Sedan	01FREE2	66	M	○	Thorax	1	8
			22	M	○	None	0	0
5	Sedan	11FLEE3	70	M	×	Thorax	2	17
			47	M	×	Neck	1	11

* Hospitalized period
** All drivers were buckled.

Case 1 Two small sedans were impacted in a longitudinal direction and got similar damages as seen in Figure 10. Two sedans have 12FDEW3 CDC code

Figure10. Comparison of vehicle damage (Case 1)

Table 2 presented the detailed injury type and severity by body part. There were multiple rib fractures with lung contusion in thorax and liver and skin contusion in abdomen. Maximum AIS was 3 of the older driver in Case 1. However, there were multiple minor injuries (MAIS 1) in face, spine, upper and lower extremities reported for the younger driver in the similar accident.

Table2.
Medical records in Case 1 (65 year-old driver vs. 42 year-old driver)

Driver's age: 65 year-old		
Body	Injury	AIS
Thorax	Rt. Multiple Rib Fr. with Flail	450211.3
Thorax	Rt. Hemothorax	442200.3
Thorax	Lung Contusion	441402.3
Abdomen	Liver Contusion	541810.2
Face	Skin Multiple Laceration	210600.10553
Face	Rt. Eyelid Laceration	210600.10155
Abdomen	Skin Contusion	510402.1

Driver's age: 42 year-old		
Body	Injury	AIS
Face	Skin Contusion	210402.1
Face	Skin Abrasion	210202.1
Spine	Neck Spine Strain	640278.1
Upper Ex	Rt. Hand Skin Contusion	710402.1
Upper Ex	Rt. Hand Skin Abrasion	710202.1
Lower Ex	Knee Joint Sprain	874010.1
Lower Ex	Knee Contusion	810402.1
Lower Ex	Knee Abrasion	810202.1

Case 2 In Case 2, there was 91FREW2 CDC code in each sedan, and likewise the older driver had MAIS 3 injury in thorax while the younger driver minor contusion in head and spine.

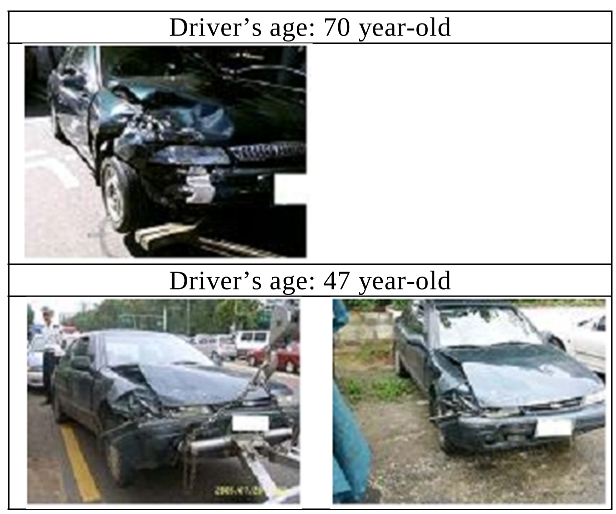

Figure11. Comparison of vehicle damage (Case 2)

Table3.
Medical records in Case 2 (70 year-old driver vs. 47 year-old driver)

Driver's age: 70 year-old		
Body	Injury	AIS
Thorax	Rt. 8-10 Rib Fractures	450203.3
Lower Ex	Pelvic Ring Fracture	856161.3

Driver's age: 47 year-old		
Body	Injury	AIS
Head	Cerebral Concussion	161000.1
Spine	Neck Spine Strain	640278.1
Spine	Lumbar Spine Strain	640678.1

Case 3 Figure 12 and Table 4 presented CDC code was 12FDEW2 in SUV and the older driver suffered from MAIS 3+ cerebrum contusion, rib and sternum fractures. However, the younger driver didn't get any injury.

Figure12. Comparison of vehicle damage (Case 3)

Table4.
Medical records in Case 3 (65 year-old driver vs. 57 year-old driver)

Driver's age: 65 year-old		
Body	Injury	AIS
Head	Cerebrum Contusion	140602.3
Thorax	Rt. 3-4 Lt 1 Rib Fractures	450203.3
Thorax	Sternum Fracture	450804.2
Spine	4-5 Neck Disc Herination	650200.2
Spine	6-7 Neck Disc Bulging	650299.2
Spine	Lumbar Spine Strain	640678.1

Case 4 In each accident, both drivers were protected by airbags that mitigated the injuries (Figure 13 and Table 5). Therefore, the older driver got MAIS 1 thoracic and neck injury and the younger got no injury.

Figure13. Comparison of vehicle damage (Case 4)

Table5.
Medical records in Case 4 (67 year-old driver vs. 33 year-old driver)

Driver's age: 67 year-old		
Body	Injury	AIS
Thorax	Rt. 9 Rib Fracture	450201.1
Spine	Neck Spine Strain	640278.1

Case 5 Figure 14 and Table 6 shows another example of thoracic injuries of the elderly.

Figure14. Comparison of vehicle damage (Case 5)

Two vehicles were impacted in 11 o'clock direction with 11FLEE3 in Figure 14. Table 5 showed that the older driver got sternum fracture (MAIS 2) and minor contusion. The younger driver got neck spine strain (MAIS 1).

Table6.
Medical records in Case 5 (66 year-old driver vs. 22 year-old driver)

Driver's age: 66 year-old		
Body	Injury	AIS
Thorax	Sternum Fracture	450804.2
Spine	Neck Spine Strain	640278.1
Upper Ex	Rt. Skin Contusion	710402.1
Whole	Multiple Skin Contusion	910400.1

Driver's age: 22 year-old		
Body	Injury	AIS
Spine	Neck Spine Strain	640278.1
Spine	Lumbar Spine Strain	640678.1
Lower Ex	Rt. Cruciate ligament Sprain	874010.1
Lower Ex	Rt. Knee Contusion	810402.1

Thoracic injury analysis

In this step, the further study was performed to clarify the cause of rib fractures of the elderly drivers from the in-depth study by examining 3D model reconstructed by Mimic software using CT images.

Case 1 Figure 15 shows vehicle damage in Case 1. Mid-size sedan (MY07) was crushed in car-to-car collisions and airbag was deployed. The belted elderly driver (69 year-old man) was injured as indicated in Table 8. By examining 3D reconstruction of CT images, the cause of injury was found that his sternum and ribs were fractured along seat belt line.

Figure15. Vehicle damage (Case 1)

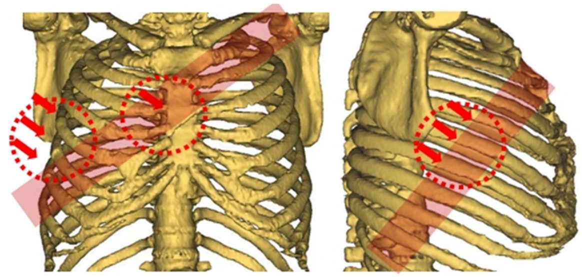

Figure16. 3D model of thoracic CT images (injured by seat belt)

Table7.
Medical records (69 year-old driver)

Driver's age: 69 year-old		
Body	Injury	AIS
Thorax	Rt. 5-7 Rib Fractures	450203.3
Thorax	Rt. Hemothorax	442200.3
Thorax	Sternum Fracture	450804.2

Table8.
Evaluation of injury severity using 3D model of thoracic CT images (69 year-old driver)

Positoin	Severity	Evaluation
Sternum	serious	AIS 3
R5	moderate	
R6	serious	
R7	serious	

Case 2 Another case is presented that SUV was damaged (Figure 17) and 75 year-old male was injured in a driver's side (Figure 18 and Table 9). He was belted and airbag was deployed. As shown in Table 10, the examination of 3D model of thoracic CT images gives the description that how rib fractures occurred and that what's the source (airbag and seat belt). 3D model provided more detailed injury characteristics of each rib cage.

Figure17. Vehicle damage (Case 2)

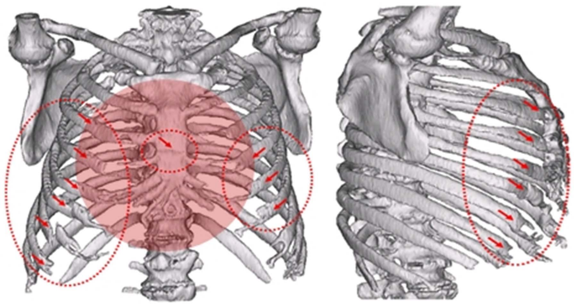

Figure18. 3D model of thoracic CT images (injured by airbag and seat belt)

Table9.
Medical records (75 year-old driver)

Driver's age: 75 year-old		
Body	Injury	AIS
Thorax	Rt. 3-8, Lt. 4-9 Rib Fractures	450203.3
Thorax	Hemothorax	442200.3
Thorax	Sternum Fracture	450804.2
Abdomen	Liver Laceration	541822.2
Lower Ex	Rt. Knee Laceration	810600.1

Table10.
Evaluation of injury severity using 3D model of thoracic CT images (75 year-old driver)

Positoin	Severity	Evaluation
Sternum	minor	AIS 3
R3	moderate	
R4	serious	
R5	serious	
R6	severe	
R7	severe	
R8	moderate	
L4	minor	
L5	moderate	
L6	moderate	

CONCLUSIONS

Through three approaches using real world crash data analysis, in-depth case study, and thoracic injury analysis, this research concluded the relationship between age and the incidence of thoracic injuries in various crash accidents as following.

(1) Thorax is the most vulnerable body region of elderly drivers. The possibility is 2.6 times higher in frontal and side impact, and 4.8 times in rear end impact.

(2) In frontal crashes, MAIS2+ thoracic injuries are prevalent (10% for under 24 age group, 27% for over 65 age group) compared to MAIS3+ (4% for under 24 age group, 2.4% for over 65 age group). Obviously, head and neck injuries are still dominant in frontal impact no matter how a driver is old, but as a driver is older, it is remarkable that the percentage of thoracic injury becomes doubled.

(3) In lateral and rear end crashes, MAIS3+ thoracic injuries increase significantly as a driver get older (up to 50% in side, 23% in rear).

(4) Total ten cases were further examined to figure out the difference of injuries of the elderly and the non-elderly in the same accidents in detail one by one. In all cases, the elderly drivers suffered from neck and thoracic injuries together while non-elderly drivers suffered from neck injuries or had no injury.

(5) 3D reconstruction using CT images was attempted for two cases in this study. 3D model can provide more detail trace or imprint of the impact exerted on rib cage. This can provide what is the source of injury accurately. Even this method is useful; the quantitative and qualitative measurement should be developed continuously.

(6) 3D model of thoracic injury can be used to evaluate and validate computational human dummy model.

(7) Seat belt and airbag should be designed to improve the protecting capability of reducing thoracic injuries in frontal collisions. For example, it can be possible by controlling the load limiter of seat belt, airbag pressure and timing, etc.

(8) Evaluation of the performance of restraint systems for the elderly should be developed as the old population grows rapidly

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ACCIDENT AND INJURY RISKS OF ELDERLY CAR OCCUPANTS

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ABSTRACT

The demographic change and the expected change in driving patterns of elderly require adoption of cars in larger scale to this group than it was the case in the past. This study focusses on the special situation of elderly as car driver (w.r.t. accident risk) and car occupant (w.r.t. injury risks).

The main data sources for this study were accident studies from the literature (mainly CCIS and GIDAS focusing on frontal impacts with newer cars), German national accident data and general literature. Based on the findings from literature possibilities for adoption of cars for elderly drivers were developed.

In addition to the accident situation additional needs of elderly w.r.t. car design and ergonomics were analysed. This analysis is also based on German national car registration statistics.

Elderly car drivers have more often accidents in situations that are complex, e.g., crossings. In addition to that reaction time seems to cause additional risks. However, it needs to be stated that elderly are a very heterogenic group w.r.t. the ability to drive a car.

Looking at the injury risks it is clear that elderly obtain more often severe injuries than younger occupants, e.g., the death rate in relation to the number of involved accidents is much higher. Looking at different body regions the main problem is associated to rip fractures.

The impact speed is almost similar to this of younger drivers excluding very young drivers.

Elderly car owners are using mainly three different groups of cars. The first group is composed of top seller cars; the second group are cars with a higher seating position that allows easier access into the car and suggests a better overview; finally premium cars are often registered for elderly.

In order to improve car safety for elderly special conditioned driver assistance systems (e.g., crossing assistant) and smart restraint systems are required.

BACKGROUND

The demographic change of our society is also an issue for the mobility behaviour. It can be stated that not only the number of people who are older than 60 years is increasing, but also that the mobility of elderly people increases. Owning a driving license is normally in this generation even for women. These factors mean that more and more elderly use a car. Consequently, two fundamental questions follow from these facts: Are there characteristics of a vehicle, which should be adjusted specifically for senior drivers, here are primarily the vehicle manufacturers asked and how must be physical limitations addressed, which are widely common for elderly people. To answer these questions it is necessary to look at specific injury risks of elderly people and to understand their behaviour in the traffic. For that an accident study was conducted. It was also investigated whether or not there are typical cars, which are preferred by senior drivers.

INJURY RISKS

The following analysis is based on German and UK national accident data and the in-depth data bases GIDAS and CCIS. GIDAS data sampling is optimised to be representative for Germany [Hautzinger, 2006] while for CCIS bias towards newer cars, more severe accidents and overrepresentation of elderly occupants is reported [Thompson, 2011].

Injury severity is coded in the national statistics as

- killed (all persons who died within 30 days after the accident as a direct result of the accident),
- severely injured (all persons who were taken to hospital immediately after the accident for medical treatment for more than 24 hours),
- slightly injured (all other injured persons),
- uninjured.

The German national data from 2011 shows that the risk of being involved in an accident decreases (by using the number of slightly injured occupants as an indicator for the number of accidents) with age but the risk of being severely injured or killed when an accident happens is increasing, see *Figure 1*.

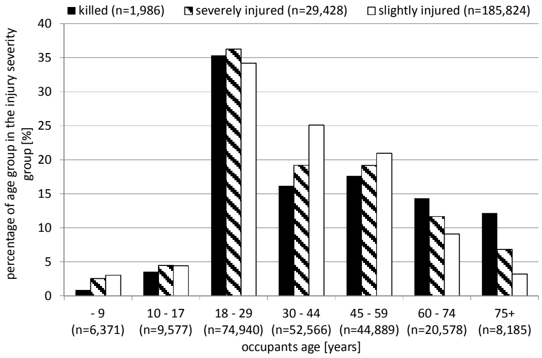

Figure 1. Injury severity dependent on age in German national accident data 2011 [DESTATIS, 2012].

The analysis of the national UK accident data of 2008 involving occupants of cars with registration data October 2003 or later shows a similar picture, *Figure 2*.

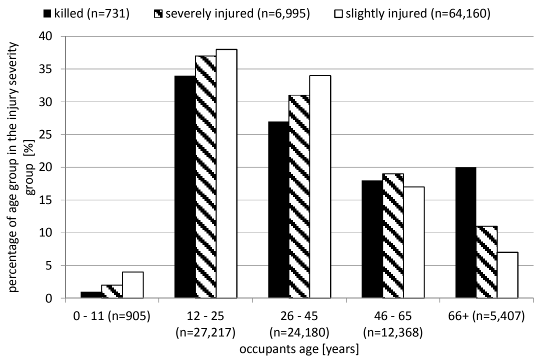

Figure 2. Injury severity dependent on age in UK national accident data 2008 (only cars with first registration October 2003 or later) [Richards, 2010].

The analysis of frontal impact accidents involving ECE R94 compliant cars also shows a higher injury risk for elderly than for younger occupants. The proportion of killed and seriously injured people is considerably larger for occupants older than 45 years compared to the younger ones, see *Figure 3*. The tendency is getting worse with age.

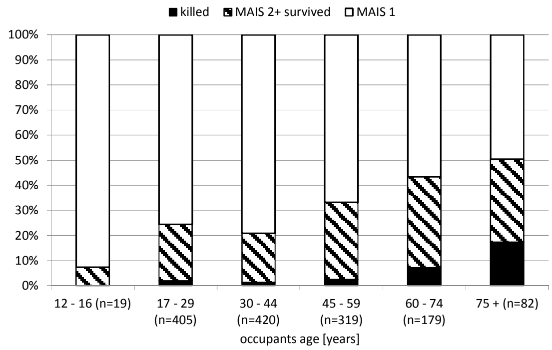

Figure 3. Injury severity dependent on age in CCIS data base, frontal impacts, ECE R94 compliant cars [Thompson, 2011].

Based on the same CCIS data set Thompson et al. [Thompson, 2012] analysed the injured body regions dependent on age. This analysis shows that for most of the body regions age seems not to influence the occurrence of AIS 2+ injuries except for chest and legs, see *Figure 4*. The decrease of leg AIS 2+ injuries with age seems not to be based on physiological differences between younger and older subjects but more a result of the individual accidents. Ridella et al. [Ridella, 2012] showed a considerably higher injury risk for legs in occupants above 75 years based on US accident data.

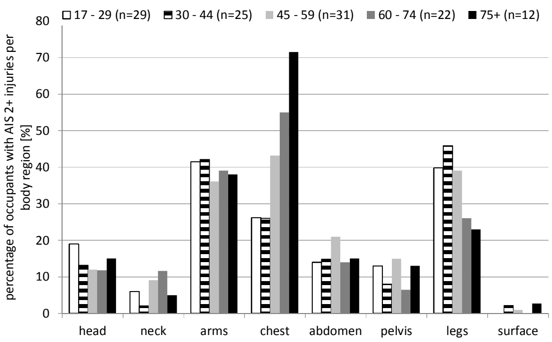

Figure 4. Injury body region dependent on age, CCIS data base, frontal impacts, ECE R94 compliant cars [Thompson, 2011].

In contrast, the considerable increase of chest injuries can be explained with physiological developments while aging. The bone structure changes its mechanical properties and becomes brittle with age [Hardy, 2005]. The hypothesis can be confirmed when looking more in detail into the chest injuries. Especially the risk for rib fractures and sternum fractures increases with age, see *Figure 5*.

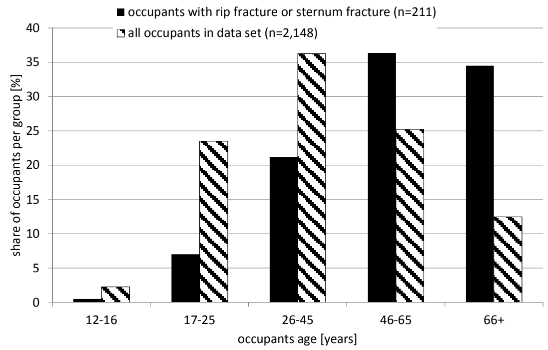

Figure 5. Share of occupants with rip fractures or sternum fractures dependent on age, CCIS frontal impact data involving cars with first registration date 2000 or later [Carroll, 2009].

Chest injuries are mainly caused by contact with the restraint systems (belt, airbag) – in contrast to injuries caused by intrusion. Following that it appears as expected that the injury causation by restraint system increases for occupants with an age above 45, see ***Figure 6***. It is important to note that „injury caused by restraint system" does not mean that the injury risk would be lower without restraint system but that it can be expected that the injury severity could be reduced by improvements of the restraint system or the cabin pulse.

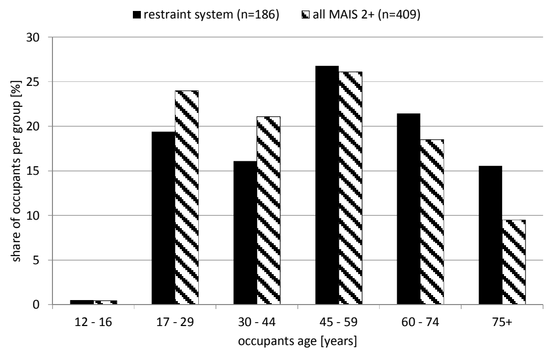

Figure 6. Injury caused by contact to the restraint system dependent on age in comparison to all MAIS 2+ injuries, CCIS frontal impact data involving ECE R94 compliant cars [Thompson, 2011].

Otte et al. [Otte, 2012] compared the occurrence of rib fractures between younger (17 to 30 YO) and elderly (50 years old or older) belted drivers in car-to-car or single car accidents. GIDAS data of the years 1999 to 2009 were used. The risk for sustaining chest injuries and in particular rib fractures or sternum fractures is significantly dependent on age. Rib fractures and rib series fracture already occured with an delta-v of 31 – 40 km/h in the 50+ group while these injuries were observed in the younger control group with delta-v exceeding 51 km/h, see ***Figure 8***.

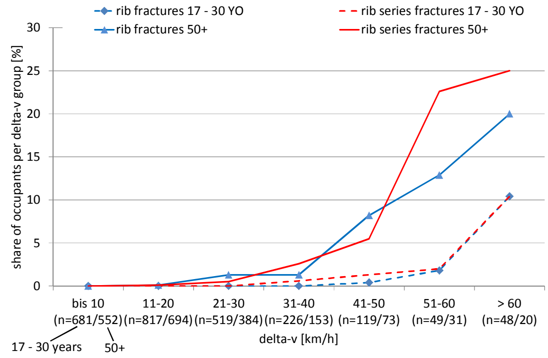

Figure 7. Comparison of the risk for rib fractures dependent on delta-v and age, GIDAS data 1999-2009, belted drivers [Otte, 2012].

Kent et al. [Kent, 2003] analysed the risk for rib fractures and rib series fractures (fracture of seven or more ribs) dependent on the chest compression (relative deflection) and came to similar results. The 50th percent rib fracture risk for 30 years old is related to approx. 35% chest compression while it is approx. 13% for 70 YO, see ***Figure 7***. If the chest compression limits are transferred to Hybrid III 50%ile male dummy they would correspond to 80 mm for the 30 YO and 30 mm for the 70 YO, respectively. The rib deflection limit is today 50 mm in Europe and 76.2 mm in the US.

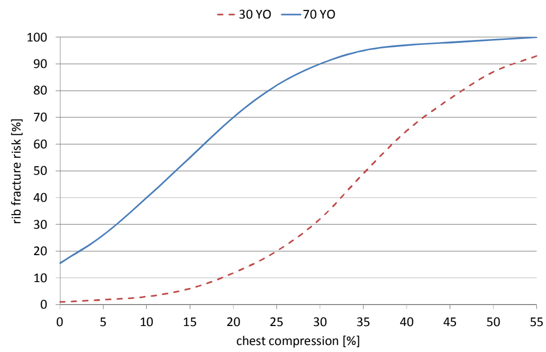

Figure 8. Comparison of rib fracture risk for 30 YO and 70 YO dependent on chest compression [data according to Kent, 2003].

In summary the injury risk increases with age which is mainly caused by physiological changes of the bones to which the restraint system cannot be adequately adjusted to. The main difference between elderly and younger can be seen for the risk for rib fractures.

TYPICAL ACCIDENT SITUATIONS OF ELDERLY DRIVERS

For the analysis of typical accident situation elderly drivers are involved in the German national accident data from 2010 was analysed more in detail. For the following analysis of kind of accident and type of accident it is important to note that all car drivers were counted; that means that for multiple car accidents the accident was counted multiple times. This approach increases the number of car-to-car accidents artificially. Normally the analysis of type of accident and kind of accident is done for the driver that caused the accident according to police reports only. However, for this paper it was considered to be important to count all accidents elderly driver are involved in without concentrating on the "faulty" driver. Following that the overrepresentation of car-to-car accidents was accepted. Kind of accident and type of accident allow looking for critical situations depending on age. The kind of accident describes of the entire course of events in an accident the direction into which the vehicles involved were heading when they first collided on the carriageway or, if there was no collision, the first mechanical impact on a vehicle. The following 10 kinds of accidents can be distinguished [DESTATIS, 2011a]:

1) Collision with another vehicle which starts, stops or is stationary.
   - Starting or stopping are here to be seen in connection with a deliberate stopover which is not caused by the traffic situation. Stationary vehicles within the meaning of this kind of accident are vehicles which stop or park at the edge of a carriageway, on shoulders, on marked parking places directly at the edge of a carriageway, on footpaths or parking sites. The traffic to or from parking spaces with a separate driveway belongs to No. 5 kind of accidents.
2) Collision with another vehicle moving ahead or waiting.
   - Accidents caused by a rear-end collision with a vehicle which either was still moving or stopping due to the traffic situation. Rear-end collisions with starting or stopping vehicles belong to the No. 1 kind of accidents.
3) Collision with another vehicle moving laterally in the same direction.
   - Accidents occuring when driving side by side (sideswipe) or when changing lanes (cutting in on someone).
4) Collision with another oncoming vehicle.
   - Collisions with oncoming traffic, none of the colliding partners having had the intention to turn and cross over the opposite lane.
5) Collision with another vehicle which turns into or crosses a road.
   - This kind of accident includes collisions with crossing vehicles and with vehicles which are about to enter or leave from/to other roads, paths or premises. A rear-end collision with vehicles waiting to turn belongs to the No. 2 kind of accidents.
6) Collision between vehicle and pedestrian
   - Persons who work on the carriageway or still are in close connection with a vehicle, such as road workers, police officers directing the traffic, or vehicle occupants who got out of a broken down car are not considered to be pedestrians. Collisions with these persons are recorded under the No. 10 kind of accidents.
7) Collision with an obstacle in the carriageway.
   - These obstacles include for instance fallen trees, stones, lost freight as well as unleashed animals or game. Collisions with leashed animals or riders belong to the No. 10 kind of accidents.
8) Leaving the carriageway to the right or left.
   - These kinds of accidents do not involve a collision with other road users. There may however be further parties involved in the accident, e.g. when the vehicle involved in the accident veered off the road trying to avoid another road user and did not hit him.
9) Accident of another kind.
   - This category covers all accidents which cannot be allocated to one of the kinds of accidents listed before.

*Figure **9*** shows that especially crossing situations are challenging/risky for elderly drivers. The share of the kind of accident „collision with another vehicle that turns into or is crossing a road" significantly increases with age and is the kind of accident being most relevant for elderly. Furthermore "collisions with pedestrians" also occur more often with elderly drivers but the absolute numbers are relatively low. For collisions with vehicles that are driving in the same or opposite direction elderly drivers are underrepresented. However, in absolute numbers collisions with vehicles that are moving ahead or are waiting is also relevant for elderly.

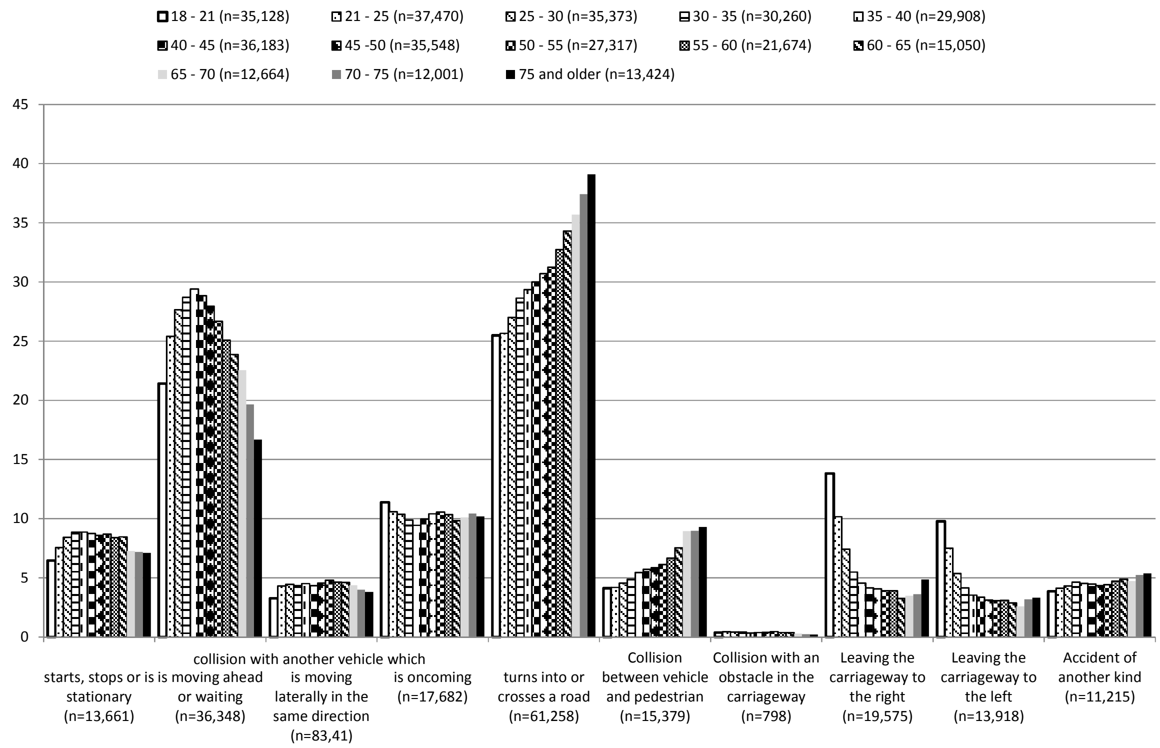

Figure 9. Kind of accident dependent on drivers age (multiple counting for car-to-car accidents).

The type of accident describes the conflict situation which resulted in the accident, i.e. a phase in the traffic situation where the further course of events could no longer be controlled because of improper action or some other cause. Unlike the kind of accident, the type of accident does not describe the actual collision but indicates how the conflict was touched off before this possible collision. The determination of the type of accident also plays an important role for local accident analysis since the type of accident is marked by coloured pins on the maps of the local police authorities. The following seven types of accidents are distinguished [DESTATIS, 2011a]:

1) Driving accident
   - The accident was caused by the driver’s losing control of his vehicle (due to not adapted speed or misjudgement of the course or condition of the road, etc.), without other road users having contributed to this. As a result of uncontrolled vehicle movements, however, a collision with other road users may have happened. A driving accident however does not include accidents in which the driver lost control of his vehicle due to a conflict with another road user, an animal or an obstacle on the carriageway, or because of a sudden physical incapacity or a sudden defect of the vehicle. In the course of the driving accident, this vehicle may collide with other road users, so that this is not necessarily a single vehicle accident.
2) Accident caused by turning off the road
   - The accident was caused by a conflict between a vehicle turning off and another road user approaching from the same or opposite direction (incl. pedestrians) at crossings, junctions and entries to premises or car parks. Whoever follows the priority turn of a main road is not considered as turning off.
3) Accident caused by turning into a road or by crossing it
   - The accident was caused by a conflict between a road user turning into a road or crossing it and having to give way and a vehicle having the right of way at crossings, junctions, or exits from premises and car parks.
4) Accident caused by crossing the road
   - The accident was caused by a conflict between a vehicle and a pedestrian on the carriageway, unless the pedestrian walked along the carriage-way and unless the vehicle turned off the road. This applies also where the pedestrian was not hit by the vehicle. Even if the pedestrian who caused the accident was not hit, the accident is classified as caused by crossing the road. A collision with a pedestrian walking along the carriageway is recorded as a No. 6 type of accident.
5) Accident involving stationary vehicles
   - The accident was caused by a conflict between a moving vehicle and a

parked/stopping vehicle or a vehicle manoeuvred in connection with parking/ stopping. Accidents with vehicles waiting just because of the traffic situation are not included.

6) Accident between vehicles moving along in carriageway
   - The accident was caused by a conflict between road users moving in the same or opposite direction, unless this conflict belongs to a different type of accident.
7) Other accident
   - This includes all accidents that cannot be allocated to any other type of accident. Examples: U-turning, reversing, accidents between parked vehicles, obstacle or animal on the carriageway, sudden failure of the vehicle (brake failure, defective tyre, etc.).

When analysing the type of accident dependent on age the absolute and relative high number of "accident caused by turning into a road or by crossing it" is remarkable, see *Figure **10***. Accidents caused by turning off the road are also increasing with age but with much lower extend than the before mentioned type.

For the accident type "crossing accidents" there is a slight increase of the share of accidents with age, see *Figure **10***. However, the increase is smaller than it was expected based on the distribution of kind of accident "collision between vehicle and pedestrian". The other pedestrian accidents are likely included in the accident type "accident caused by turning off the road".

Driving accidents are mainly an issue for younger drivers as expected after the analysis of the kind of accident "leaving the road to the left or right".

Accidents with vehicles that are traveling in the same or opposite direction involve less elderly drivers than younger ones. This was also expected because of the distribution of the kinds of accident.

In summary the analysis of kind of accident and type of accident shows two important deficits for elderly drivers. These are

1) the correct perception of complex traffic situation (e.g., in crossings)
2) slower reaction time, as shown for example in the distribution of pedestrian accidents

In general these findings are supported by literature and also by the analysis of mistakes causing accidents.

According to Chaparro et al., [Chaparro, 2005], Staplin et al. [Staplin, 1998] and Weller et al. [Weller, 2008] elderly drivers often suffer from problems in situations that require divided attention. Being focused on one task is especially in complex situations an issue.

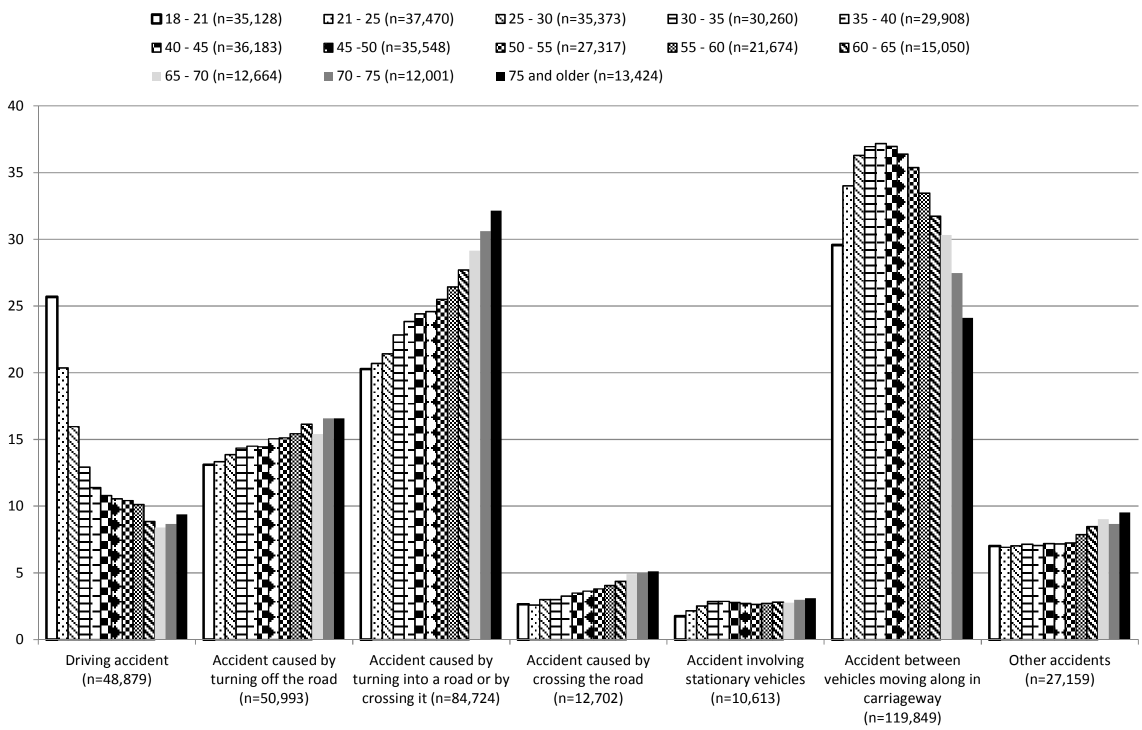

Figure 10. Type of accident dependent on drivers age (multiple counting for car-to-car accidents).

Reaction time between younger and elderly probands was analysed by Eder [Eder, 2005]. In average the reaction time of elderly was considerable longer in laboratory experiments and in driving trials.

However, it is important to note that the performance of elderly based on the literature mentioned above is very heterogenic. That means while the younger control group performed very equally for the elderly a large spread was observed. In general being old with respect to the mental capabilities to drive a car cannot be counted in years. It is more an issue of mental fitness than of actual age.

When looking into the cause of accidents for elderly drivers the main issues are right of way as well as turning, U-turns, reversing, pull-into the traffic, start-up (*Figure **11***). In addition fitness to drive without alcohol problems was detected more often for elderly than for others. However, this cause of accident is very seldom.

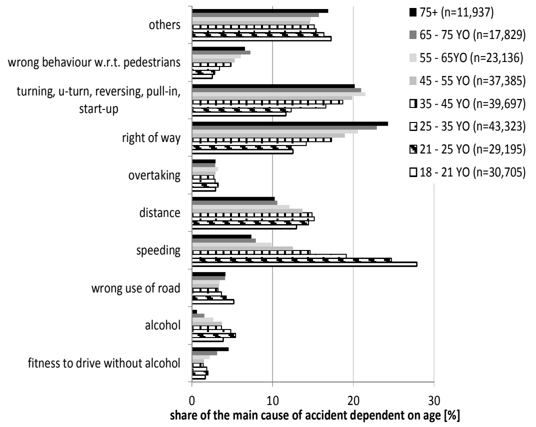

Figure 11. Accident causation dependent on age [DESTATIS, 2011b].

In order to achieve a more complete picture of the accident circumstances the time of accident and the location of accident are analysed in a last step. Elderly people seem to focus their time in traffic more than others to the time between 9:00 and 19:00 (*Figure **12***). Between 0:00 and 6:00 seniors are almost not present in accidents. The same is true for the time from 20:00 to 0:00. The main traffic activity time of elderly drivers appears to be the morning to early noon while for younger it is more the afternoon, evening and the night.

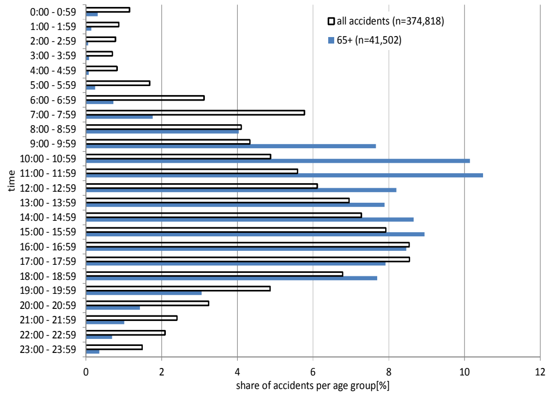

Figure 12. Time of accident in comparison between drivers with an age above 65 years and all drivers [data according to DESTATIS, 2011a and DESTATIS, 2011b].

When analysing the local distribution of accidents between elderly and younger drivers there is almost no difference for drivers with an age above 35 years, see *Figure **13***.

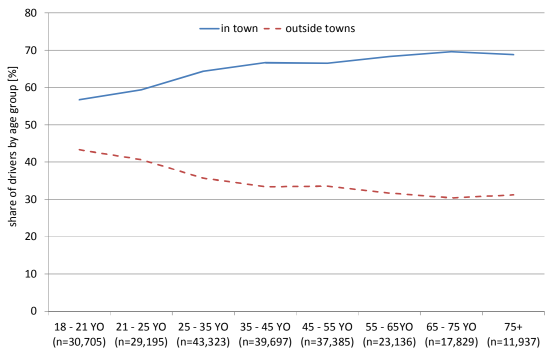

Figure 13. Location of accident in comparison between drivers with an age above 65 years and all drivers [data according to DESTATIS, 2011a and DESTATIS, 2011b].

In summary, most of the accidents involving elderly are happening inside towns in crossing situations and during daytime.

The two specific problems of elderly, complex situations and slower reaction time should be possible to be addressable by adopted driver assistance systems.

MEASURES TO ADDRESS THE NEEDS OF ELDERLY CAR OCCUPANTS

The main requirements for passive safety for European cars are defined by ECE R94 and ECE R95 as well as Euro NCAP. For frontal impact ECE R94 and Euro NCAP are currently looking into the safety performance of cars in accidents with relative high speed and moderate overlap in order to limit intrusions into the cabin. The injuries the elderly are mainly suffering from, chest injuries, appear to be more a result of large overlap accidents with high acceleration loading. Furthermore the accident severity in the Euro NCAP test is quite high. The common idea of NCAP tests that a high accident severity would protect occupants in severe and less severe accidents equally is questionable. Especially elderly occupants seem to suffer from safety systems that are designed for good protection in high speed accidents.

Historically the car safety systems improved continuously. From static two-point belt in the beginning of car safety activities restraint systems with multiple stage airbags as well as belt systems with pretensioner and adaptable load limiter are available. However, todays smart restraint systems do not consider the vulnerability of the occupant, they just take into account a prediction of accident severity and the occupant's stature and weight. One could question why it is important to consider the vulnerability of the occupant as any measure in favor of vulnerable occupants would also improve the situation for less sensitive occupants. But there is a possibility to adjust safety margins for the risk to underestimate the accident severity based on vulnerability. That means for an optimum protection of elderly it might be acceptable to minimize the safety margin in order to keep the loads within the estimated accident severity as small as possible while increasing the safety margin for younger occupants because they are able to sustain larger loads, as shown above. A possibility to detect the vulnerability of the occupant by the scanning of the bone structure was presented by Hardy et al. [Hardy, 2005].

Furthermore it seems to be important to adjust the test severity and the dummy limits to the accident situation of elderly and the vulnerability of elderly. The limits of today seem to be more appropriate for younger occupants which was historically correct, as most of the car occupants were of this group. With the changing mobility pattern of elderly adjustments are necessary. However, the requirements for the passenger compartment integrity may not be compromised in while addressing the needs of elderly. ECE R94 and Euro NCAP had a very good influence on passive safety. That means that an additional test would be required, i.e. a full frontal test.

In addition to passive safety measures the adoption of driver assistance systems to the individual driver's needs is important. Driver assistance system can only exploit their maximum active safety performance if they are supporting the driver at an appropriate time. When warning or intervening to early they are becoming annoying for the driver and when acting too late the safety benefit is marginal. As individuals have different needs it is important to assess the individual needs of the driver in order to adopt the system. Especially the braking assistant system and a crossing assistant system are systems that are believed to have high benefit for elderly when they are adjusted.

Current Situation and Discussion Concerning Car Homologation

ESP and braking assistant system are already included in the legal framework. From 2014 all newly registered vehicles need to be equipped with ESP and from 2015 with braking assistant system, respectively.

The Informal Group on Frontal Impact of GRSP is working since 2008 on the development of a new frontal impact regulation. In the 2011 terms of reference of this group is asked to address amongst others an improved protection of elderly [GRSP, 2012]. This shall be achieved by the introduction of a full width restraint system test. However, it seems that the test speed will be fixed to 50 km/h. From the accident data mentioned above and the discussion concerning adjustable safety margins for different age groups a lower test severity might be appropriate.

VEHICLE SELECTION OF ELDERLY AND THEIR REQUIREMENTS

Even if the group of elderly drivers increases, and thus a customer group with certain needs, there is no car manufacturer who advertises directly with age-appropriate vehicles. Simply because of image reasons those "elderly peoples' cars" could not be sold well. Nevertheless, it is reality that most manufacturers offer vehicles, which are bought particularly by elderly and which obviously provide certain qualities that are important for them.

When looking into the statistics of the vehicle fleet in Germany and the age of the holder a clear preference of certain vehicle models becomes visible. For vehicle owners who are 60 years or older, on the one hand, the classic volume models from German manufacturers like VW Golf, Mercedes C-Class, Opel Astra and Audi A4 are strongly represented, on the other hand the small car segment (minis and super minis) with the Renault Clio, Opel Corsa and VW Polo plays an important role. A third category includes vehicles with a high seating position and a corresponding high entry. These cars are also very frequently represented (VW Golf Plus, Opel Meriva, Mercedes Class A) (Figure 14).

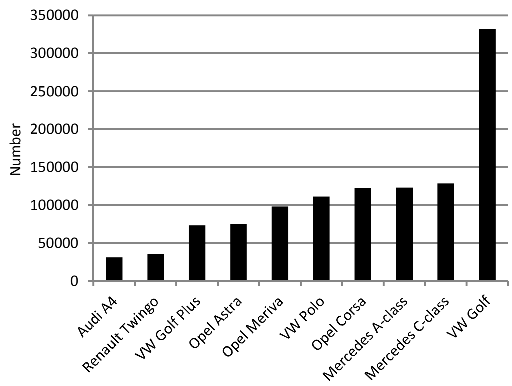

Figure 14. Most popular cars for holders with an age of 60+ [KBA, 2012].

Obviously, some vehicle models are very popular for customers who are 60 years or older. In Figure 15, vehicles are shown, where at least two-thirds of the holders are seniors. There are models included, which are practically because of their construction and size, but which find possibly less attention for younger customers because of their design. Furthermore, models are represented, who belong to the higher price segment (Mercedes C and E Class). Also well represented are vehicle models with a high seating position (Renault Modus, Renault Scenic, Mercedes B Class, Golf Plus, Citroen Xsara Picasso, Renault Megane Scenic).

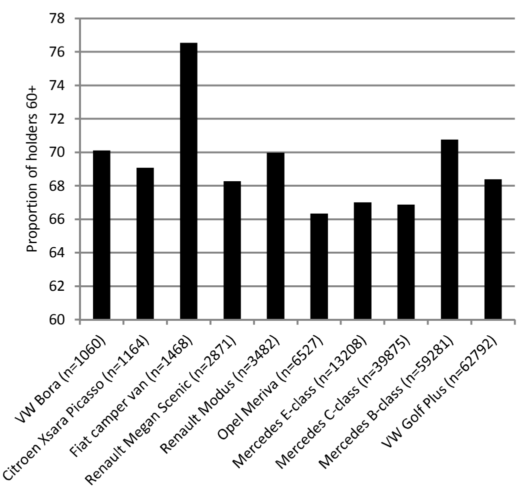

Figure 15. Vehicle models with at least 66% car holders 60+ [KBA, 2012].

With the elevated seating position generally a larger doorway and also a large angle of door opening is associated. These aspects allow a more convenient entry and exit also with limited mobility. Simultaneously the visibility out of the vehicle is improved.

The requirements for a senior-friendly car go far beyond a proper seating position. In addition to a good circumferential visibility, which should also be available with limited freedom of movement, all interfaces between driver and car should be designed in a way that they are easy to use and that they do not distract attention from the road. This means for all drivers, but especially for older drivers that operating devices should be designed large and to be easy available. Instrument readings and displays must be easy to read; the menu from the on-board computer should be intuitive and comprehensible [DVR, 2009]. Especially for driver assistant systems it is important that the messages a clear and the letters are large enough and with good contrast [Bunji, 2006]. If this is not the case the risk coming from distraction might be higher than the benefit. Furthermore an easy accessibility of the trunk and a bright headlight were mentioned as useful car equipment by elderly people.

In general, equipment, that is popular with seniors, is usually not disadvantageous for younger drivers. For example, the elevated seating position is well accepted by women and ergonomic arrangement of the controls is also welcome for younger drivers.

CONCLUSIONS

Elderly car occupants are at lower risk to be involved in accidents but when they are involved they have a considerably higher risk to be severely injured or killed than younger car occupants. The main difference in the vulnerability is coming from the chest fragility. Restraint systems that are better adjusted to the chest injury risk of elderly are expected to reduce the injury risk.

Elderly drivers are mainly involved in accidents that are occurring in complex situations (e.g., crossings). Driver assistant systems (especially a crossing assistant) would help to address the assistant needs of elderly drivers if their alarming and intervening levels can be adjusted to the individual driver.

There are three car categories that are especially of interest for elderly car owners in Germany. These are cars with a high seating position like MPVs, Vans and SUVs, small cars and high volume models. In addition the share of elderly owners for high price models is often also relatively high.

ACKNOWLEDGEMENTS

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SEATBELT POSITIONING DURING PREGNANCY

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ABSTRACT

The objective of this study is to investigate correct seat belt use rates in pregnancy. A structured questionnaire study was centred at the antenatal clinic in Luton and Dunstable Hospital NHS Trust together with Loughborough University in the UK. In addition further responses received via the Internet. Questionnaire responses from the UK were from pregnant women into their 6 to 40+ of pregnancy. Through the website further responses were also received from North America. The women were asked about their use of seat belts and specifically how the shoulder and lap portions of the 3-point seatbelt were positioned. Women were also asked about their experiences about using airbags and head restraints whilst pregnant.

The responses about seatbelt use in pregnancy were analysed and the main safety concerns are found to be low levels of correct seatbelt positioning. Seatbelt use in pregnancy is high in the UK, however less than 13% of the seatbelt users had correctly positioned both portions of the belt. The rate of seatbelt and correct seat belt use in the North American countries is lower than UK.

The research will be extended and a world-wide study will be conducted through collaboration with researchers and motor manufacturers globally to investigate the needs and requirements of pregnant occupants as passengers and drivers.

INTRODUCTION

A report from the Office for National Statistics [1] states that UK women make an average 613 trips per year by car, which is similar to men. According to [2], women in the UK travels 4,573 miles a year on average. Women of childbearing age travel by car more often than men, and during pregnancy women have different travel patterns and preferences due to alterations to their physical form and emotions.

Pregnancy causes wide ranging changes in size and shape that are not limited to the abdomen. The hips and breasts also enlarge greatly in size [3]. Investigation into the safety of using the seat belt in pregnancy has established that the seat belt should be used in pregnancy [4], and that a three-point belt is preferable to a lap only belt [5], [6]. Use of the seat belt in the correct position is also important to minimize the risk of injury to the fetus. The correct positioning has been adopted by current guidelines by the UK Department for Transport [7] and the National Highway Traffic Safety Administration in the USA [8], stating that '*the lap strap should go across the hips, fitting comfortably under the bump, while the diagonal strap should be placed between the breasts and around the bump'* as demonstrated in Figure 1.

In the UK alone there are 750,000 pregnancies each year [9]. The "Automotive Design: Incorporating the Needs of Pregnant Women" project has addressed issues such as seatbelt safety, travel patterns, behaviours, needs and preferences in a holistic manner for the first time and provides explicit information about pregnant women. The project
provides a comprehensive analysis of lap and shoulder belt positioning used by pregnant women, as the correct placement of the lap and shoulder sections simultaneously could help the seat belt to function as intended. During this project have been collected data from women around the world; however this paper focuses on the needs of the UK-based pregnant women only.

METHOD

Pregnant respondents answered a 'Pregnancy and Driving Questionnaire' in an interview or by self-completion. The questionnaire was also available for online completion. This Questionnaire can be found at http://pregnantdriver.lboro.ac.uk in five languages (English, Spanish, Italian, Turkish and French). 243 sets of questionnaire responses from the UK had been processed and reported in this article. Respondents were reminded repeatedly to compare their pre-pregnancy experiences with their experiences during pregnancy. Questions about all aspects of car travel both as drivers and as passengers were included in the questionnaire. The questions regarding seatbelts were particularly designed to understand the level of 'correct usage' of these systems. The average gestation levels of the pregnant women recruited to this study was 29.5 weeks. The majority of these women normally occupy the driver's seat, and occasionally use the front or rear passenger seats, and in a few cases the normal occupant position is unknown. Throughout this paper the data analysis refers only to this sample of UK based pregnant women.

Figure 1. **A pregnant woman demonstrating the correct wear of the 3-point seatbelt**

RESULTS

Using the Seatbelt & Correct Positioning

It is a legal requirement in the UK to wear seatbelts both as drivers and passengers [10]. Pregnant women are not exempt to this rule [7]. Only 6 of the 286 did not wear their seatbelt that is 98% of the UK pregnant women in this sample used their seat belt during car travels. Among those, 243 of the women completed the Questionnaire fully to provide us with detailed description of the way they wear their seatbelts (Table 1). Table 1 also shows the percentages for the shoulder and lap section wearing style combinations. In the Table red numbers show the incorrect and the blue numbers represent the correct positions defined by the Department for Transport [7] for the two sections of the 3-point seatbelt. The correct wear of the seatbelt during pregnancy is wearing the shoulder section of the seatbelt, between the breasts and around the abdomen, and the lap section across the hips underneath the abdomen (simultaneously).

The data reveals that slightly more than half of the pregnant women position the shoulder section of the seatbelt correctly and only about quarter of the sample position the lap section correctly (Table 1). These rates however include incorrect usage of the complementary section of the 3-point seatbelt.
The seatbelts are designed to protect the car occupants when they are used 'correctly' not necessarily 'correctly in part'. When the entire seat belt positioning is considered only 31 of 243 (12.7%) of UK pregnant women simultaneously positioned both the shoulder and lap sections correctly. That means, approximately only one in eight pregnant women is properly protected by the restraint systems during travel.

This rate might seem low in comparison with previously published studies. This apparent disagreement is due to a lack of clear definition of correct seatbelt positioning in previous researchers' surveys hence clustering the correct and incorrect lap belt positions in one group. Similar mistakes were made for the shoulder belt positions in previous studies.

Many authors described the correct lap belt position as underneath the abdomen, but this does not clearly distinguish between placing the lap belt across the upper thighs (incorrect) and the correct position across the hips according to guidelines [11] of American College of Obstetrics and Gynaecology. Previous papers [12][13][14][15] report a high incidence of correct positioning such as approximately 79%, 69%, 78%, 40-66% respectively. If we combine these two categories as the previous authors did, our data similarly gives 54% (131 of 243) for correct lap portion positioning.

The papers by [12] and [16] state the shoulder belt should pass 'between the breasts' with no mention of how the shoulder belt should be placed on the shoulder. Both of these papers also give a limited range of positions for the shoulder belt. The options in these papers are: behind the back or not used, under the arm, and between the breasts.

This could mean that women who place the belt in any position across their trunk (but not under the arm) are forced to select 'between the breasts' because it is the only available option. Their correct seat belt positioning ratios of 91% and 53-68% could therefore include incorrect positions where the shoulder belt lays off the shoulder, as well as the correct position between the breasts. If we combine these two categories as the previous authors did, our data similarly gives 64% (155 of 243) for correct shoulder portion positioning. The examples could be extended further.

This shows that the surveys could be misleading if the 'correct wear' of the seatbelt is not defined properly.

Table 1. Shoulder and lap belt combinations rates of usage and percentages for UK based pregnant women

	Shoulder Belt				
	Above both breasts	Across one breast & across abdomen	Between breasts & around abdomen	Off shoulder & around abdomen	Total
Lap Belt					
Across upper thighs	10 4.1%	14 5.8%	35 14.4%	9 3.7%	68 28.0%
Across hips underneath abdomen	10 4.1%	18 7.4%	**31 12.8%**	4 1.6%	63 25.9%
Across abdomen	16 6.6%	20 8.2%	62 25.5%	14 5.8%	112 46.1%
Total	36 14.8%	52 21.4%	128 52.7%	27 11.1%	243 100%

Summary of Table 1

Correct entire belt positioning: 31 of 243 pregnant women (12.8%)

Correct shoulder belt positioning: 128 of 243 seatbelt users (52.7%)
Most common incorrect shoulder belt position:
Across one breast & across abdomen: 52 of 243 seatbelt users (21.4%)

Correct lap belt positioning: 63 of 243 seatbelt users (25.9%)
Most common incorrect lap belt positions:
Across abdomen: 112 of 243 seatbelt users (46.1%)
Flat across upper thighs: 68 of 243 seatbelt users (28.0%)

Further Issues Concerning Seat Belt Positioning

The problems of using seat belts in pregnancy and educating pregnant women for positioning the belt correctly were documented in a related study [16]. A number of further factors such as gestation, number of previous pregnancies, passenger/driver seat position, income and education levels are investigated for whether they influence how pregnant women are positioning their seat belt. The correct positioning rates for each of these factors are summarised below in Table 2.

The rates of correct seat belt positioning seemed to improve with the progression of pregnancy. The second and third trimesters were focused since most significant physical changes occur during these periods and the sample in the first trimester women was very small. The correct positioning rate is 13% in the second trimester, and 19% in the third trimester. Some women also reported that as pregnancy progresses the enlarged abdomen holds the lap belt down more securely across the hips. A trend is also revealed that women with more experience of pregnancy seem to be positioning the seat belt correctly more often. 15% of the women in their first pregnancy had the seat belt correctly positioned, but this increased to 17% in the women with 1-3 previous pregnancies and 18% for four or more previous pregnancies.

The majority of the women in our sample were drivers. There was a marked difference in the correct seat belt positioning according to the occupant position. 19% of drivers had their seat belt correctly positioned, whereas the correct positioning figures were only 3% for the front passengers. Both of rear passengers in our survey positioned their seat belts incorrectly a conclusion cannot be reached as the sample was far too small.

None of the women who had compulsory education only were positioning the seat belt correctly, but it should be noted that it was only a small sample of 5 women. The Further education group and Higher Education group represented a higher rate with 18% and 16% of correct positioning respectively.

Table 2. Variables influencing correct seat belt positioning during pregnancy.

Variable	Group	Number of pregnant women in group	Correct seat belt positioning rate
Trimester	First trimester	12	0%
	Second trimester	98	13%
	Third trimester	176	19%
Experience of pregnancy	First pregnancy	123	15%
	1-3 previous pregnancies	136	17%
	4 or more pregnancies	17	18%
Car seat normally occupied	Driver's seat	237	19%
	Front passenger seat	37	3%
	Rear passenger seat	2	0%
Education level	Compulsory education	5	0%
	Secondary/Further education	89	18%
	Higher education	181	16%

Attitudes Toward Belt Use

Respondents commonly expressed concern that the seat belt was incorrectly positioned, and 25% of the sample said they did not feel safe whilst using the seat belt. In some cases, women ceased using the seat belt due to the fear that the seat belt might harm the fetus in a collision, or due to discomfort. This also shows the importance of comfort whilst using the seat belt, since it can influence whether or not the women are using the seat belt.

A common problem was that the lap portion of the seat belt tended to ride up onto the abdomen during car travel, even after it was placed correctly across the hips at the start of the journey. Many women took action to prevent the lap belt from contacting the pregnant abdomen in order to protect the fetus or to make themselves more comfortable. Some chose to use a lap belt-positioning device to hold the seat belt in the correct position across their hips. None of these women had checked the validity of additional devices with their insurers. The other method that women used was to hold the belt away from the bump with their hands or thumbs. Similarly, women were also holding the belt away from their neck because it was cutting in and rubbing them. The women were not aware that holding the belt away could create slack in the belt and may increase the risk of injury.

CONCLUSIONS AND DISCUSSION

Most pregnant women experience a wide range of problems with driving, with using passive safety systems. The main safety concerns are with the low levels of correct seat belt and head restraint positioning. Analysis of 286 questionnaires showed that 98% of the pregnant women in the UK use their seat belt during pregnancy. It is worth noting that this group voluntarily found us and completed the questionnaire, suggesting high motivation. On the other hand, this has added an extra value to our findings: the current guidelines for correct seat belt positioning were followed by less than 13% of the pregnant women in the UK who were proactively seeking information about safe driving during pregnancy.

Both lap and shoulder portions of the belt must simultaneously be positioned correctly otherwise the seat belt may be prevented from operating as intended. Car occupant position and experience of previous pregnancies could influence the correct seat belt positioning.

Accommodating women's altered size and shape and other pregnancy-related changes and symptoms is a 'safety' rather than simply 'comfort' issue since *discomfort* can cause women to take unsafe actions such as not wearing the seat belt or modifying its usage. Improving safety for pregnant car travellers requires a combined approach of increasing awareness of correct positioning and better designs to meet the needs of the pregnant occupant.

"Automotive Design: Incorporating the Needs of Pregnant Women" project provides explicit information about pregnant women. Improving the safety for pregnant car travellers is important. The research will be extended and a world-wide study will be conducted through collaboration with researchers and motor manufacturers globally to investigate the needs and requirements of pregnant occupants as passengers and drivers.

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INCIDENCE AND RISK OF DIRECT STEERING WHEEL IMPACT IN VEHICLES EQUIPPED WITH ADVANCED AIR BAGS

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ABSTRACT

Despite the widespread availability of airbags and a belt use rate of over 85%, U.S. drivers involved in crashes continue to be at risk of serious thoracic injury. One hypothesis is that this risk may be due to the lack of airbag deployment or the airbag 'bottoming-out' in some cases. The objective of this study is to determine the incidence and thoracic injury risk of direct steering wheel contact due to airbag "bottoming-out".

The analysis is based upon cases extracted from the National Automotive Sampling System Crashworthiness Data System (NASS/CDS) database for case years 1997-2011. The NASS/CDS data set was restricted to vehicles of model year 1998 and later. The approach was to compare the frontal crash performance of sled-certified airbags, sometimes called depowered airbags, with advanced airbags involved in frontal crashes. NASS/CDS steering wheel deformation measurements were used to identify cases in which thoracic injuries may have been caused due to steering wheel impact and deformation. The distributions of injuries for all cases were determined by body region and injury severity. These distributions were used to compare and contrast injury outcomes for cases with frontal airbag deployment for both belted and unbelted drivers.

Among frontal crash cases with belted drivers, observable steering wheel deformation occurred in less than 4% of all cases, but accounted for 29% of all MAIS3+ belted drivers and 28% of belted drivers with serious thoracic injuries (AIS3+). Similarly, observable steering wheel deformation occurred in approximately 13% of all cases with unbelted drivers involved in frontal crashes, but accounted for 58% of MAIS3+ unbelted drivers and 66% of unbelted drivers with serious (AIS3+) thoracic injuries.

INTRODUCTION

Seatbelts and airbags are the two primary components of the safety system that helps to secure the occupant and reduce the rapid deceleration experienced by occupants in a frontal crash. However, despite the widespread availability of airbags, and seatbelt usage over 85% in the United States, drivers still may contact the steering wheel in the event of a crash, and may subsequently incur serious injury as a result of steering wheel impact.

The design of frontal airbags, one potential influence on the incidence of steering wheel deformation, has evolved through several generations since their first introduction into the U.S. fleet in selected models in the 1970s. Driver airbags first became mandatory for vehicles in the U.S. fleet in 1994. In response to changes in Federal Motor Vehicle Safety Standard No. 208 (FMVSS 208) [1], depowered frontal airbags, sometimes called sled-certified airbags, were introduced into the U.S. fleet in 1998. Depowered airbags were intended to reduce the risk of injury to front seat occupants by reducing the force with which these airbags were deployed. Advanced airbags, sometimes referred to as Certified Advanced 208 Compliant (CAC) airbags, began to be phased into the U.S. fleet in model year 2004 with complete phase in by model year 2007. A few models contained CAC-airbags as early as model year 2003. Like depowered airbags, advanced airbags sought to reduce occupant risk by employing a sophisticated system of occupant sensors and a two-stage inflator design which could tailor the force of deployment to the severity of the crash, the location of the occupant, and belt status. Some manufacturers included some of the features of advanced airbags, e.g. dual inflators, in their sled-certified airbag designs.

One concern has been whether advanced airbags may be associated with higher injury risk than earlier airbag designs. Based on an analysis of Fatality Analysis Reporting System (FARS), Braver et al [2] reported that the mortality for belted drivers was higher for advanced airbag equipped vehicles than for sled-certified vehicles. One hypothesis is that drivers may be bottoming-out airbags in which only a single stage was deployed. If the airbag was bottomed-out, the driver could directly impact and deform the steering wheel assembly which underlies the airbag. The hypothesis is that steering wheel deformation would then be correlated with greater frontal crash injury risk.

Objective

The objective of this study is to determine the factors associated with steering wheel deformation during a frontal crash and the resulting injury outcomes.

Approach

Our approach was to compare frontal crash injury risk in vehicles with and without measurable steering wheel deformation. The study was based upon real world crashes extracted from the National Automotive Sample System's (NASS) Crashworthiness Data System (CDS). NASS is a crash data collection program established by the National Highway Traffic Safety Administration (NHTSA). Each year NASS/CDS investigates approximately 5,000 cases, selected from police reported crashes at 24 sites across the United States. NASS crash investigators document vehicle damage, occupant impacts with the interior, and crash site evidence, such as skid marks, and damage to roadside objects. In addition, the nature and severity of the injuries sustained by the occupants are collected through the review of medical records and interviews with the crash victims.

The following study is based upon cases extracted from NASS/CDS 1997-2011. In order to be included in the dataset, cases were required to meet the following conditions:

- Vehicles model year 1998 and newer
- Drivers age 12 and older
- Frontal impacts with airbag deployed
- Exclude rollover cases
- Exclude cases involving driver ejection
- Belt use was known
- Steering wheel deformation was recorded

These criteria were chosen to include only the latest safety technologies. The model year 1998+ restriction was chosen to coincide with the year depowered airbags were introduced into the U.S. fleet. These countermeasures are designed to protect occupants involved in frontal crashes. Rollover crashes account for an over-representative number of serious injuries and deaths from car crashes, but the injurious circumstances are often unclear. Due to the complex nature of rollovers, they were not included in this analysis.

This study considered both the effect of belt usage, and the type of frontal airbags in the vehicle. Our dataset contained two generations of airbag designs: 1) depowered airbags introduced in 1998 and 2) Certified Advanced 208 Compliant (CAC) airbags. CAC airbags, sometimes called advanced airbags, first began to be phased into the U.S. fleet in model year 2004 with complete phase in by model year 2007. A few models contained CAC-airbags in model year 2003. The type of driver airbag was identified for each vehicle prior to the analysis [3].

NASS describes the severity of occupant injuries based on the Abbreviated Injury Scale (AIS). AIS ranks injury severity on a scale of 1-6 based on its threat to the life of the occupant [4]. AIS=1 is a minor injury, AIS=3 is a serious injury and AIS=6 is an unsurvivable injury. Our analysis classified injury severity by the maximum AIS (MAIS) level injury sustained by an occupant. For drivers who were fatally injured, MAIS was set to 6 regardless of individual injury level. The injuries were further classified by body region, i.e. the head, face, neck, chest, abdomen, spine, upper extremities, and lower extremities. The injury distribution was described by computing the highest, i.e. most severe, injury sustained in each body region. In the analysis which follows, NASS sample weights were applied in order to represent the national population.

In the analysis which follows, we seek to answer the following questions:

- How frequently does steering wheel deformation occur?
- What are the injury outcomes of steering wheel deformation?
- What causes steering wheel deformation to occur?
- What controls the magnitude of steering wheel deformation?

For the steering wheel analysis, the dataset was then further divided into those vehicles with and without steering wheel deformation. Cases with steering wheel deformation were identified with the NASS/CDS variable "rimdef", and subsequently grouped by the occupant injuries recorded by NASS/CDS. In this analysis, the comparison between vehicles with and without measurable steering wheel deformation was based upon the risk of injury. For a particular body region, the risk of injury is expressed in terms of the fraction of cases at a given severity, as shown in equation (1), where n is the number of cases at a given severity and N_{Total} is the total number of cases with known injury severity. The following analysis also presents the relative risk, or the ratio of risk of injury in vehicles with steering wheel deformation versus in vehicles without steering wheel deformation, as shown in equation (2), where $R_{with\ Deformation}$ is the risk of injury with steering wheel deformation, and $R_{without\ Deformation}$ is the risk of injury without steering wheel deformation.

$$Risk\ of\ Injury = \frac{n}{N_{Total}} \qquad (1)$$

$$Relative\ Risk = \frac{R_{With\ Deformation}}{R_{Without\ Deformation}} \qquad (2)$$

Confidence intervals were computed in our analysis using SAS routines SurveyReg, SurveyFreq, and SurveyLogistic to account for the complex sampling scheme employed by NASS/CDS. The cases collected in NASS/CDS are clustered into 24 primary sampling unit (PSU). The cases are further separated into 10 strata based on factors which include vehicle damage and the severity of the occupant injuries.

Results

Dataset Composition Table 1 presents the composition of the belted driver dataset for both unweighted and weighted values. The dataset is organized based on the steering wheel (SW) deformation, as well as the number of drivers sustaining MAIS 2+ and MAIS 3+ injuries. Likewise, the composition of the dataset for unbelted drivers is presented in Table 2 as a function of steering wheel deformation and MAIS level. Steering wheel deformation was not recorded in 426 cases, while another 171 cases involved steering wheel deformation caused by a person or object other than the driver, e.g. rescue personnel or occupant compartment collapse. These cases were omitted from the dataset.

Table 1
Dataset Composition by Steering Wheel Deformation for Belted Drivers

Driver Injury Level	Unweighted		
	Total	No Measurable SW Deformation	Measurable SW Deformation
Exposed	10,429	9,604	825
MAIS 2+	2,136	1,637	499
MAIS 3+	984	643	341
Driver Injury Level	Weighted		
	Total	No Measurable SW Deformation	Measurable SW Deformation
Exposed	3,290,900	3,172,037	118,863
MAIS 2+	288,036	244,481	43,555
MAIS 3+	74,588	52,780	21,808

Table 2
Dataset Composition by Steering Wheel Deformation for Unbelted Drivers

Driver Injury Level	Unweighted		
	Total	No Measurable SW Deformation	Measurable SW Deformation
Exposed	2,407	1,705	702
MAIS 2+	982	505	477
MAIS 3+	599	249	350
Driver Injury Level	Weighted		
	Total	No Measurable SW Deformation	Measurable SW Deformation
Exposed	611,062	532,286	78,776
MAIS 2+	109,695	69,533	40,162
MAIS 3+	45,059	18,918	26,141

Lastly, the dataset was broken down by airbag type. Table 3 presents the unweighted and weighted values for the belted drivers. The composition of the dataset for unbelted drivers is presented as a function of airbag type in Table 4.

Table 3
Dataset Composition by Airbag Type for Belted Drivers

Driver Injury Level	Unweighted		
	Total	Depowered Airbag Vehicles	CAC Vehicles
Exposed	10,429	7,522	2,907
MAIS 2+	2,136	1,618	518
MAIS 3+	984	762	222
Driver Injury Level	**Weighted**		
	Total	Depowered Airbag Vehicles	CAC Vehicles
Exposed	3,290,900	2,550,071	740,829
MAIS 2+	288,036	229,192	58,844
MAIS 3+	74,588	55,522	19,066

Table 4
Dataset Composition by Airbag Type for Unbelted Drivers

Driver Injury Level	Unweighted		
	Total	Depowered Airbag Vehicles	CAC Vehicles
Exposed	2,407	1,855	522
MAIS 2+	982	782	200
MAIS 3+	599	478	121
Driver Injury Level	**Weighted**		
	Total	Depowered Airbag Vehicles	CAC Vehicles
Exposed	611,062	487,600	123,462
MAIS 2+	109,695	86,479	23,217
MAIS 3+	45,059	35,070	9,989

Frequency of Steering Wheel Deformation
Figure 1 shows the distribution of cases with and without measurable steering wheel deformation for drivers exposed to frontal crashes, with MAIS2+ injuries and with MAIS3+ injuries. Only 4% of belted drivers were involved with a steering wheel with any measurable deformation. However, this 4% of cases was overrepresented in the injury outcomes, and was associated with 15% of MAIS2+ drivers and 29% of MAIS3+ injured drivers. Even for drivers wearing their belts with deployed airbags, steering wheel impact with measurable deformation still accounted for nearly one-third of serious to fatally injured belted drivers.

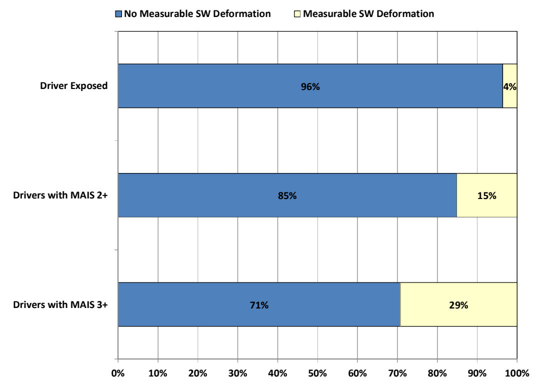

Figure 1. Distribution of Belted Drivers with and without Steering Wheel Deformation

Figure 2 shows the distribution of cases with and without measurable steering wheel deformation for unbelted drivers exposed to frontal crashes, with MAIS2+ injuries and with MAIS3+ injuries. As might be expected unbelted drivers were more likely to cause steering wheel deformation (13%) than belted drivers (4%). In most belted cases, the three point belt keeps the driver out of the steering wheel. Although a small fraction, the 13% of drivers in vehicles with steering wheel deformation is overrepresented in the injury outcomes. This small fraction is associated with 37% of MAIS2+ drivers and well over half (58%) of MAIS3+ unbelted drivers. Clearly, failure to wear a safety belt puts unbelted drivers at a higher risk of impacting the steering wheel than belted drivers. The result was a sharply elevated risk of injury.

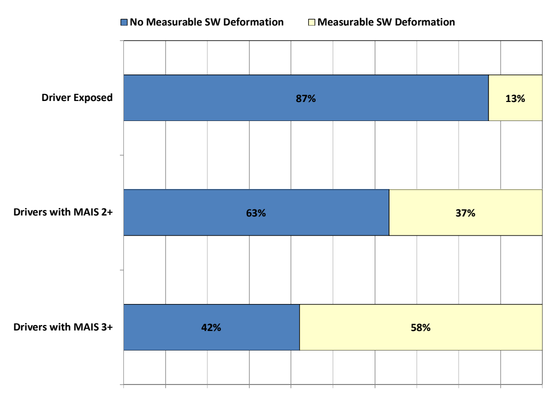

Figure 2. Distribution of Unbelted Drivers with and without Steering Wheel Deformation

Injury Consequences of Steering Wheel Deformation for Belted Drivers Figure 3 presents the distribution of total delta-V for vehicles with and without measurable steering wheel deformation. The median delta-V for crashes without measurable steering wheel deformation was 19 km/hr while the median delta-V for crashes with measurable steering wheel deformation was 30 km/hr. This figure shows that, as might be expected, steering wheel deformation is more likely to occur in higher severity crashes.

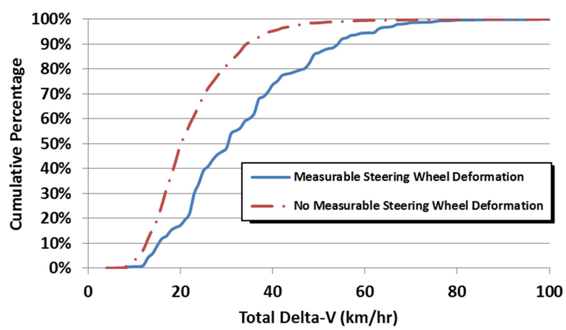

Figure 3. Total Delta-V Distribution of Vehicles With and Without Steering Wheel Deformation (Belted Drivers)

Figure 4 compares the distribution of the risk of AIS2+ injuries for cases with and without measurable steering wheel deformation. For all body regions, measurable steering wheel deformation was associated with a higher risk of AIS2+ injury. The lower extremities had the highest risk of all body regions. Head and chest were the body regions with the third and fourth highest risk of AIS2+ injury.

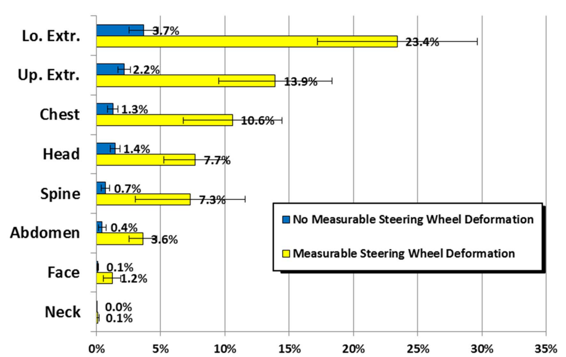

Figure 4. Risk of AIS2+ Injuries by Body Region for Belted Drivers

Figure 5 compares the risk of AIS3+, or serious injuries, for cases with and without measurable steering wheel deformation. For all body regions, measurable steering wheel deformation was associated with a higher risk of AIS3+ injury. Lower extremity carried the highest risk of AIS3+ injury. The thorax carried the second highest risk of injury from steering wheel deformation.

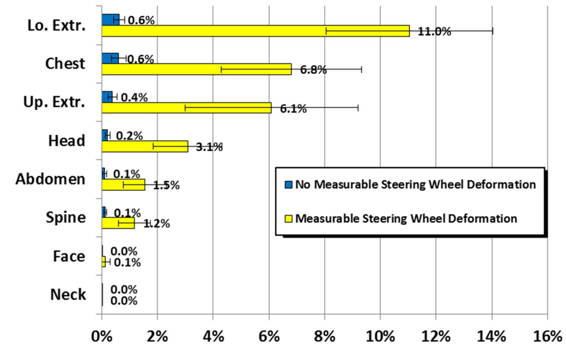

Figure 5. Risk of AIS3+ Injuries by Body Region for Belted Drivers

Figure 6 and Figure 7 shows the relative risk of AIS2+ and AIS 3 injuries in vehicles with steering wheel deformation when compared to vehicles without steering wheel deformation, respectively. The risk of AIS2+ thorax injury increases by a factor of 8 if there is steering wheel deformation. Even more worrisome is that the risk of AIS3+ thorax injury increases by a factor of 11 if there is steering wheel deformation. For AIS2+ injuries, the increase in risk was statistically significant in all body regions except the neck. For AIS3+ injuries, the increase in risk was statistically significant for all body regions except face and neck.

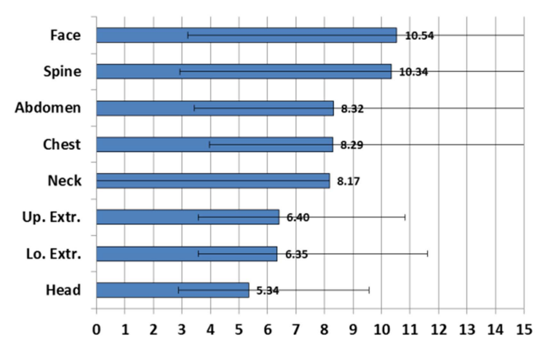

Figure 6. Relative Risk of AIS2+ Injuries by Body Region for Belted drivers with and without steering wheel deformation

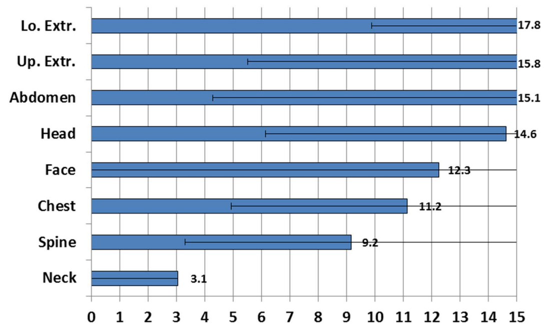

Figure 7. Relative Risk of AIS3+ Injuries by Body Region for Belted drivers with and without steering wheel deformation

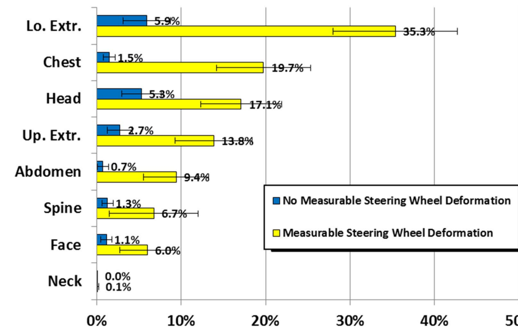

Figure 9. Risk of AIS2+ Injuries by Body Region for Unbelted Drivers

Injury Consequences of Steering Wheel Deformation for Unbelted Drivers Figure 8 presents the distribution of total delta-V for vehicles with and without measurable steering wheel deformation. The median delta-V for crashes without measurable steering wheel deformation was 20 km/hr while the median delta-V for crashes with measurable steering wheel deformation was 30 km/hr. As with belted drivers, steering wheel deformation for unbelted drivers is more likely to occur in higher severity crashes.

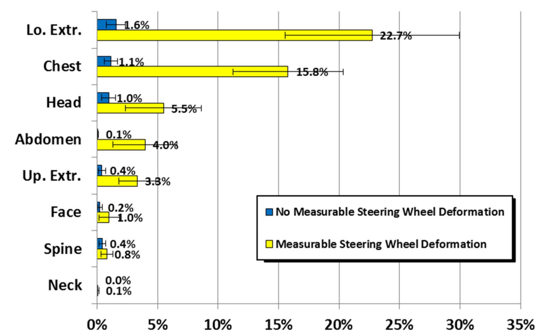

Figure 10. Risk of AIS3+ Injuries by Body Region for Unbelted Drivers

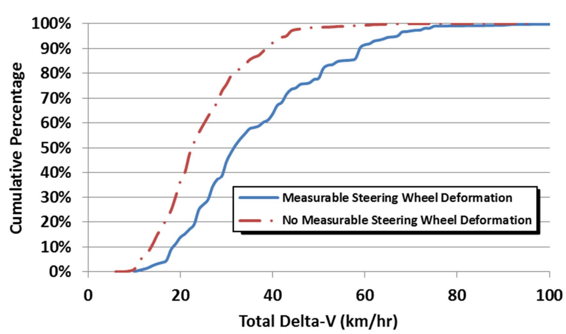

Figure 8. Total Delta-V Distribution of Vehicles With and Without Steering Wheel Deformation (Unbelted Drivers)

Figure 11 and Figure 12 shows the relative risk of AIS2+ and AIS 3 injuries as a ratio of risk of injury in vehicles with steering wheel deformation and those without steering wheel deformation, respectively. The risk increases by a factor of 13 for AIS2+ thoracic injury and by a factor of 14 for AIS3+ injury if there is steering wheel deformation.

Figure 9 compares the distribution of the risk of AIS2+ injuries between cases with and without measurable steering wheel deformation. Likewise, Figure 10 compares the risk of AIS3+, or severe injuries, for cases with and without measurable steering wheel deformation. For all body regions, steering wheel deformation was associated with a higher risk of injury.

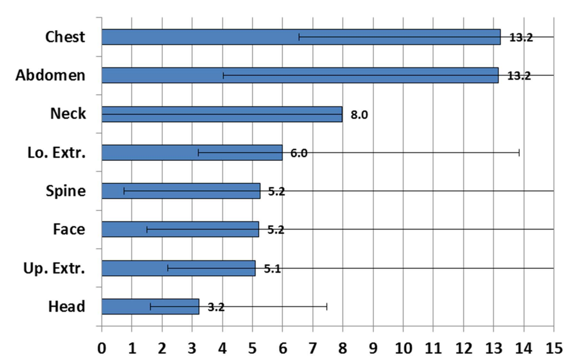

Figure 11. Relative Risk of AIS2+ Injuries by Body Region for Unbelted Drivers with and without steering wheel deformation

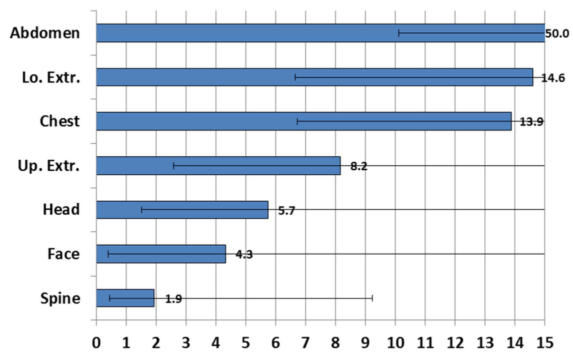

Figure 12. Relative Risk of AIS3+ Injuries by Body Region for Unbelted Drivers with and without steering wheel deformation

Factors which Influence Steering Wheel Deformation Magnitude In order to determine the potential factors that may influence the severity of steering wheel impact, we approximated the complex interaction between the driver and the vehicle's restraint system with a simple mass-spring system. For a steering wheel with a linear spring stiffness in which an occupant of mass *m* contacts the steering wheel at velocity *v*, the steering wheel-restraint deformation x can be computed as follows:

$$\frac{1}{2}mv^2 = \frac{1}{2}kx^2 \tag{3}$$

$$x = \left(\sqrt{\frac{m}{k}}\right)v \tag{4}$$

This simple model does not, of course, account for the non-linear force-deflection of the belt-airbag-steering wheel system, but is useful to identify the factors which are likely to control steering wheel deformation. As a first approximation, this qualitative analysis indicates that steering wheel deformation is likely to be influenced by the delta-V, the mass of the occupant, and the stiffness of the belt-airbag-steering wheel system.

The effect of multiple event crashes was also considered in the analysis. In 34% of the cases the vehicle experienced multiple crash events, e.g. a crash where the vehicle strikes a guardrail, and was then redirected onto the road where it collided with another vehicle. In these multiple event crashes, the airbag may inflate during the first event to protect the occupant, but after deflating does little to help the occupant when it is deflated during the subsequent events.

Test of Model Effects To account for the stratified sampling scheme used by NASS/CDS, the SurveyReg function in SAS 9.2 was used to test the effect of each of the independent variables in a Wald test. Magnitude of steering wheel deformation was used as the response. The weight of the occupant, as well as the longitudinal and lateral delta-V were included as continuous covariates. The belt status and type of airbag were included in the analysis as categorical covariates. The effect of multiple event crashes was used as a categorical variable (1 if crash involved multiple events, 0 if single event crash) and tested for its effect on steering wheel deformation. The dataset considered for the Wald test and the subsequent regression model used only cases with measurable steering deformation.

As shown in Table 5, longitudinal delta-V, occupant weight, and belt were statistically significant at the alpha=0.05 level in influencing steering deformation. However, lateral delta-V, the type of airbag, and the factor of multiple event crashes did not have a statistically significant effect on magnitude of steering wheel deformation.

Table 5
Test of Model Effect Result by SAS

Variable	F Value	Pr > F
Longitudinal Delta-V	9.89	0.002
Lateral Delta-V	0.12	0.731
Weight	10.85	0.001
Belt Status	6.87	0.010
Advanced airbag	2.51	0.115
Multiple Crash Events	1.06	0.305

The effect of multiple events can also be illustrated using the distribution of steering wheel deformation. Figure 13 and Figure 14 shows that for single and multi-event crashes, there was little difference in the magnitude of steering wheel deformation for either belted or unbelted drivers

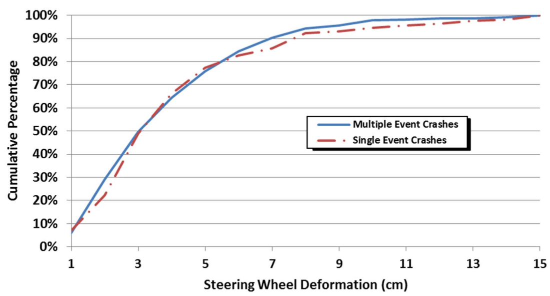

Figure 13. Belted Driver Steering Wheel Deformation Distribution for Multiple and Single Event Crashes

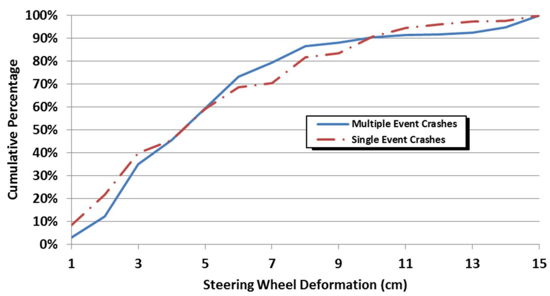

Figure 14. Unbelted Driver Steering Wheel Deformation Distribution for Multiple and Single Event Crashes

Multiple Linear Regression Model Based on the model effect test result, the following variables were used to create a linear regression model: longitudinal delta-V, weight, and belt status. The height of driver, although generally correlated with weight, was excluded in favor of weight. In this analysis, the weight of the driver serves as a better representative of the inertial loading of the driver upon the airbag. Another Wald Test of effects was performed using the three chosen variables to determine their significance. The result of the model effect test of the three variables tabulated in Table 6 suggests all three chosen variables are statistically significant to the model. However, the model intercept was not considered significant.

Table 6
Test of Model Effect Result by SAS

Variable	F Value	Pr > F
Intercept	1.63	0.2027
Longitudinal Delta-V	10.14	0.0017
Weight	10.34	0.0015
Belt Status	6.57	0.0112

Table 7 presents the estimated coefficient of each variable and its corresponding 95% confidence limits. For the categorical variables, “Belt Status”, the estimated coefficient is multiplied by 1 for unbelted drivers. Otherwise, the coefficient is multiplied by zero to indicate no effect. Note that none of the coefficients, except the intercept, span zero, indicating we can reject the null hypothesis that any of the coefficients are zero.

Table 7
Multiple Linear Regression Parameter Estimates

Variable	Coefficient Estimates	95% Confidence Limits	
Intercept	0.738	-1.108	2.584
Longitudinal Delta-V	0.0454	0.0173	0.0736
Weight	0.0259	0.01	0.0418
Belt Status	0.89	0.205	1.576

Model Validation Figure 15 illustrates the linear regression model comparison for both belted and unbelted drivers. The figure compares the predicted steering wheel deformation of a 70 kg driver in a belted or unbelted scenario. The model shows that, given the same longitudinal delta-V, an unbelted driver is expected to experience larger steering wheel deformation in a frontal crash.

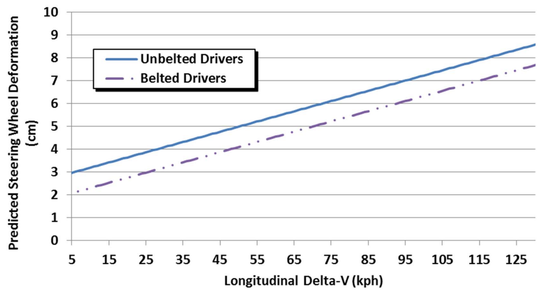

Figure 15. Linear Regression Model for Belted and Unbelted 70 kg Driver

Figure 16 and Figure 17 shows the actual versus predicted steering wheel deformation for belted and unbelted scenarios, respectively. A linear line with a slope of one has been included for comparison. For both belted and unbelted drivers, the model was able to predict steering wheel deformation for the large portion of the cases with deformation ranging from 3 to 7 cm.

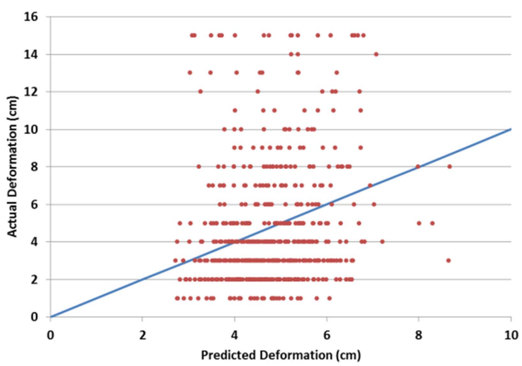

Figure 16. Model Validation – Actual Deformation against Predicted Deformation for Belted Driver

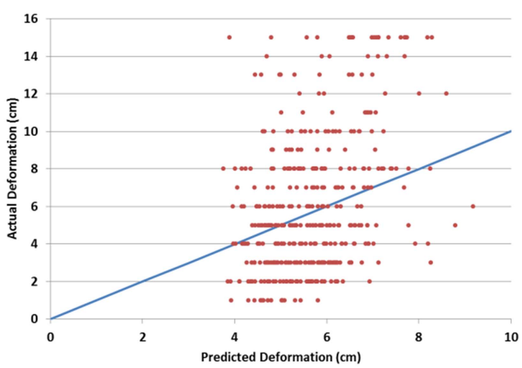

Figure 17. Model Validation – Actual Deformation against Predicted Deformation for Unbelted Driver

Factors which Influence the Incidence of Steering Wheel Deformation In addition to modeling the magnitude of steering wheel deformation, we are also interested in the delta-V threshold at which steering wheel deformation first becomes measurable. In this section, we use logistic regression to model the probability of steering wheel deformation as a function of delta-V, belt use, and occupant weight.

The probability of the discrete outcome can be estimated using a logistic regression. A logistic regression model was constructed using the SurveyLogistic function of SAS 9.2. Similar to the regression model, the logistic model also considers the stratified sampling scheme used by NASS/CDS, and contains the three variables: longitudinal delta-V, weight, and belt status.The estimated coefficient of each variable and its respective 95% confidence interval are tabulated in Table 8.

Table 8
Logistic Regression Parameter Estimates

Variable	**Coefficient Estimates**	**95% Confidence Limits**	
Intercept	-6.3029	-7.156	-5.4497
Longitudinal Delta-V	0.0683	0.0593	0.0773
Weight	0.0231	0.0153	0.0308
Belt Status	0.6693	0.4628	0.8758

Table **9** lists the result of the Chi-Square test which test against the null hypothesis that at least one of the variables' regression coefficients is equal to zero in the model. Based on the calculated Chi-Square value and the associated probability, we can reject the null hypothesis that at least one of the variables' regression coefficients is equal to zero.

Table 9
Testing Global Null Hypothesis

Test	Chi-Square	DF	Pr > ChiSq
Likelihood Ratio	174,721	3	<.0001
Score	233,606	3	<.0001
Wald	274	3	<.0001

Using the parameter estimates in Table 8 and the logarithmic regression equation shown in equation (5), the probability of steering wheel deformation for a 70 kg belted and unbelted driver can be estimated with respect to longitudinal delta-V, as shown in a Figure 18.

$$P = \frac{e^{(Intercept+A*Delta-V+B*Weight+C*Belt)}}{1+e^{(Intercept+A*Delta-V+B*Weight+C*Belt)}} \quad (5)$$

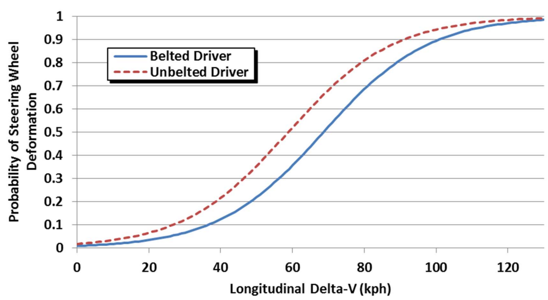

Figure 18. Probability of Measurable Steering Wheel Deformation for Belted and Unbelted 70kg Driver

Figure 19 and Figure 20 illustrate the 95% confidence limits constructed by the logistic regression analysis for a 70 kg belted and unbelted drivers.

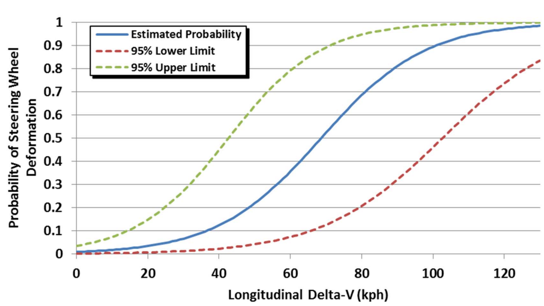

Figure 19. Probability of Measurable Steering Wheel Deformation for 70kg Belted Driver

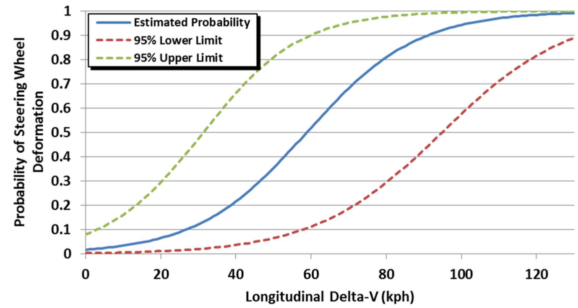

Figure 20. Probability of Measurable Steering Wheel Deformation for 70kg Unbelted Driver

Discussion

This analysis sought to characterize the factors influencing steering wheel deformation in a frontal crash. As a first step, we considered a simplified linear model to relate steering wheel deformation with delta-V. The linear regression model included longitudinal delta-V, weight, and belt status and showed statistical significance in predicting steering wheel deformation. Each of these variables constituted a significant contribution in the response variable, steering wheel deformation.

The linear regression model indicated that unbelted drivers were likely to experience larger steering wheel deformation. For two drivers of the same weight experiencing identical delta-V during a frontal crash, our model predicted that the unbelted driver would experience on average approximately 1 cm greater steering wheel deformation. The model also suggests that a driver of greater weight will experience greater steering wheel deformation. On average, the linear regression model estimates that steering wheel deformation will increase by 0.26 cm per 10 kg of weight increase. Likewise, a driver involved in a higher delta-V crash will likely experience greater steering wheel deformation. On average, the linear regression model estimates that steering wheel deformation will increase by 0.45 cm per 10 km/hr increase in delta-V. However, no statistically significant difference was observed between advanced airbags and sled-certified airbags in terms of steering wheel deformation. Multiple event crashes were also found to be statistically insignificant in affecting steering wheel deformation.

The risk of any steering wheel deformation was also a function of delta-V, belt use, and driver weight. A 70-kg driver has a 10% probability of deforming the steering wheel at 27 km/hr. By comparison, a belted driver of the same weight must be in a much more severe crash (delta-V = 36 km/hr) to have the same 10% chance of any measureable steering wheel deformation.

Our study has several limitations. The analysis did not consider the effect of load-limiting seatbelts or seat-belt pre-tensioners. These enhancements to seat belts were introduced concurrently with the transition from sled-certified airbags to CAC airbags and may have affected the stiffness of the combined seat belt-airbag-steering wheel system. Our linear model of the driver restraint system does not, of course, account for the non-linear force-deflection of the belt-airbag-steering wheel system, but was regardless useful to identify the factors which are likely to control steering wheel deformation. Follow-on studies will investigate non-linear models of this system. The initial proximity of the driver with respect to the steering wheel is not recorded in NASS/CDS. We initially considered using driver height as one indication of likely driver proximity to the airbag. However, driver weight and driver height are highly correlated. Here we chose to use driver weight rather than height in order to capture inertial loading of the airbag by the driver. It may be possible however to infer driver-airbag proximity using other methods in follow-on studies. Finally, our analysis used delta-V as a measure of crash severity. Delta-V does not capture the influence of crash pulse which may also affect driver-steering wheel interaction.

CONCLUSIONS

This study has investigated the incidence of steering wheel deformation and the associated driver injury outcome. The study was based upon the analysis of 10,429 belted drivers and 2,407 unbelted drivers of MY 1998 and later passenger vehicles. Our conclusions are as follows:

- Only 4% of belted drivers were involved with a steering wheel with any measurable deformation. However, this 4% of cases was overrepresented in the injury outcomes, and was associated with 15% of MAIS2+ drivers and 29% of MAIS3+ injured drivers.

- Unbelted drivers were more likely to be associated with steering wheel deformation (13%) than belted drivers (4%). In most belted cases, the three point belt keeps the driver out of the steering wheel. Although a small fraction, the 13% of unbelted drivers in vehicles with steering wheel deformation is overrepresented in the injury outcomes. This small fraction was associated with 37% of MAIS2+ drivers and well over half (58%) of MAIS3+ unbelted drivers. Clearly, failure to wear a safety belt puts unbelted drivers at a higher risk of impacting the steering wheel than belted drivers. The result is a sharply elevated risk of injury.

- The incidence of steering wheel contact increases as higher delta-V increases. Crashes with measurable steering wheel deformation had a median delta-V of about 19 mph, compared to a median delta-V of about 14 mph in cases without steering wheel deformation.

- The risk of both AIS2+ and AIS3+ injury was greater for crashes involving steering wheel deformation. For belted drivers in crashes with steering wheel deformation, the risk of AIS2+ thoracic injury was 13 times greater than for crashes without steering wheel deformation. The risk of AIS3+ thoracic injury was 14 times greater than for crashes without steering wheel deformation.

- The analysis of our NASS/CDS dataset indicated that longitudinal delta-V, belt usage, and occupant weight were the primary factors which influenced both the incidence and magnitude of steering wheel deformation. The proposed linear regression model estimates 1 cm greater steering wheel deformation for unbelted driver, an approximate 0.27 cm increase in steering wheel deformation per 10 kg increase in driver weight, and an approximate 0.45 cm increase in steering wheel deformation per 10 km/hr increase in delta-V. After controlling for crash severity, driver belt use, and driver weight, our analysis showed no statistically significant difference in the magnitude of steering wheel deformation between sled-certified airbags and CAC airbags.

Even in vehicles equipped with airbags, serious thoracic injury is associated with steering wheel impact and deformation. This study demonstrates that a promising path for further thoracic injury reduction lies in enhancements to airbag and belt systems which reduce steering wheel impact. The study also shows that, even for the most advanced restraint system, the importance of investigating the steering wheel as a driver load path in addition to simply the airbag and belts. Without factoring in the steering rim load path, the assessment of airbag and belts effectiveness may be incorrect in serious injury cases.

ACKNOWLEDGEMENTS

Toyota Motor Corporation is gratefully acknowledged for providing the funding for this study.

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CHARACTERISTICS OF CRASHES WITH MULTIPLE FRONTAL IMPACTS

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Paper Number 13-0061

ABSTRACT

Data from the National Automotive Sampling System – Crashworthiness Data System (NASS CDS)[1] were analyzed to determine the characteristics of multiple-frontal impact crashes with the objective of identifying opportunities for employing safety systems. Multiple impacts initiated by a frontal impact accounted for about 24% of the population of seriously injured (MAIS 3+) drivers in recent model passenger vehicles. Multiple frontal impacts alone accounted for 10% of the seriously injured driver population. Lane departure and roadway departure were the most frequent pre-crash events. The proportion of kinetic energy remaining after the first impact was identified as a possible predictor of the likelihood of multiple impacts.

INTRODUCTION

Multiple impact crashes are those in which a vehicle sustains two or more collisions in the course of a single crash sequence. According to National Automotive Sampling System (NASS) Crashworthiness Data System (CDS), between 1997 and 2006, nearly 16 million occupants were involved in multiple impact collisions. The data further indicates that while only 30 percent of all occupants are involved in multiple impacts, this population accounts for nearly half of all seriously injured occupants (defined as occupant Maximum Abbreviated Injury Score of 3 or greater (MAIS 3+)). Occupants in multiple impacts are almost twice as likely to be seriously injured when compared with their counterparts in single impacts.

This work expands upon previous research on multiple impacts by focusing on the study of multiple impacts in which a vehicle sustained at least two separate impacts to the front of the vehicle in the course of a single crash sequence, referred to herein as multiple-frontal impacts. An analysis of available crash data and subsequent individual case reviews is presented. Multiple frontal impacts were examined to identify possible collision avoidance / mitigation and crashworthiness countermeasures. The analysis and results presented here are excerpted from a larger work by the authors on the topic. [1]

PRIOR WORK

Limited prior work has been completed on the study of multiple impacts in general, and no prior work has focused specifically on multiple frontal impacts. However, the findings of this work relating to multiple impacts overall appear to correlate well with results from the earlier works.[2]

The distribution of vehicles by collision type in the NASS CDS correlates well with the distributions presented by Fay and Sferco in 2001 [2], however NASS CDS exhibits an elevated contribution from multiple impacts. Fay and Sferco found multiple impacts to constitute 26.5% to 29% of the vehicle population in crash data from the United Kingdom and Germany (GIDAS)[3] while NASS CDS, over equivalent time periods, found this percentage to be 37.2% to 39%. In line with Fay and Sferco's conclusion that the proportion of vehicles in multiple impacts would increase as time progressed, a study of NASS CDS for more recent years has found the proportion of multiple impacts to have increased to 39.8%. The finding that the majority of multiple impacts involved only two impacts was also confirmed, with two impact multiple impacts constituting over half of all multiple impacts. Fay and Sferco also identified that multiple impacts accounted for a significant proportion, 30% to 43% of seriously injured occupants (depending on data source, UK or

[1] NASS CDS is a database of a representative sample of two-away crashes on U.S. roads.

[2] A brief summary of the comparison of current data and previous works is presented here; the complete analysis with full tables may be found in reference [1].

[3] German In-Depth Accident Study; accident analysis study conducted in Germany collecting data on approximately 2000 case per year in a manner similar to the NASS CDS system, more info available at www.gidas.org,

Germany). NASS CDS data indicates that multiple impacts accounted for a larger proportion of the injured population over the same time period, and that this proportion has increased in recent years. (Table 1)

Table 1.
Distribution of MAIS 3+ Population
By Impact Type,
Comparison of GIDAS & NASS CDS data [4]

MAIS 3+ Rate			
Impact Type	**GIDAS 1996 - 2000**	**NASS CDS 1996 - 2000**	**NASS CDS 2001 - 2006**
Single Frontal	33%	31%	28%
Single Side	21%	14%	12%
Single Rear	2%	1%	1%
Single Rollover	1%	4%	4%
Multiple Impact	43%	50%	55%

In 2003, Leonard and Frampton [3] presented a follow on paper to Fay and Sferco which examined data from the United Kingdom and focused on the seriously injured. Again, the data from NASS CDS over an equivalent time period found similar distributions of this population, with multiple impacts constituting a larger proportion of the seriously injured population than rollovers.

In 2004, Digges and Bahouth [4] performed an analysis updating earlier work by Fay at al. with NASS CDS data from 1998-2000. Their work confirmed that multiple impacts continued to contribute significantly to the seriously injured population. Digges and Bahouth also identified that the frontal-frontal, side-side, and frontal – side type multiple impacts constituted the majority of seriously injured occupants in multiple impacts. This work found similar results.

J. Bahouth's 2004 dissertation under the direction of Digges [5] further examined general multiple impacts to identify characteristics of injurious multiple impacts. Using NASS CDS data from 1998-2002, J. Bahouth classified multiple impacts where both delta-v's [5] were greater than 15 mph or where the second impact was of a greater severity than the first impact (secondary / primary)[6] as "consequential multiple impact crashes" which were linked with serious injury. As presented here, the current analysis has identified a similar link between the secondary / primary type multiple impacts, specifically multiple frontal impacts, and injury.

Also in 2004, Logan, Scully and Fildes [6] used ANCIS (Australia) crash data and found similar conclusions to that of earlier work. Notably, Logan et al. found multiple impacts constituted 32% of the data they examined and that these collisions were linked with elevated occurrences of serious injury.

Most recently in 2009, Raj and Digges [7] examined fatal frontal collisions with airbag non-deployments and found that 90% of this population included multiple impacts. The most common sequence of impacts in this population was impacts with curbs / guardrails followed by impacts with narrow objects. Impacts with roadside and narrow objects were also found in this work to be associated with higher instances of occurrence of multiple frontal impacts in general and injurious multiple frontal impacts specifically.

METHODOLOGY

The data source for this analysis was the NASS CDS for calendar years 1988 – 2006.[7] The data were analyzed in three ways. First, the data elements currently existing in the entire database were examined to determine the frequency of multiple impact and their characteristics. Second, it was found that some useful variables were available after certain calendar years and in those analyses the data was limited accordingly. Finally, the case by case analysis was limited to calendar years 1997 – 2006

[4] Calculated using data in Table A-1. Values for GIDAS calculated from results published in Fay and Sferco 2001 [2]. Data presented is extracted from complete work which is the basis for this paper [1].

[5] Delta-v is the change in speed of a vehicle in the course of a single impact. For example, a vehicle which decelerates from 15 mph to 0 mph in a collision experienced a delta-v of 15 mph.

[6] Throughout this work, the impacts in a multiple impact collision sequence will be referred to in two ways. When referred to sequentially, the impacts will be referred to as the first or initial impact and the second or subsequent impact. When referred to in terms of severity, the most severe impact will be referred to as the primary impact and the second most severe impact will be referred to as the secondary impact. Note that the references in terms of severity (primary / secondary) are assigned to impacts, independent of their order in the collision sequence.

[7] Data from 1988-2006 was selected for the initial analysis to capture data on all multiple impacts which were present in the available data at the time the study was conducted. Analysis of individual variables was limited to shorter time periods that depended on the availability of the variable.

when case images and scene diagrams were readily available for review. Figure 1 illustrates the subsets which were created from the overall NASS CDS 1988-2006 dataset.

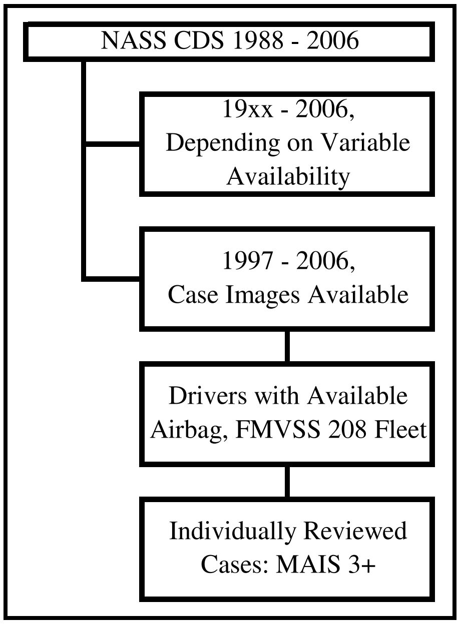

Figure 1. Schematic of Data Subsets.

The CDS database was first examined for a means of identifying multiple impacts in general. Manipulation of the vehicle number (VEHNO) and object contacted (OBJCONT) elements in the event file were necessary to create collision sequence histories for each vehicle in the database.[8] The modified database was then used to identify vehicles involved in two or more collisions in the course of a single crash sequence.

Multiple impacts were then classified by the general area of damage elements defined for the most severe (primary) impact (GAD1) and the second most severe (secondary) impact (GAD2). Due to their rarity and the lack of safety systems designed for and available to address them, collision sequences involving undercarriage impacts were eliminated from the analysis. Similarly, rollovers involve markedly different dynamics than planar crashes and collision sequences involving them were also eliminated from the analysis. Serious injury rates per 100 exposed occupants were then examined to identify possible relationships with the directions of impacts in a collision sequence. Unidirectional multiple-impacts, impacts in which a vehicle sustained more than one impact in the same direction (frontal, side, rear) were identified for further analysis based upon frequency and injury rate. Of the population of unidirectional multiple-impacts, multiple frontal impacts were selected to for examination of possible countermeasures. Rates of serious injury in multiple frontal impacts were contrasted with the injury rates in single frontal impacts which have a high effectiveness for current countermeasures in preventing serious injury. The occupant protection analysis was limited to belted drivers in vehicles equipped with airbags to identify more specifically where current frontal impact occupant protection countermeasures were failing to address multiple frontal impacts.

The general population of vehicles and occupants were used to examine multiple frontal impacts from the perspectives of countermeasures to prevent or predict multiple frontal impacts. A specific subset of the population, seriously injured belted drivers in vehicles with frontal airbags in multiple frontal impacts, was then selected for individual case reviews to examine possible occupant protection countermeasures.

The analyses were oriented so as to address three safety areas in which countermeasures might be developed. The pre-crash environment was examined in order to assist in developing safety systems to prevent the crash from occurring. The elements of the pre-crash and crash environment that could lead to the prediction of a multiple impact were examined to assist in developing crash protection countermeasures. Finally, in depth studies of multiple impact crashes with injuries were undertaken in order to better define opportunities for crash protection.

Prevention

To identify opportunities for the prevention of multiple frontal impacts, an analysis of the pre-impact location (PREILOC), accident type (ACCTYPE), and approximate travel / impact speed (IMPACTSP, TRAVELSP, SPLIMIT) elements was conducted. The rates of occurrence of multiple frontal impacts in relation to each of the variables were examined to identify pre-impact conditions which were correlated with the occurrence of

[8] The events in a collision are saved in an EVENT file in the NASS dataset, with a single entry for each event. In the case of a vehicle being involved in more than one event in a collision, the vehicle may have multiple entries in the EVENT file associated with it. The EVENT file was manipulated so all ordered events pertaining to a given vehicle collision sequence appeared in a single entry.

additional frontal impacts after an initial frontal impact.

Prediction

The data was further examined to characterize the dynamics of the vehicle during the crash sequence which could indicate an increased likelihood of the occurrence of multiple frontal impacts when compared to single frontal impacts. The principal direction of force (PDOF), specific horizontal location (SHL), type of damage distribution (TDD), and the object contacted (OBJCONT) elements were examined. The rates of occurrence of multiple frontal impacts in relation to each of the variables were examined to identify conditions during the initial impact which were correlated with the occurrence of additional frontal impacts. The data element only analysis was supplemented using reconstructions of the vehicle motion in the individual case reviews. An examination was conducted of the relationship between the proportion of kinetic energy remaining after the first impact and the occurrence of a second impact.

Protection

Data to characterize the motion of the vehicle throughout the multiple frontal impact collisions were limited in the original dataset. Cases involving belted drivers in vehicles with airbags available were reviewed individually and the motion of the vehicle throughout the collision was reconstructed to examine opportunities for occupant protection countermeasures. The order of severity of the impacts, impact speeds, delta-v's, objects contacted, and injury description variables were all analyzed to determine possible differences in injury severity and causation between single frontal impacts and multiple frontal impacts. The reconstructions of the vehicle motion in the individually reviewed cases were used to estimate the distance and time between impacts, and the relationship of lane / roadway departure relative to the impact sequence.

RESULTS

Population Identification

Table 1 displays the distribution of all occupants of all vehicles by number of recorded events. Approximately 25% of vehicles and occupants are involved in collision sequences with multiple events. Two-event collisions constituted approximately 75% of multiple event collision sequences (Table 2).

Table 2.
Distribution of Vehicles and Occupants
By Number of Events,
NASS CDS 1997-2006 [9]

No. of Events	Vehicles		Occupants	
	Raw	*Weighted*	*Raw*	*Weighted*
1	53,539	33,921,445	76,418	45,164,629
2	18,583	8,424,865	28,336	11,853,331
3+	8,909	2,774,325	13,940	3,999,423

Table 2 displays the MAIS 3+ injury rates for single and multiple impact crashes by crash direction. Nearly all multiple impact types sustain higher rates of serious injury when compared with single impacts. Unidirectional multiple impacts have higher rates of serious injury that single impacts. Unidirectional multiple frontal impacts have higher rates of serious injury than all types of single impacts. Only multiple impacts involving an initial impact to the side of the vehicle have higher rates of serious injury than unidirectional multiple frontal impacts (Table 3).

Table 3.
MAIS 3+ Injury Rate per 100 Exposed Drivers,
NASS CDS 1997 – 2006 [10]

Single Impact		**Multiple Impact**			
		Uni-directional		*Multi-directional*	
Frontal	12	Frontal-Frontal	21	Side-Frontal	29
				Frontal-Rear	17
				Frontal-Side	16
				Rear-Frontal	5
Side	15	Side-Side	24	Side-Frontal	29
				Side-Rear	25
				Frontal-Side	16
				Rear-Side	11
Rear	3	Rear-Rear	18	Side-Rear	25
				Frontal-Rear	17
				Rear-Side	11
				Rear-Frontal	5

[9] The NASS CDS is a statistically based sample of certain types of crashes on U.S. roads. Unweighted refers to the raw number of cases present in the NASS CDS dataset. Weighted data refers to the raw cases when multiplied by a weighting factor which relates individual raw cases to the number of actual cases predicted by the sampling system to have occurred on U.S. roads.

[10] All drivers with a known MAIS in vehicles with a known GAD were included in this tabulation to provide an understanding of general injury rates while also providing a distribution of all vehicles. No account was made for belts use or airbag availability / deployment status. Calculated using data in Tables A-2 and A-3.

When examining the distribution of seriously injured (MAIS 3+) drivers in the general population, multiple impacts initiated with a frontal impact accounted for 24% of the population, second only to single frontal impacts. (Figure 2)

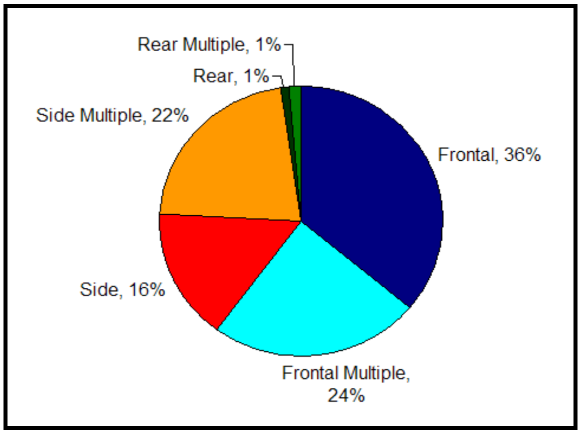

Figure 2. Distribution of MAIS 3+ Drivers by General Area of Damage of First Impact and Type of Impact, CDS 1997-2006. [11]

Prevention

The rate of occurrence of multiple frontal impacts for vehicles that departed the roadway prior to any impact was over five times the rate for vehicles which remained in their lane and was two and a half times the rate for vehicles which departed their lane but remained on the roadway prior to any impact (Table 4).

Table 4.
Vehicles by Pre-Impact Location and Type of Frontal Impact, NASS CDS 1997-2006 [12]

Pre-Impact Location	Type of Frontal Impact	
	Single	*Multiple*
Stayed in lane	71.7%	35.3%
Left travel lane	13.8%	15.4%
Departed Roadway	13.9%	48.2%

For seriously injured belted drivers in vehicles with an airbag available in multiple frontal impacts, cases in which the vehicle departed the roadway prior to any impact constituted 60 percent of the population. These occupants were twice as likely to sustain serious injury when compared to those multiple frontal impact cases where the vehicle did not depart the roadway prior to any impact. (Table 5)

Table 5.
Belted Drivers w/ Airbag Available, Multiple Frontal Impacts, NASS CDS 1997-2006 [13]

Pre-Impact Location (PREILOC)	Maximum AIS	
	2-	*3+*
Stayed in lane	605	51
Left travel lane	194	30
Departed Roadway	548	127
Unknown if left lane	9	0
Remained off road	5	1
Entered roadway	1	0
Returned to road	6	2
Unknown	1	1

Four of the five accident types involving only frontal impacts with the highest rates of occurrence of multiple frontal impacts involved roadway departure. (Table 6)

Table 6.
Frontal Impact Accident Types with Highest Rates of Multiple Frontal Impacts, NASS CDS 1992 – 2006 [14]

Frontal Impact, Accident Type (ACCTYPE)		
Category, Configuration, Accident Type	**% of Population**	**Rate of Multiple Impacts**
Single Driver, Right Roadside Departure, Drive Off Road	6.72%	36%
Single Driver, Left Roadside Departure, Drive Off Road	3.87%	36%
Same-Trafficway - Opposite Direction, Sideswip Angle, Lateral Move	1.08%	36%
Single Driver, Right Roadside Departure, Control / Traction Loss	2.87%	29%
Single Driver, Left Roadside Departure, Control / Traction Loss	2.51%	26%

[11] Calculated using data in Tables A-2 and A-3.

[12] Calculated using data in Table A-4. Percentages are of vehicle population with known pre-impact location. Pre-Impact locations of 'remained off road', 'entered roadway', and 'returned to road' accounted for only approximately 1% of each population and were left off of this summary chart.

[13] MAIS 2- indicates occupants with a Maximum Abbreviated Injury Score of 2 or less (0,1,2).

[14] There are 99 possible accident types across 6 categories and 13 configurations. 18 accident types accounted for 88% of the population. This table presents the five categories which each accounted for more than 1% of the population with the highest rates of multiple frontal impacts. The additional categories have been excluded for brevity.

The results of the analyses identified that lane departure prior to a frontal impact was associated with a more than doubling of the rate of occurrence of multiple frontal impacts and roadway departure was associated with a rate of occurrence more than five times that of vehicles which remained in their lane prior to any frontal impact. Multiple frontal impacts involving roadway departure accounted for 60% of the seriously injured population and were associated with rates of serious injury double that of multiple frontal impacts not involving roadway departure.

Prediction

Offset impacts and sideswipes or collisions with narrow object were associated with higher rates of multiple frontal impacts when compared to single frontal impacts (Tables 7 and 8).

Table 7.
Frontal and Multiple Frontal Impacts
by Specific Horizontal Location of First Impact, NASS CDS 1992 – 2006 [15]

Specific Horizontal Location (SHL) of First Impact	% of Population		Rate of Multiple Frontal Impacts
	Single	Multiple	
Center	1%	2%	20%
Distributed	53%	34%	7%
Driver's Side 1/3	10%	23%	21%
Passenger's Side 1/3	9%	22%	24%
Driver's Side 2/3	15%	10%	7%
Passenger's Side 2/3	12%	8%	8%
Total % / Average Rate	100%	100%	11%

Table 8.
Frontal and Multiple Frontal Impacts
by Type of Damage Distribution of First Impact, NASS CDS 1992-2006 [16]

Type of Damage Distribution (TDD) of First Impact	% of Population		Rate of Multiple Frontal Impacts
	Single	Multiple	
Narrow Impact	3%	12%	34%
Corner	8%	12%	16%
Sideswipe	1%	6%	45%
Wide Impact Area	60%	34%	7%
No CDC	24%	24%	12%
Unknown	3%	13%	33%
Total % / Average Rate	100%	100%	12%

Elevated rates of occurrence of multiple frontal impacts were also associated with initial impacts with objects likely to yield or redirect a vehicle (highlighted in yellow) (Table 9).

Table 9.
Multiple Frontal Impacts
By Object Contacted in First Impacts, NASS CDS 1992-2006 [17]

Object Contacted (OBJCONT) in the First Impact	Type of Impact		Rate of Multiple Frontal Impacts
	Single	Multiple	
Moving Vehicle	82.48%	45.77%	7%
Small / Breakaway Narrow Object	0.90%	13.76%	67%
Roadside Terrain / Object	1.30%	13.04%	57%
Large / Non-Breakaway Narrow Object	7.67%	8.87%	13%
Fixed Object: Concrete Barrier / Other Barrier / Wall	2.82%	7.73%	27%
Vehicle Not In Transit	2.39%	3.69%	17%
Fixed Object: Other / Unknown	0.37%	3.15%	53%
Non-motorist / Non-fixed	1.00%	2.54%	25%
Fixed Object: Impact Attenuator / Building / Bridge	0.88%	0.98%	13%
Unknown Narrow Object	0.14%	0.40%	27%
Unknown Event or Object	0.00%	0.02%	50%
Other: Train	0.03%	0.02%	8%
Non-collision	0.01%	0.02%	33%
Other: Other Event	0.01%	0.02%	33%
Total % / Average Rate	100.00%	100.00%	12%

The analyses identified the connection between increased rates of multiple frontal impacts in offset / narrow first impacts and first impacts with objects likely to yield under impact or redirect the impacting vehicle.

The proportion of kinetic energy remaining after the first impact, P_{ke} was approximated as the ratio of the squares of the estimated speed after the first impact, $V_{pre\ first\ impact}$, and the estimated speed before the first impact, $V_{post\ first\ impact}$. (Equation 1)

$$P_{ke} = (v_{post\ first\ impact})^2 / (v_{pre\ first\ impact})^2 \quad (1).$$

A logistic regression modeling the occurrence of injurious (driver MAIS 3+, belted, airbag available) multiple frontal impacts when compared with the population of injurious single frontal impacts identified the proportion of kinetic energy remaining after the first impact as an indicator of increased likelihood.[18] The model has a maximum rescaled R-squared of 0.4005, with an intercept estimate of -

[15] Calculated using data in Table A-5.

[16] Calculated using data in Table A-6.

[17] Calculated using data in Table A-7.

[18] See Results in appendix B.

4.4601 and a coefficient for the proportion of kinetic energy remaining of 6.8073, both of which were statistically significant ($P < 0.0001$). The probability of a frontal impact resulting in a multiple-frontal impact crosses the 50% mark at a proportion of kinetic energy remaining of 66%. The model shows promise for the utility of the predicted proportion of kinetic energy remaining to predict multiple frontal impacts. The strength of the model could likely be improved with future refinement of the data system to capture more and accurate information about multiple impacts. (Figure 3)

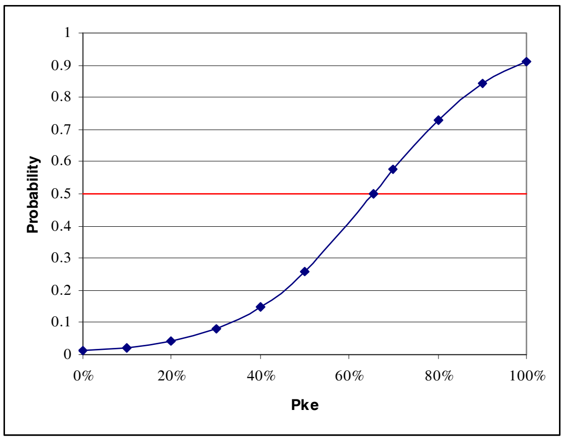

Figure 3. Plot of Probability of Multiple Frontal Impact as a Function of the Proportion of Kinetic Energy Remaining After an Initial Frontal Impact.[19]

Protection

Table 10 shows that multiple frontal impacts are twice as likely to result in serious injury to a belted driver in a vehicle with an airbag available than a single frontal impact. This table also illustrates how other analyses which ignore impacts beyond the most severe impact or which eliminate multiple impacts all together may be missing important information regarding the causation of injuries. Note that despite the rate of serious injury in multiple frontal impacts being double that of single frontal impacts, the overall serious injury rate of 8% for frontal impacts is driven by the preponderance of single frontal impacts in the data set. (Table 10)

[19] Detailed results of model fit may be found in reference [1].

Table 10.
Belted Drivers, Airbag Available,
By Collision Type,
NASS CDS 1997-2006 [20]

Crash Type	Exposed	MAIS 3+	Rate	Percent of Population	Percent of MAIS 3+
Frontal Single	10,148	740	7%	88%	79%
Frontal-Frontal	1,409	195	14%	12%	21%
Total	11,557	935	8%	100%	100%

Multiple frontal impacts in which the more severe impact occurred after the first impact (Secondary / Primary) were nearly twice as likely to result in serious injury among belted drivers of vehicles with airbags available. (Table 11)

Table 11.
Belted Drivers, Airbag Available,
By Order of Severity of Impacts,
NASS CDS 1997 – 2006, Unweighted Data

Impact Order	MAIS		MAIS 3+ Rate
	2-	3+	
Primary - Secondary	818	91	10%
Secondary - Primary	483	114	19%

Multiple frontal impacts in which the more severe impact occurred first in the collision sequence (Primary / Secondary) had a higher concentration of seriously injured occupants at delta-v's below 20 mph. Comparatively, when the most severe impact occurred after the first collision in the impact sequence (Secondary / Primary), the concentration of seriously injured occupants extended into higher delta-v's up to 40 mph. This difference may be related to the combination of delta-v's of the impacts. In primary-secondary type impacts, a lower primary delta-v is necessary to cause injury when combined with a secondary impact. Conversely, in a secondary – primary type impact, a higher impact speed may be required at the first impact (regardless of delta-v) which is then carried over to the second impact (primary delta-v). Seriously injured occupants in single frontal impacts were concentrated in the delta-v range of 11 to 30 mph (Table 12, Figures 4 and 5).

[20] Calculated using data in Table A-8

Table 12.
Belted Drivers, Airbag Available,
By Delta-V of Most Severe Impact,
NASS CDS 1997-2006, Unweighted Data [21]

Delta-V Range of Most Severe (Primary) Impact (mph)	MAIS 3+ Rate		
	Single Frontal	Multiple Frontal	
		Primary - Secondary	*Secondary - Primary*
x <= 10	1%	2%	2%
10 < x <= 20	4%	9%	11%
20 < x <= 30	18%	11%	31%
30 < x <= 40	36%	37%	50%
40 < x <= 50	67%	100%	67%
50 < x <= 60	89%	100%	50%
60 < x <= 70	100%	-NA-	100%
Average	7%	9%	19%

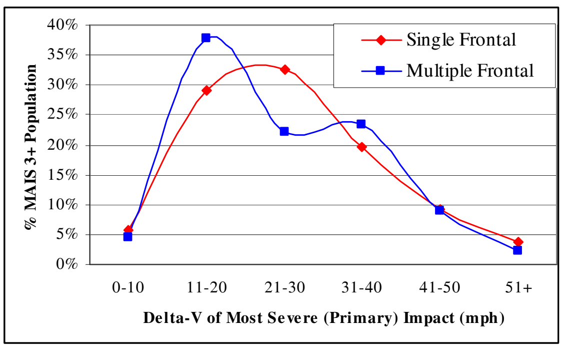

Figure 4. Belted Drivers, Airbag Available, MAIS 3+ Population, By Crash Severity, NASS CDS 1997-2006, Unweighted Data.[22]

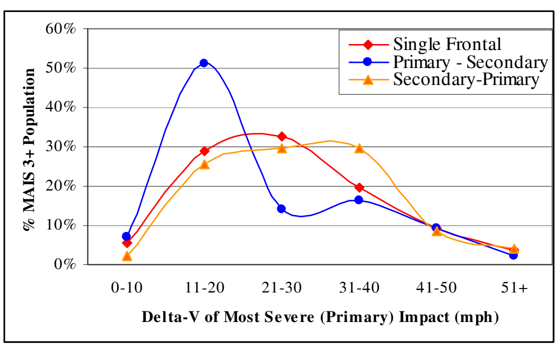

Figure 5. Belted Drivers, Airbag Available, MAIS 3+ Population, By Crash Severity, NASS CDS 1997-2006, Unweighted Data. [23]

When comparing single and multiple frontal impacts where the belted driver of a vehicle with an airbag available sustained a serious injury, it was found that unlike single frontals where other vehicles are most often the object contacted, multiple frontal impacts involved more collisions with fixed objects. (Table 13)

Table 13.
MAIS 3+ Belted Drivers, Airbag Available,
Single and Multiple Frontal Impacts
By Object Contacted, NASS CDS 1997-2006 [24]

Object Type	Object Contacted (OBJCONT)			
	Single Frontal	*Multiple Frontal*		
		All Impacts	First Impact	Second Impact
Vehicle	80%	31%	19%	12%
Fixed Object	18%	43%	13%	30%
Small / Breakaway Object & Non-Fixed Object	2%	17%	10%	6%
Roadside Terrain / Object	1%	9%	7%	2%
Total	100%	100%	50%	50%

Using the same data, when the distribution of objects contacted was examined according to each impact, it was observed that in multiple frontal impacts, while the first object contacted is still most often another vehicle, the second object contacted is often a fixed object. (Table 14)

[21] Calculated using data in Table A-9.

[22] Calculated using data in Table A-9.

[23] Calculated using data in Table A-9.

[24] Calculated using data in Table A-10.

Table 14.
MAIS 3+ Belted Drivers, Airbag Available, Single and Multiple Frontal Impacts, Objects Contacted by Impact, NASS CDS 1997-2006 [25]

Object Type	Object Contacted (OBJCONT)		
	Single Frontal	*Multiple Frontal*	
		First Impact	Second Impact
Vehicle	80%	38%	23%
Fixed Object	18%	27%	60%
Small / Breakaway Object & Non-Fixed Object	2%	21%	13%
Roadside Terrain / Object	1%	14%	4%
Total	100%	100%	100%

For multiple frontal impacts in which the most severe impact occurred after the initial impact, the head / face / neck ranked body region group was the most often injured region of the body, accounting for 56% of the MAIS 3+ injuries by ranked body region. This is an increase when compared with the overall multiple frontal impact population in which the head / face / neck only accounts for 47% of the serious injuries. In multiple frontal impacts in which the most severe impact occurred first in the collision sequence, the head / face / neck accounted for a smaller proportion of injuries, 36%, with an increase in extremity injuries when compared with single frontal impacts. (Table 15)

Table 15.
Individually Reviewed Cases, By Ranked Body Region [26]

Ranked Body Region	MAIS 3+ Drivers		
	All	Primary - Secondary	Secondary - Primary
Head / Face /Neck	47%	36%	56%
Thorax / Abdomen / Spine	13%	11%	15%
Lower Extremity	20%	25%	16%
Upper Extremity	19%	27%	13%

Over half of the multiple frontal impacts had impacts after the initial collision occurring within 100 ft of the initial impact. (Table 16)

Table 16.
Individually Reviewed Cases By Distance Between Impacts [27]

Distance Between Impacts (ft)	Population %
x <= 100	51%
100 < x <= 200	29%
200 < x <= 300	10%
300 < x <= 400	1%
400 < x <= 500	6%
500 < x	4%
Total	100%

Approximately half of the multiple frontal impacts had impacts after the initial collision occurring less than 2 seconds after the initial impact. (Table 17)

Table 17.
Individually Reviewed Cases By Time Between Impacts [28]

Minimum Time Between Impacts (S)	Population %
t <= 1	15%
1 < t <= 2	36%
2 < t <= 3	15%
3 < t <= 4	7%
4 < t <= 5	7%
5 < t	19%
Total	100%

While only 49% of all multiple frontal cases in the original dataset were reported as having involved roadway departure, 77% of the multiple frontal impacts cases individually reviewed involved roadway departure. Roadway departure, as determined from the individual case reviews, identified 19 cases (out of the total of the 108 individually reviewed cases) where the pre-impact location variable in the original dataset (PREILOC) did not accurately identify the involvement of roadway departure (highlighted in yellow). 80% of the individually reviewed cases with roadway departure involved roadway departure prior to any impact. (Table 18)

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[25] Calculated using data in Table A-10.

[26] Calculated using data in Table A-11.

[27] Calculated using data in table A-12.

[28] Calculated using data in Table A-13.

Table 18.
Individually Reviewed Cases,
Comparison of Roadway Departure
And Coded Pre-Impact Location

Pre Impact Location					
		From PREILOC Variable			
From Case Analysis		*Stayed in Lane*	*Left Travel Lane*	*Departed Roadway*	*Returned to Road*
Stayed in Lane		2	0	0	0
Left Travel Lane	Before Any Impact	1	9	3	0
	After First Impact	8	1	1	0
Departed Roadway	Before Any Impact	1	2	62	1
	After First Impact	13	3	1	0

Multiple frontal impacts where the most severe impact did not occur first in the collision sequence had higher concentrations of injured occupants at higher severities than single frontal impacts. The head / face / neck body region constituted the highest proportion of the serious injuries in multiple frontal impacts where the most severe impact did not occur first in the collision sequence.

The individual case reconstructions also identified that over half of multiple frontal impacts had impacts after the initial impact occurring within 100 ft of the initial impact. Half of the cases had subsequent impacts occurring 2 seconds or less after the initial impact. More than three quarters of the individually reviewed cases involved roadway departure, most of which occurred before any impacts in the collision sequence.

DISCUSSION

This work examined the occurrence of multiple frontal impacts from the perspective of developing countermeasures to prevent these crashes from occurring, predict their occurrence in the course of a crash sequence, and protect occupants in multiple events.

Lane or roadway departure occurred in 64% of multiple frontal impact crashes and was associated with a nearly fourfold increase in the rate of occurrence of multiple frontal impacts when compared with single impacts. This finding holds great promise for possible safety benefits of lane / road departure warning systems being implemented in the vehicle fleet today and an analysis of the impact of electronic stability control systems with respect to the occurrence of multiple impacts may identify additional benefits of this existing technology.

The examination of the dynamics of the vehicle during the collision identified that increased rates of multiple frontal impacts are associated with offset impacts and impacts with objects which yield or are designed to re-direct a vehicle. The proportion of kinetic energy remaining after the first impact was identified as a possible predictor of the likelihood of multiple impacts. Combined, these findings indicate that the incorporation of algorithms to identify collisions which are unlikely to bring a vehicle to a stop or are resulting in re-direction would enable the design of occupant protection countermeasures to address multiple frontal impacts.

Multiple frontal impacts were identified as having an elevated rate of serious injury (MAIS 3+). Of the population of seriously injured drivers, 24% were involved in multiple impacts initiated by a frontal impact. Multiple frontal impacts alone accounted for 10% of the seriously injured driver population. These findings highlight the risk these collisions pose and the opportunity to improve safety by addressing them.

The in-depth study of individual cases found that the initial impact was the most severe in 44% of the crashes. A vehicle was the most frequent initial contact when the initial impact was most severe. For the 56% of the crashes in which subsequent impacts were most severe, a fixed object was the most frequent severe contact. The in-depth study produced the following observations. (1) The mean crash severity for multi-impact frontal crashes was higher than for single event frontal crashes. (2) The highest mean crash severity occurred when the subsequent impact was more severe than the initial impact (3) About half of the crashes had a distance greater than 100 ft between the impacts and a time interval greater than 2 seconds. (4) The body region most frequently injured was the head. Combined, these findings regarding the conditions within multiple frontal impacts in which optimally protected drivers (belted with airbag available) are being injured provide insight into parameters for a multiple frontal impact protection system. Such a system would have to be better suited to address acceleration pulses associated with higher severity collisions into fixed and generally narrow objects. The triggering system for any countermeasures must be able to sustain its capability for at least two seconds after the initial impact. Finally, multiple frontal impact countermeasures should be focused on protecting the head / face / neck body region.

OBSERVATIONS / LIMITATIONS

The study of multiple impacts suffers significantly from the current design of the databases recording information on crashes. While information regarding some aspects of multiple impacts could be ascertained from the current design, individual case analysis was required to properly identify and code important aspects of these complex collisions. Details about impacts other than the most severe impact in a collision sequence are often overlooked or dismissed. This work has expanded upon earlier works to indicate the dangers posed by these types of collisions and the benefits which added detail in current databases could provide. Most notably, and as indicated in the complete work by these authors, the study of multiple impacts in general could benefit significantly from the widespread adoption and proper implementation of electronic data recorders (EDRs) in vehicles. EDRs which can record multiple events would provide a wealth of data presently being left out of current databases for a variety of reasons. Despite data limitations, the findings of this study are consistent with earlier works and results from the general study and the individual case reviews are also consistent.

CONCLUSIONS

Multiple impacts initiated by a frontal impact account for about 24% of the population of seriously injured (MAIS 3+) drivers in recent model passenger vehicles. Multiple frontal impacts alone accounted for 10% of the seriously injured driver population. Lane departure and roadway departure were the most frequent pre-crash events. The proportion of kinetic energy remaining after the first impact was identified as a possible predictor of the likelihood of multiple impacts. About 50% of the crashes in an in-depth study had a time interval of 2 seconds or less between the impacts. In the majority of these crashes, the subsequent impact was more severe than the initial impact. The head / face / neck body region constituted a highest proportion of the serious injuries in multiple frontal impacts where the most severe impact did not occur first in the collision sequence. Countermeasures in both crashworthiness and crash avoidance appear possible to address this opportunity to reduce casualties. Crash imminent and crash triggered braking systems which would reduce velocity prior to and after an initial impact would reduce the probability of vehicles in frontal impacts being involved in subsequent impacts. Lane and roadway departure prevention and warning systems as well as ESC systems could also reduce the chances of multiple frontal impacts. Occupant protections systems developed to address multiple frontal impacts should focus on retaining capability for deployment for up to two seconds after the initial impact and maintaining safety belt protection for periods beyond 2 seconds.. Deployment strategies which allow occupant protection systems to function during subsequent impacts which are more severe than the initial impact would address those situation which are associated with elevated levels of serious injury.

ACKNOWLEDGMENTS

Funding for this research has been provided, in part, by private parties, who have selected Dr. Kennerly Digges [and the FHWA/NHTSA National Crash Analysis Center at the George Washington University] to be an independent solicitor of and funder for research in motor vehicle safety, and to be one of the peer reviewers for the research projects and reports. Neither of the private parties have determined the allocation of funds or had any influence on the content.

The authors wish to thank Dr. Azim Eskandarian, Dr. Pedro F. Silva, Dr. Samar Hamdar and Dr.William T. Hollowell for their review and suggestions during the course of this research.

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Definitions / Abbreviations:

ACCTYPE : NASS CDS variable, Accident Type.

ANCIS : Australian National Crash In-Depth Study.

CDS : Crashworthiness Data System.

GAD1, GAD2 : NASS CDS variable, General Area of Damage.

GIDAS : German In-Depth Accident Study.

IMPACTSP : NASS CDS variable, Impact Speed.

MAIS : Maximum Abbreviated Injury Score.

MAIS 3+ : Maximum Abbreviated Injury Score of 3 or greater (3,4,5,6)

MAIS 2- : maximum Abbreviated Injury Score of 2 or less (0,1,2)

NASS: National Automotive Sampling System.

OBJCONT1, OBJCONT2 : NASS CDS variables, Object Contacted.

PDOF1, PDOF2 : NASS CDS variable, Principal Direction of Force.

P_{ke} : Proportion of kinetic energy remaining after an initial impact.

PREILOC : NASS CDS variable, Pre-Impact Location.

Primary Impact : most severe impact in a multiple impact collision sequence.

Primary – Secondary : Multiple impact collision sequence in which the first impact is the most severe impact.

Secondary Impact : impact in a multiple impact collision sequence which is not the most severe impact.

Secondary – Primary : Multiple impact collision sequence in which the first impact is not the most severe impact.

SHL1, SHL2 : NASS CDS variables, Specific Horizontal Location

SPLIMIT : NASS CDS variable, Speed Limit

TDD1, TDD2 : NASS CDS variables, Type of Damage Distribution

TRAVELSP : NASS CDS variables, Travel Speed

VEHNO: NASS CDS variable, identifies a particular vehicle in a crash.

$v_{post\ first\ impact\ t}$: Vehicle speed after the first impact

$v_{pre\ first\ impact}$: Vehicle speed prior to first impact

Appendix

Table A-1.
Population of Occupants by Impact Type, Comparison of GIDAS & NASS CDS data.

Impact Type	GIDAS 1996 - 2000		NASS CDS 1996 - 2000		NASS CDS 2001 - 2006	
	MAIS					
	2-	3+	2-	3+	2-	3+
Single Frontal	3,103	96	10,274	1,841	12,967	1,984
Single Side	1,381	61	3,459	849	4,278	819
Single Rear	801	6	974	45	1,189	47
Single Rollover	31	3	545	255	713	316
Multiple Impact	2,040	125	8,099	2,932	11,014	3,912

Table A-2.
MAIS 2- Driver Population by Impact Type, NASS CDS 1997 – 2006

MAIS 2-					
Single Impact		**Multiple Impact**			
		Uni-directional		*Multi-directional*	
Frontal	16,401	Frontal-Frontal	2,339	Side-Frontal	946
				Frontal-Rear	598
				Frontal-Side	3,933
				Rear-Frontal	992
Side	5,569	Side-Side	2,996	Side-Frontal	946
				Side-Rear	246
				Frontal-Side	3,933
				Rear-Side	252
Rear	1,507	Rear-Rear	41	Side-Rear	246
				Frontal-Rear	598
				Rear-Side	252
				Rear-Frontal	992

Table A-3.
MAIS 3+ Driver Population by Impact Type, NASS CDS 1997 – 2006

MAIS 3+					
Single Impact		**Multiple Impact**			
		Uni-directional		*Multi-directional*	
Frontal	2,302	Frontal-Frontal	630	Side-Frontal	378
				Frontal-Rear	125
				Frontal-Side	766
				Rear-Frontal	54
Side	994	Side-Side	949	Side-Frontal	378
				Side-Rear	82
				Frontal-Side	766
				Rear-Side	31
Rear	43	Rear-Rear	9	Side-Rear	82
				Frontal-Rear	125
				Rear-Side	31
				Rear-Frontal	54

Table A-4.
Vehicles by Pre-Impact Location and Type of Frontal Impact, NASS CDS 1997-2006

Pre-Impact Location	Type of Frontal Impact	
	Single	*Multiple*
Stayed in lane	22,593	1,562
Left travel lane	4,348	680
Departed Roadway	4,364	2,134
Unknown if left lane	244	29
Remained off road	71	36
Entered roadway	63	2
Returned to road	57	14
Unknown if left lane	357	39
No Driver	1	1

Table A-5.
Frontal and Multiple Frontal Impacts by Specific Horizontal Location of First Impact, NASS CDS 1992 – 2006

Specific Horizontal Location (SHL) of First Impact	Type of Impact	
	Single	**Multiple**
Center	217	53
Distributed	9,934	781
Driver's Side 1/3	1,955	532
Passenger's Side 1/3	1,613	505
Driver's Side 2/3	2,757	219
Passenger's Side 2/3	2,308	188
Total	18,784	2,278

Table A-6.
Frontal and Multiple Frontal Impacts by Type of Damage Distribution of First Impact, NASS CDS 1992-2006

Type of Damage Distribution (TDD) of First Impact	Type of Impact	
	Single	**Multiple**
Narrow Impact	1,147	586
Corner	3,064	576
Sideswipe	341	281
Wide Impact Area	22,759	1,705
No CDC	9,192	1,203
Unknown	1,311	639
Total	37,814	4,990

Table A-7.
Multiple Frontal Impacts
By Object Contacted in First Impacts,
NASS CDS 1992-2006

Object Contacted (OBJCONT) in the First Impact	Type of Impact: Single	Type of Impact: Multiple
Moving Vehicle	31,344	2,292
Small / Breakaway Narrow Object	343	689
Roadside Terrain / Object	493	653
Large / Non-Breakaway Narriow Object	2,915	444
Fixed Object: Concrete Barrier / Other Barrier / Wall	1,072	387
Vehicle Not In Transit	909	185
Fixed Object: Other / Unknown	139	158
Non-motorist / Non-fixed	381	127
Fixed Object: Impact Attenuator / Building / Bridge	334	49
Unknown Narrow Object	54	20
Unknown Event or Object	1	1
Other: Train	12	1
Non-collision	2	1
Other: Other Event	2	1
Total	38,001	5,008

Table A-8.
Belted Drivers, Airbag Available,
By Collision Type,
NASS CDS 1997-2006

Number of Impacts: Type	Number of Impacts: Rate	Impact Direction: Type	Impact Direction: Rate	Occupant: Type	Occupant: Rate	Belt Use: Type	Belt Use: Rate	Population by MAIS: 2-	Population by MAIS: 3+
Single	10%	Frontal	10%	Driver	10%	Belted	7%	9,408	740
						Unbelted	24%	1,396	448
				Other	8%	Belted	6%	2,301	149
						Unbelted	17%	409	83
		Other	11%	Driver	11%	Belted	9%	4,503	427
						Unbelted	31%	475	211
				Other	9%	Belted	7%	1,452	114
						Unbelted	21%	206	56
Multiple	17%	Frontal-Frontal	18%	Driver	19%	Belted	14%	1,214	195
						Unbelted	32%	354	164
				Other	18%	Belted	15%	285	51
						Unbelted	25%	89	29
		Other	17%	Driver	17%	Belted	13%	6,106	874
						Unbelted	35%	1,134	622
				Other	15%	Belted	12%	1,747	228
						Unbelted	28%	398	152

Table A-9.
Belted Drivers, Airbag Available,
By Delta-V of Most Severe Impact,
NASS CDS 1997-2006, Unweighted Data

Delta-V Range of Most Severe (Primary) Impact	MAIS: Single Frontal		MAIS: Multiple Frontal: *Primary - Secondary*		MAIS: Multiple Frontal: *Secondary - Primary*	
	2-	3+	2-	3+	2-	3+
x <= 10	2,607	30	142	3	52	1
10 < x <= 20	3,684	153	224	22	100	12
20 < x <= 30	782	172	48	6	31	14
30 < x <= 40	183	103	12	7	14	14
40 < x <= 50	24	49	0	4	2	4
50 < x <= 60	2	17	0	1	1	1
60 < x <= 70	0	3	0	0	0	1
Total	7,282	527	426	43	200	47

Table A-10.
MAIS 3+ Belted Drivers, Airbag Available,
Single and Multiple Frontal Impacts
By Object Contacted, NASS CDS 1997-2006

Object Type	Object Contacted: *Single Frontal*	Object Contacted: *Multiple Frontal*: First Impact	Object Contacted: *Multiple Frontal*: Second Impact
Vehicle	637	72	44
Fixed Object	141	51	113
Small / Breakaway Object & Non-Fixed Object	14	39	24
Roadside Terrain / Object	9	27	8
Total	801	189	189

Table A-11.
Individually Reviewed Cases,
By Ranked Body Region

Ranked Body Region	MAIS 3+ Drivers: *All*	MAIS 3+ Drivers: Primary - Secondary	MAIS 3+ Drivers: Secondary - Primary
Head / Face /Neck	47	16	31
Thorax / Abdomen / Spine	13	5	8
Lower Extremity	20	11	9
Upper Extremity	19	12	7
Total	99	44	55

Table A-12.
Individually Reviewed Cases
By Distance Between Impacts

Distance Between Impacts (ft)	N
x <= 100	43
100 < x <= 200	24
200 < x <= 300	8
300 < x <= 400	1
400 < x <= 500	5
500 < x	3
Total	84

Table A-13.
Individually Reviewed Cases
By Time Between Impacts

Minimum Time Between Impacts (S)	N
t <= 1	11
1 < t <= 2	26
2 < t <= 3	11
3 < t <= 4	5
4 < t <= 5	5
5 < t	14
Total	72

ASSESSMENT OF A PRE-CRASH SEATBELT TECHNOLOGY IN FRONTAL IMPACTS BY USING A NEW CRASH TEST SLED SYSTEM WITH CONTROLLABLE PRE-IMPACT BRAKING

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ABSTRACT

The objective of this study is to develop a new method and tools required for the evaluation of the potential benefits of pre-impact safety restraint systems.

A pre-crash sled system that can reproduce controlled pre-impact braking in combination with a variety of crash pulses was built. The sled can be customized from existing vehicles to examine a variety of restraint systems. In addition, a previously validated 50th percentile male Hybrid III dummy with a modified lumbar was employed to reconstruct realistic driver's posture changes at the pre-impact braking phase.

In order to evaluate the potential benefits of a pre-crash seatbelt (PSB), the modified dummy was placed on the sled with a standard seating posture and restrained by either a conventional seatbelt (SB) or a PSB controlled by a motor in the retractor. The sled system was then programmed to reach a steady speed of 64 km/h, followed by a 0.8 g deceleration and 0.8 seconds of duration, just before colliding against the barrier at the speed of 48 km/h.

Increased forward travelling of the upper body at the pre-impact braking phase with the SB was measured in comparison to the PSB case.

In the PSB case, full airbag deployment occurred before body-to-airbag contact, allowing the airbag in coordination with the belt to mitigate the neck loading optimally and to reduce a 15% of chest acceleration. In the SB case, body-to-airbag contact occurred before its complete deployment, causing increased neck forces and moments as well as chest acceleration. In contrast, equivalent chest deflections for both types of seatbelts were measured.

In this research, a new pre-crash sled system with the potential to evaluate pre-crash safety restraint systems was developed. Crash tests with dummies were conducted in order to examine the effectiveness of a PSB. By controlling the posture change during an emergency braking, the reduction of neck and chest injury risk in front impacts was achieved. This confirms the potential of a PSB to enhance occupant protection.

INTRODUCTION

Occupant safety in crashes has commonly been discussed by means of experiments or simulations with 50th percentile male crash test dummies and human computer models in normal sitting posture. However, posture changes occur just before the collisions due to occupant evasive maneuvers and occupant inertia, which makes it difficult to keep a normal posture just before the collision.

Changes in driver's posture and velocity during emergency maneuvers exert influence on the injury risks in front impact collisions [1]. In order to mitigate the potentially negative effects of these changes, current vehicles are equipped with pre-impact safety restraint systems. In parallel to the employment of these systems, new protocols and methods to test their performance are needed.

In order to mitigate the potentially negative effects of these posture changes, current vehicles are equipped with pre-impact safety restraint systems, such as a pre-crash seat belt (PSB) system [2][3][4][5].

With regard to the change of posture, Ejima et al. [6], based on multi-body simulations, showed that body size and initial posture affect injury outcome in frontal collision with pre-impact braking. Antona et al. [7], based on calculations with a human Finite Element (FE) model, showed differences in chest and neck interaction with restraint systems in the impact situations with/without pre-impact braking.

The performance of the pre-impact safety restraint systems can be evaluated with different methodologies. Tobata et al. [2], in their numerical and experimental study, indicated that a motor retractor which retracts belt webbing in emergency braking improves initial restraint and thereby reduces the chest acceleration of occupants in crashes. Schoeneburg et al. [5] reported that a pre-crash safety device that includes a reversible (motorized) seatbelt tensioner can reduce neck extension moment in full vehicle crash tests with pre-impact braking.

In the employment of new restraint systems, new reliable protocols and methods to test their performance are also needed. In addition, it is necessary to achieve a good balance between the evaluation of the equipment and the costs associated with the tests.

This study attempts to propose a new experimental method to assess the potential benefits of a pre-impact safety restraint system in front impact collisions. For this purpose, crash tests employing the dummies constrained on a pre-crash sled were conducted to evaluate a pre-impact safety restraint system. In addition, in order to reveal effects of PSB compared with a conventional seat belt (SB), the responses of neck and chest of a crash test dummy between the two tests were discussed.

METHODS

The methodology of this study consists of the evaluation of the potential benefits of a PSB in comparison with a SB in terms of optimized dummy interaction with the restraint systems and improvement of dummy injury indicators. This was done by conducting one crash test with a PSB and the other with a SB. The tests were conducted with the newly developed customizable pre-crash sled with a programmed pre-impact braking and a controllable crash pulse.

Pre-crash Sled System

A new sled for the crash test that can reproduce pre-impact braking and crash pulse was developed. Crash tests with the pre-crash sled were conducted on the rail of the crash test facility. The sled is accelerated on the rail by a pulling unit until it reaches the prescribed running speed. Then the sled is released from the pulling unit, and the programmed braking pulse is applied before the sled collides against the shock absorbers at the front of the fixed barrier. Figure 1 shows the scheme of the pre-crash sled system.

By replacing the shock absorbers, the sled can be used repeatedly. Hence, the performance of restraint system in crash pulse involving pre-impact braking can be evaluated at a lower cost than full-scale vehicle crash tests. In addition, less visual obstruction of the sled allows capturing the test imagery with both on-board and off-board cameras.

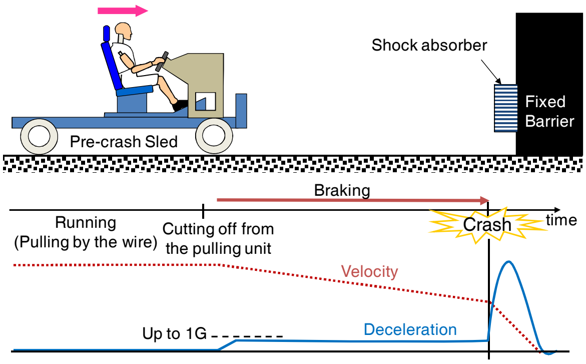


Figure 1. Scheme of the pre-crash sled system.

The sled was designed to minimize pitching mode, providing peak pitching angles at collision with around 1 degree, which allows obtaining reproducible results according to standard specifications for HYGE sleds.

For this study, the pre-crash sled was equipped with a driver’s airbag, a rigid seat, a knee bolster, and foot plates. In order to reconstruct realistic driver’s posture changes at the pre-impact braking phase, a 50th percentile male Hybrid III dummy with a modified lumbar [8] was employed. The upper body flexion characteristics were improved by modifying the shape of the lumbar section and were validated against low speed impact tests with volunteers [6]. In addition, it was confirmed that trajectory of head and chest after collision and chest sensor readings in the case of the dummy with the modified lumbar were similar to those in the case of normal Hybrid III dummy [9].

The dummy was placed on the rigid seat with a standard seating posture and restrained by a driver's three-point seatbelt in a right hand drive car configuration. Figure 2 shows a picture of the pre-crash sled system and the dummy in testing place.

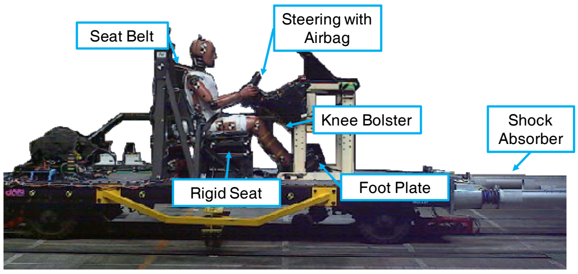


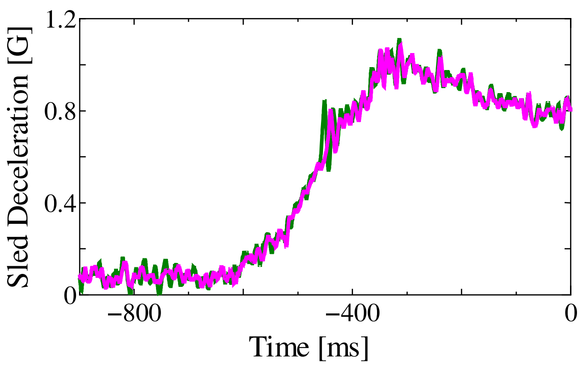
Figure 2. Picture of the pre-crash sled system.

Test Conditions

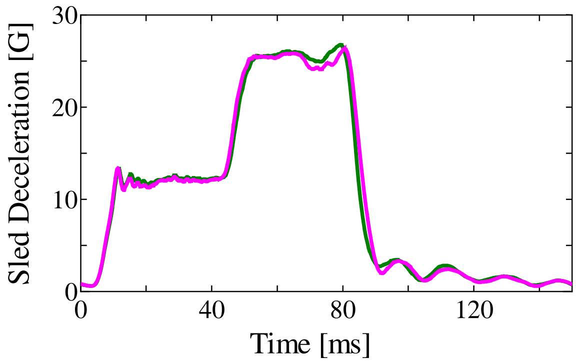
Two crash tests preceded by pre-impact braking were conducted with a SB and a PSB, respectively. Both belt systems are furnished with an emergency lock retractor, a pretensioner, and a force limiter. In addition, the PSB had a motorized retractor, which automatically tightens the belts when the vehicle's pre-collision sensing system determines an imminent collision.

Both tests were conducted under the same braking and crash conditions. The sled system was programmed to reach a steady speed of 64 km/h, followed by a 8 m/s^2 deceleration and 0.8 seconds of duration (Figure 3 (a)), just before colliding against the barrier at a speed of 48 km/h. The crash pulse (Figure 3 (b)) was based on the longitudinal component of a deceleration pulse of Offset Deformable Barrier (ODB) crash tests typically employed for passenger vehicles.

The forces exerted on the dummy were measured by load cells attached to the foot plates, the seat, the shoulder belt, and the lap belt. Kinematics of the dummy was evaluated by using dummy built-in sensors and high speed video analysis of target markers on the dummy surface.



(a) Braking Pulse



(b) Crash Pulse

Figure 3. Comparison of braking and crash pulses recorded from the tests.

RESULTS

In order to examine the differences between SB and PSB, comparisons of dummy responses in terms of sensors readings, dummy interactions with belts and airbag, and overall body kinematics are presented.

Dummy kinematics

Figure 4 indicates the comparison by means of sequential images of the tests with SB and with PSB at 0, 50, and 100 ms from the beginning of the crash

Figure 5 shows the comparison of the dummy's posture changes in two cases with respect to the seat as processed from the on-board high speed camera. Larger forward travelling distances of the upper body at the pre-impact braking phase in the SB case was measured in comparison with the PSB case. Shown in Figure 5, head displacement after the collision in the SB case was smaller than that in the PSB case because of the forward travelling distances of the upper body during the pre-impact braking. This was especially apparent in the head motion from 50 ms to 90 ms: the head in the SB case stopped rapidly after 70 ms, while the head in the PSB case decelerated gradually over crash event. In other words, the head of the dummy in the SB case stopped in a shorter distance than that in the PSB case. These results indicate that much more load was applied to head and neck of the dummy in the SB case.

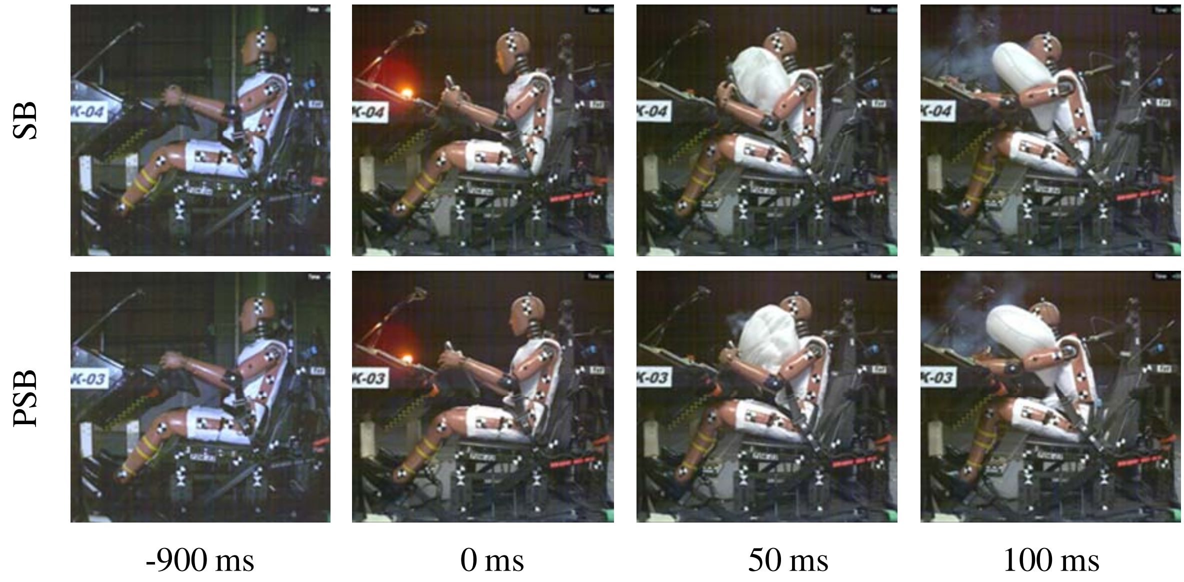
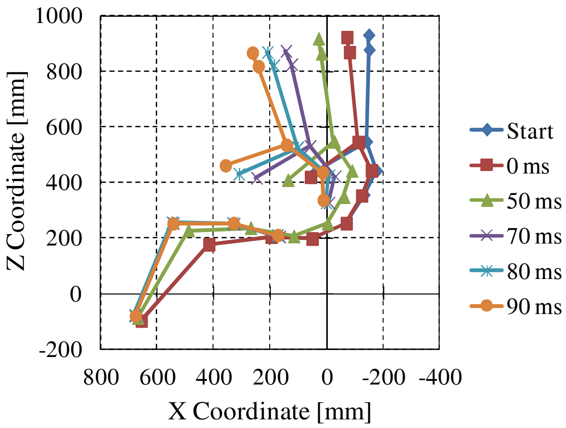
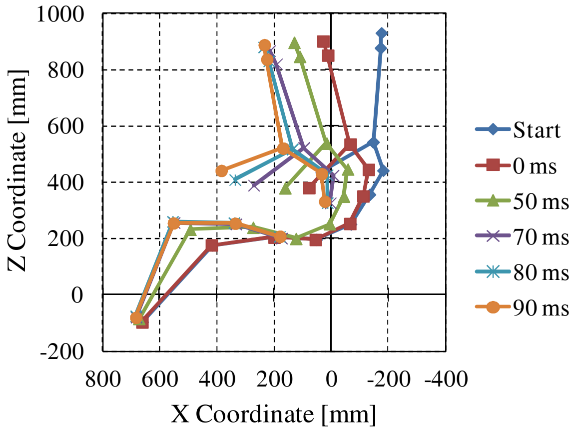


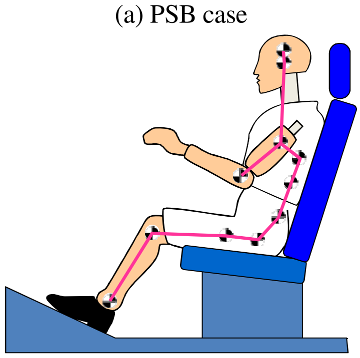
Figure 4. Sequence of pictures at -900, 0, 50 and 100 ms from the initiation of the crash for the SB test (above) and the PSB (below).



(a) PSB case



(b) SB case



(c) Marker location on the dummy

Figure 5. Trajectory of target markers attached on the head and chest with respect to seat.

Dummy sensors readings

Figure 6 to 10 show comparisons of the dummy readings of head acceleration, neck force, neck moment, chest acceleration, and chest deflection.

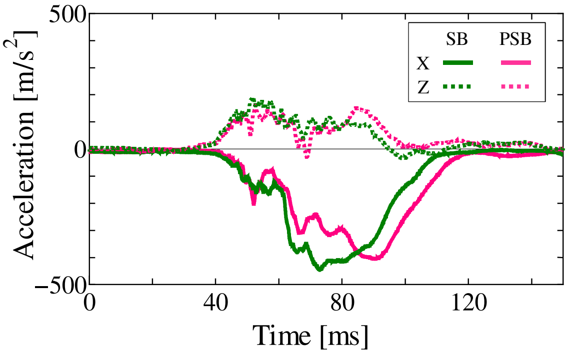


Figure 6. Head acceleration.

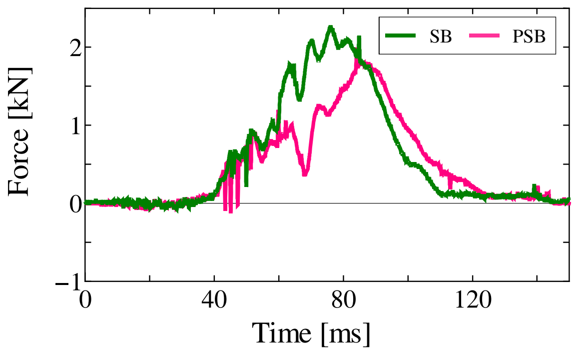


Figure 7. Neck tension-compression force.

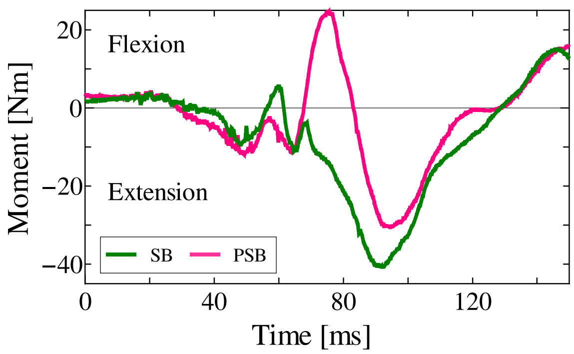


Figure 8. Neck flexion-extension moment.

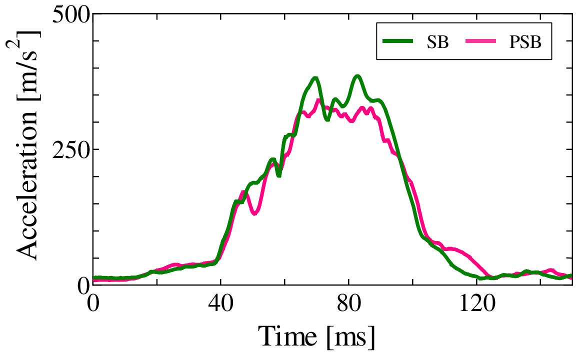


Figure 9. Chest resultant acceleration.

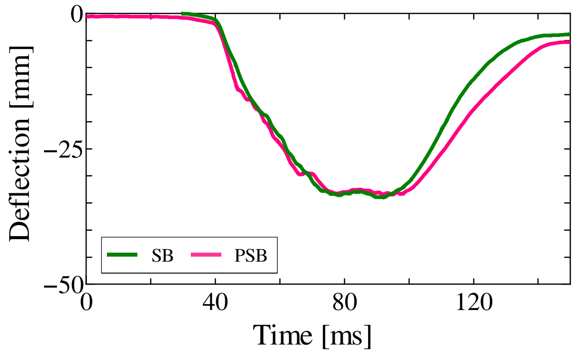


Figure 10. Chest deflection.

Comparatively higher values were obtained in the SB case regarding neck tension, neck extension, and chest resultant acceleration. As for the neck loading mechanism, while the PSB case showed both flexion and extension, only extension occurred in the SB case, with higher peak than in the PSB case.

Interaction with the belts: Measured forces

Figures 11 to 13 show the comparison of the shoulder belt forces measured at the upper right and the lower left hand side of the dummy, and the the lap belt forces measured at the dummy's right hand side. At the crash timing, the shoulder belt forces in the PSB case were slightly higher than those in the SB case. These difference are associated with the belt retraction by the PSB during the pre-impact braking. However, at crash initiation, all readings were identical in both cases, which indicates that only dummy posture differed.

During the impact, the upper shoulder belt force in the PSB test was slightly higher than that in the SB case, this effect being associated with a slight reduction of chest acceleration (Figure 9) without affecting maximum chest deflection (Figure 10).

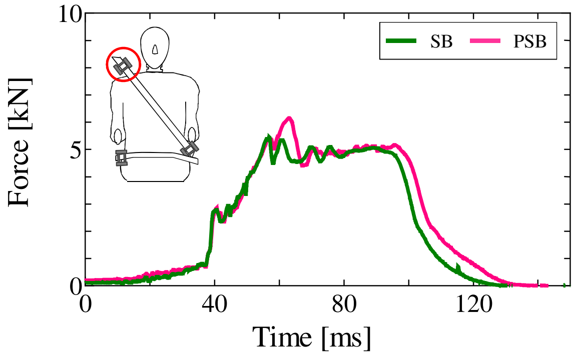


Figure 11. Upper Shoulder belt force.

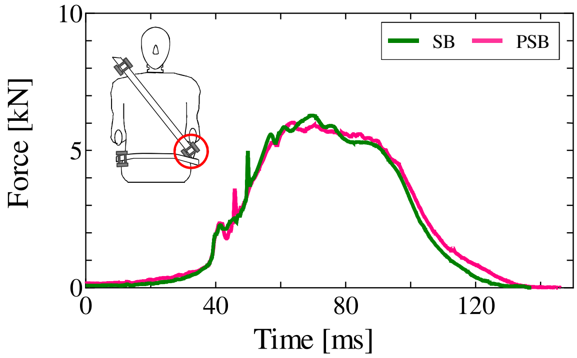


Figure 12. Lower Shoulder belt force.

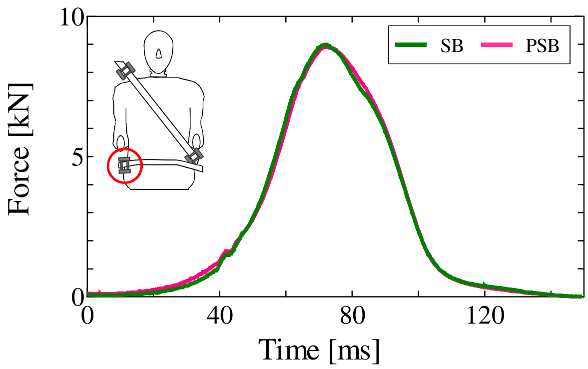


Figure 13. Lap belt force.

Interaction with the airbag: Estimated forces

In both tests, the head of the dummy initiated the contact with the airbag at around 50 ms after the beginning of the impact. From then on, the responses of head and neck showed clear differences, as indicated in the neck readings (Figures 7 and 8). In the SB test, forward bending posture of the body resulted in contact between the dummy face and the airbag before full deployment. This induced higher head and neck loads in terms of acceleration (Figure 6) and tension force (Figure 7), respectively, when compared with those in the PSB test.

In order to examine the body interaction with the airbag in more detail, time histories of the contact force with the airbag were estimated following a free body diagram method [10] sketched in Figure 14. With this method, translational motion of the head was expressed by means of neck forces and airbag contact forces in the following equation of motion:

$$m\boldsymbol{a}_{\text{head}} = \boldsymbol{F}_{\text{neck}} + \boldsymbol{F}_{\text{A/B}} \qquad (1)$$

Where

- *m:* mass of the dummy head (4.54 kg)
- $\boldsymbol{a}_{\text{head}}$: head acceleration vector
- $\boldsymbol{F}_{\text{neck}}$: neck force vector
- $\boldsymbol{F}_{\text{A/B}}$: contact force vector between the head and the airbag.

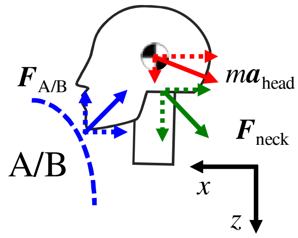


Figure 14. Sketch of free body diagram.

The airbag contact forces estimated according to equation (1) are shown in Figures 15 and 16. The contact force waveform in the longitudinal direction was similar to that of the head acceleration in longitudinal direction. The curve in the vertical direction was similar to neck tension curves, which reinforces the evidence that neck extension of the occupant out of position in the SB case is caused by the upstroke force from the airbag presented above.

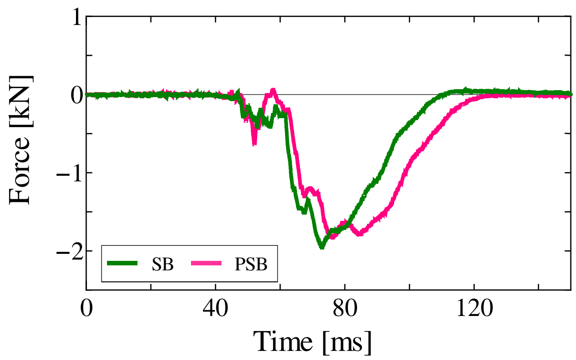


Figure 15. Estimated airbag force in longitudinal direction.

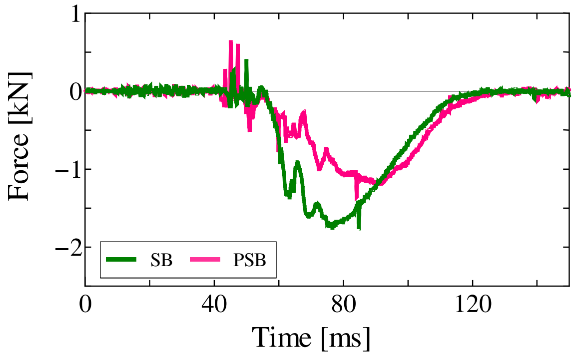


Figure 16. Estimated airbag force in vertical direction.

Figure 17 shows a comparison of acceleration vs. displacement (G-s) curves for chest and pelvis in both tests. The accelerations were taken from the dummy chest sensors in longitudinal direction and the displacements were presented as obtained from video marker tracking analysis. These curves show that the PSB worked effectively in reducing chest acceleration and forward displacement by improving initial restraint. In contrast, the G-s curves for pelvis show no difference between the two tests, observation consistent to the identical lap belt force time history measured (Figure 13), and show the lack of evidences of different contact with the knee bolster in both tests.

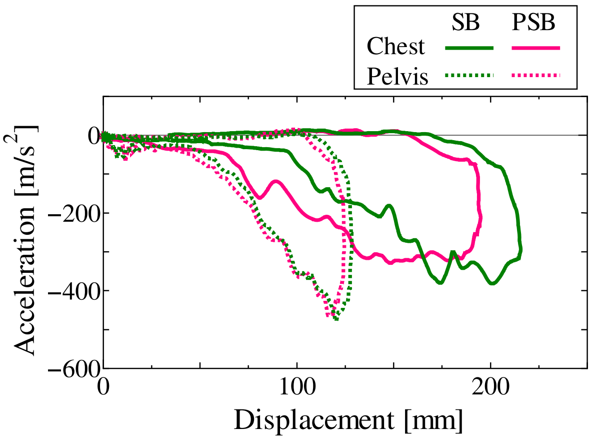


Figure 17. Acceleration-displacement curves for chest and pelvis.

Injury measures

Figure 18 shows the ratios of injury measures of the dummy to the injury criteria for these tests. These injury criteria are adopted in FMVSS 208.

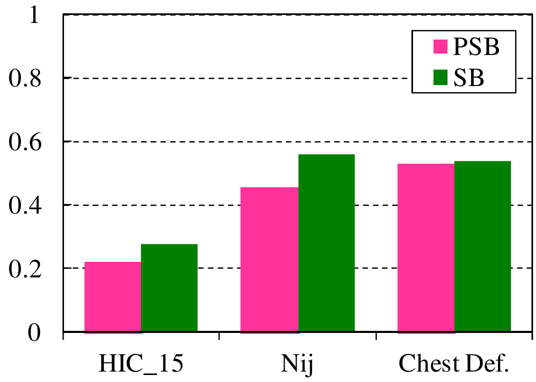


Figure 18. Dummy injury measures to injury criteria ratio.

No injury measure exceeded the corresponding injury criterion in this study. The differences of the results between the two tests were small in terms of the chest injury criteria, whereas the injury measures for head and neck in the SB case were substantially larger than those in the PSB case.

DISCUSSION

In this study, it was confirmed that neck and chest responses were improved by the PSB in crash pulse involving pre-impact braking as reported in the literature.

Schoeneburg et al. [5] reported that a pre-crash safety device with reversible (motorized) seatbelt pretensioner reduced neck extension moments in real vehicle crash tests with pre-impact braking. This improvement was associated with the improved timing interaction between the dummy and the airbag, which are usually designed for optimal protection of occupants in standard seating posture. Similar effects have been identified in different experimental studies employing out-of-position dummies [11] or Post Mortem Human Subjects (PMHS) [12], and in simulation based studies with human FE models [7].

This study is consistent with the studies mentioned above: In the SB test, the upper body of the dummy moved forward during pre-impact braking as shown in Figure 5. Therefore, the upper body was closer to steering wheel when the airbag was activated in the SB case. It is strongly possible that this difference of the posture led to the contact with the airbag before full deployment. As a result, the upstroke force from the airbag acted on the dummy face, causing neck extension shown in Figure 16. In contrast, in the PSB test, the dummy was restrained against the seat back during the pre-impact braking, which left additional space between the occupant and the steering wheel, allowing full airbag deployment before the contact to the body or the head. This led to optimized interaction with the airbag, prevention of upstroke effect on the neck, and reduction of neck moment and Nij.

Besides neck, improvements in terms of chest accelerations were observed. Early restraint facilitated higher absorption of occupant energy through the shoulder belt at an early stage of the crash, which led to a reduced transference of residual energy into the chest at the following stage. As a result, the peak value of chest acceleration as well as the chest displacement decreased.

On the other hand, since SB and PSB did not show differences in terms of chest deflection (Figure 10), the potential benefits of the PSB compared in terms of reduction of chest loading were not able to be confirmed in this study. The shoulder belt forces at the upper and lower sides shown in Figure 11 and 12, which directly influence the chest deflection measured at mid-sternum of the crash test dummy, were almost identical in both SB and PSB cases. Therefore, it appears that the identity for chest deflection was reasonable. However, the possibility that the reason for this identity is associated with the lack of biofidelity of the Hybrid III dummy employed in this study still remains. On one hand, the thoracic section of the dummy lacks biofidelity when compared with PMHS based corridors for chest deflection [13]. On the other hand, evaluating chest injury risk through mid-sternum to thoracic spine deflection in dummies may not be representative of the real injury risk for rib fractures. The latter is supported by an FE based study in which Mroz et al. [14] compared mid-sternum and multi-point based deflections of a Hybrid III FE model with a validated human FE model. In that study, it was concluded that multi-point rib deflection exceeded mid-sternum deflection in the human model, while the same effect were not confirmed with the dummy model. This indicates that it may not be possible to capture the potentials of PSB and SB for rib fractures in frontal impacts with pre-impact braking by current dummy testing and that improved dummies and complementary work with human FE models would be needed.

In order to evaluate the effects of different pre-crash restraint systems for occupant safety in vehicle crashes, conditions such as posture changes and inertia forces close to those occurring during real-life pre-impact braking need to be reproduced. Furthermore, the crash configuration involving pre-impact braking may reveal not only a new load transfer process from the restraint system and interior parts but also injury mechanism of the occupants which have not been considered so far. The sled employed in this study allows customizing the configurations of actual restraint systems, controllable combinations of braking and crash pulses, high repeatability at a low cost. This enables manufacturers to evaluate the effects of parameters of each restraint system on the occupant injury outcomes. Therefore, it can be expected that the sled contributes to the reduction of lead time for product development process and improvement of occupant safety system.

CONCLUSIONS

The new sled system developed to evaluate the potential benefits of pre-impact safety restraint systems on dummy responses at collisions has been presented. This sled can reproduce targeted crash pulses with pre-impact braking, would lead to the development of different restraint systems from current vehicles, and enables to conduct repeatable crash tests with pre-impact braking at a reduced cost. Therefore, it can be said that the sled can contribute to curtail the development period of occupant safety systems and optimize the properties of these systems.

Two crash tests were conducted to evaluate the effectiveness of a pre-crash seatbelt (PSB) system in a frontal crash with pre-impact braking. Test results showed that, in comparison with the SB, the PSB reduced forward movement during pre-impact braking. This contributed to an optimized interaction with the restraint systems, which leads to the reduction of neck tension force, neck flexion-extension moment, and chest acceleration during the impact.

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CRASH SLED TEST BASED EVALUATION OF A PRE-CRASH SEATBELT AND AN AIRBAG TO ENHANCE PROTECTION OF SMALL DRIVERS IN VEHICLES EQUIPPED WITH AUTONOMOUS EMERGENCY BRAKING SYSTEMS

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ABSTRACT

The Autonomous Emergency Braking (AEB) systems are rapidly spreading among current vehicles. In addition to the evident benefits associated with the reduction of impact speed, the AEB produces changes in the driver's posture due to inertia. Such changes need to be considered in the design process of restraint systems to optimize the protection of different occupants under all possible scenarios derived from the application of the AEB. The objective of this study is to quantify, in terms of potential reduction of injury indicators at frontal crash scenarios, two new techniques based features:
1) In-positioning function of a motorized pre-crash seatbelt (PSB) that pulls the webbing into the retractor during a pre-impact braking,
2) Enhanced interaction of an airbag with out-of-position occupants by means of a widely deployment airbag.

A series of crash sled tests were conducted with a sled system that produces controlled pre-impact braking and frontal crashes. Modified 50th percentile male and 5th percentile female Hybrid III dummies were used in order to reproduce more accurately human upper body's ability to flex forward under pre-impact braking conditions. The modifications were done at the abdomen-lumbar region and were validated against low speed sled tests with volunteers. The dummies were placed on the sled system and restrained with either a conventional seatbelt or a PSB, in combination with either a normal airbag or a widely deployment airbag. The pre-crash sled was accelerated to a speed of 64 km/h followed by a 0.8 g deceleration, prior to collision against a barrier at a speed of 48 km/h.

Less upper body forward motion during pre-impact braking was observed for the dummies with PSBs, compared to those with conventional seatbelts. This confirmed that the PSB was effective in restraining dummy's posture, thus leading to a proper restraint by the airbag and decreased injury values at the head-neck region. These observations were more pronounced for the 5th percentile female Hybrid III dummy. In addition, the widely deployment airbag contributed to the reduction of injury values.

INTRODUCTION

In vehicle crash safety studies, driver’s behavior and injury mechanisms at crash are often discussed. In such discussions, knowledge obtained from crash tests with standard Anthropometric Test Devices (ATD) in ideal seating postures is often assumed to be representative of the real crash situation. However, driver’s posture varies according to age, gender, and physique. In addition, in real crashes, the posture may change just before the collision due to either body inertial loading by AEB or driver's crash avoidance maneuvers. Consistent with the latter, the analysis of traffic accident data in Japan revealed that around 60% of drivers took crash avoidance maneuvers such as braking, swerving, or both of them at the pre-crash phase [1]. The same accident data source suggested that the type of pre-crash reaction might show differences in injury site and injury degree. Therefore, further examination of restraint systems that account for posture changes, their influence on the driver motion at the pre-crash phase, and their possible influence in terms of safety improvements is needed.

Commercially available vehicles have been equipped with pre-crash seatbelts, a restraint system device designed to control posture changes during the pre-crash phase. In addition, this device enhances driver's restraint after collision by automatically furling the belt with the electric motor [2]. Good et al. [3] investigated the basic features of the restraint effect of a pre-crash seatbelt based on data from tests with volunteers and ATD, and defined the appropriate posture changes for a numerical model that takes the effects of the pre-crash seatbelt into consideration. Schöeneburg et al. [4] reported that a pre-crash safety device with reversible seatbelt tensioner reduced neck extension moment in crash tests involving pre-impact braking. All these studies suggest that driver's posture change of the driver in the pre-crash phase influences the occupant injury.

In addition, most available studies focused mainly on average-size occupants. Small-size occupants, who are more vulnerable to the impact of a deploying airbag due to proximity to the steering wheel, would be relatively more exposed to non-optimized interaction with the airbag. Therefore, it is also important to make quantitative analysis on the relationship between accident avoidance maneuver and the amount of posture changes for small-size occupants.

In this study, a 5th percentile female Hybrid III dummy (AF05 dummy) employed as a surrogate of small-sized occupants is evaluated in addition to a 50th percentile male Hybrid III dummy (AM50 dummy). The effects of the body forward displacement during the pre-impact braking on the injury measurements at crash, and the potential improvements due to the in-positioning function of the PSB and a widely deployment airbag for out-of-position occupants, are evaluated with a pre-crash sled system [5][6], developed by Japan Automobile Research Institute (JARI), that produces controlled pre-impact braking and frontal crashes.

METHODS

The methodology of this study consists of a series of five crash tests to evaluate the potential safety improvements of a PSB in comparison to a conventional seatbelt (conventional SB) for both an AM50 and an AF05 dummies. In addition, for the AF05 dummy, a normal airbag (spec1 AB) was tested and compared with a widely deployment airbag (spec2 AB). Table 1 below shows the test matrix from this study and a description of the test apparatus, the restraint systems, the dummies and the testing conditions utilized in this study follow.

Table1.
Test Matrix

No.	Dummy	Seatbelt	Airbag
1	AM50	Conventional	Spec1
1-1		PSB	Spec1
2	AF05	Conventional	Spec1
2-1		PSB	Spec1
2-2		PSB	Spec2

Test apparatus

This study employed the pre-crash sled developed by JARI (See Figure 1). The sled reproduces controlled emergency braking prior to impact and can be customized to include different restraint systems from actual vehicles.

The crash tests with the sled are conducted on the rail of vehicle crash test facilities at JARI. The sled is accelerated on the rail by a pulling unit until it reaches a target speed. Then, the sled is released from the pulling unit, and a programmed braking pulse is applied before the sled collides against a row of shock absorbers placed in front of a fixed barrier.

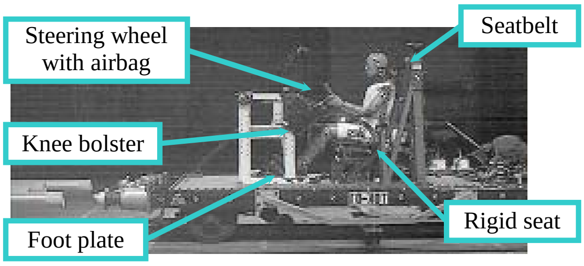


Figure1. Picture of the pre-crash sled with a dummy and the restraint systems used in this study

Restraint systems

The pre-crash sled was equipped with a three point seatbelt, a driver's airbag, a steering wheel, a steering column, a knee bolster, foot plates and a rigid seat. The rigid seat was used to eliminate the difference in seat deformation characteristics between car models. Either the conventional SB or the PSB were used for the tests. Both belt systems have an emergency lock retractor, a pre-tensioner and a force limiter. In addition, the PSB has a motorized retractor which automatically tightens the belts when the vehicle's pre-collision sensing device determines that a collision is imminent. Finally, two kinds of airbags were used: the spec1 AB or the spec2 AB.

Dummy modifications and positioning

Upper body flexion of Hybrid III dummies at braking has been shown to be lower than human volunteers under the same conditions [7]. Good et al. [8] also reported that these dummies were poor human surrogates when acted on by a motorized shoulder belt tensioner while out-of-position. To mitigate these limitations, AM50 and AF05 dummies were modified in order to match their kinematics to human volunteer data during pre-impact braking for males and females, respectively.

Modified AM50 dummy In a previous study [7] the lumbar section of the AM50 dummy (Figure 2) was modified and validated against emergency braking sled test data with male volunteers [9]. These modifications were further analyzed to confirm that upper body motion, chest acceleration and chest deflection of the modified dummy was comparable to those of the original dummy in 55 km/h crash tests without pre-impact braking [10]. The modified and validated dummy was used for the tests conducted in this study.

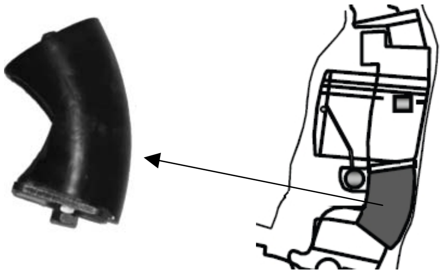


Figure2. Scheme of modified lumbar section for the AM50 dummy

Modified AF05 dummy The abdominal insert of the AF05 dummy affects upper body flexion due to interaction with the ribcage. Therefore, instead of modifying the lumbar section as in the AM50 dummy, the upper part of the abdominal insert, was partially removed in order to facilitate upper body flexion during braking. Figure 3 shows a scheme of the modified part in the AF05 dummy.

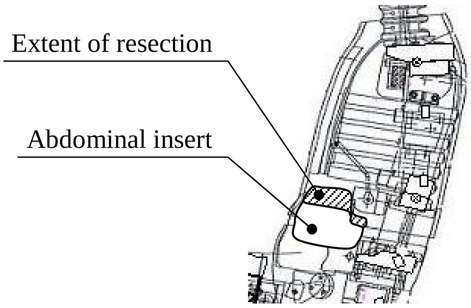


Figure3. Scheme of modified abdominal insert for the AF05 dummy

To confirm the validity of the modification, a braking test was conducted with the dummy under the same testing conditions as available female volunteer tests [11]. Although the modified dummy still presents some limitations in terms of head motion due to the rigid neck of the dummy, comparison of results (Figure 4) indicate that the shoulder motion of the modified dummy became close to that of the volunteers.

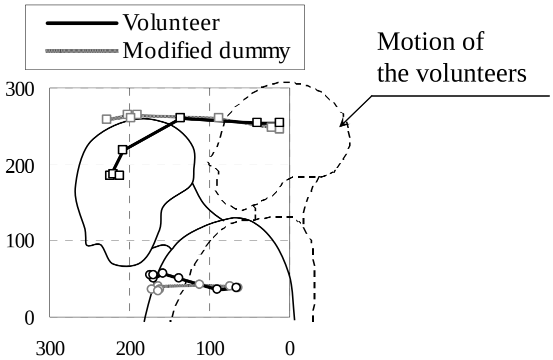
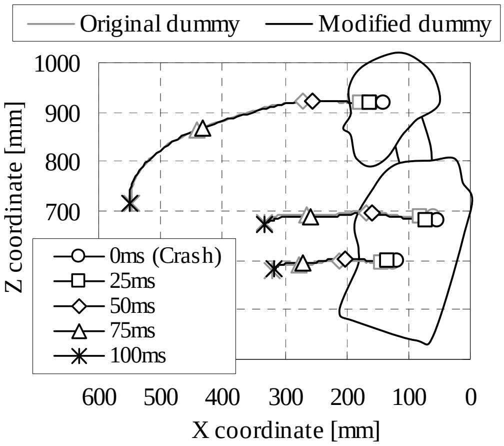
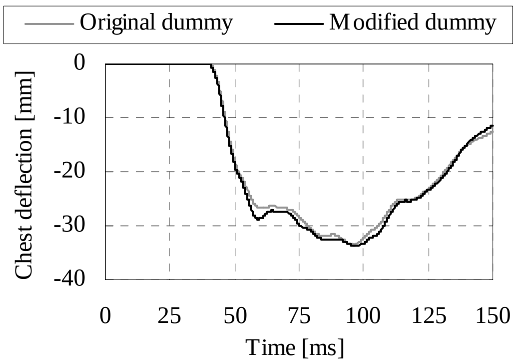


Figure4. Comparison of head and shoulder motion between the modified AF05 dummy and female volunteers under braking condition

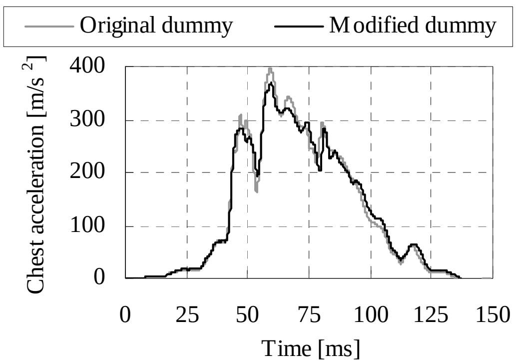
In order to verify that the reliability of the dummy at crash conditions was not affected by the modifications, additional front impact tests were conducted with the modified dummy and the original dummy. Upper body motion, chest acceleration and chest deflection for both dummies were equivalent for the original and the modified dummies, as shown in figure 5. Therefore the usability of the modified dummy for the purpose of this study was confirmed.



(a) Head, shoulder and chest motions



(b) Chest deflection



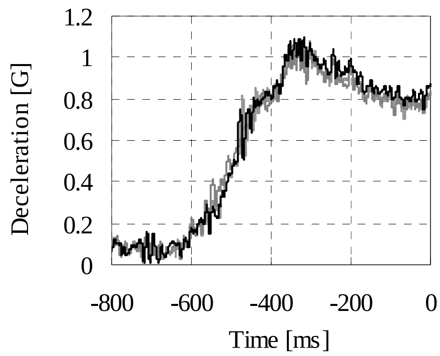
(c) Resultant chest acceleration

Figure5. Comparison between modified AF05 Hybrid III dummy and the original dummy during a 48km/h collision

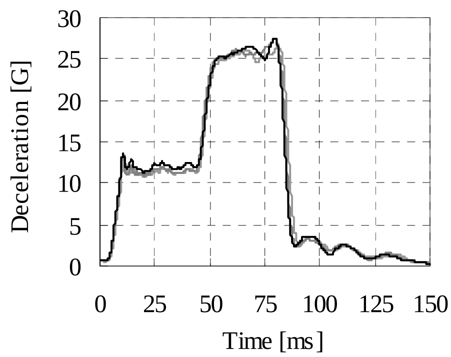
Dummies positioning Both modified and validated dummies were placed on the sled seat according to FMVSS208 standard definitions, respectively.

Braking and crash test conditions

All the five tests were performed under equivalent braking and crash conditions shown in figure 6. The sled system was programmed to reach a steady speed of 64 km/h, followed by 0.8G (Figure 6(a)), just before colliding against the barrier at a speed of 48 km/h. The crash pulse (Figure 6(b)) was similar to the longitudinal component of deceleration pulse used for offset deformable barrier crash test typically employed for passenger vehicles.



(a) Braking pulse



(b) Crash pulse

Figure6. Braking and crash pulses of the pre-crash sled tests in this study

RESULTS

Baseline injury values from tests with the conventional seatbelt and the normal airbag

Table 2 and figure 7 show the result of the sled tests of the conventional system using modified AM50 and AF05 dummies. Head injury values were at levels far from risk of injury. Hence, no further consideration on potential head injuries is done in this study. In contrast, chest deflection and neck injury values were relatively high as compared to the injury criteria established by the FMVSS208 standard; especially the neck injury value of AF05 dummy was close to the criterion.

Table2.
Test results

No.	Dummy	HIC_{15}	Nij	Chest Def. [mm]
1	AM50	196	0.56	34.0
2	AF05	194	0.85	26.0

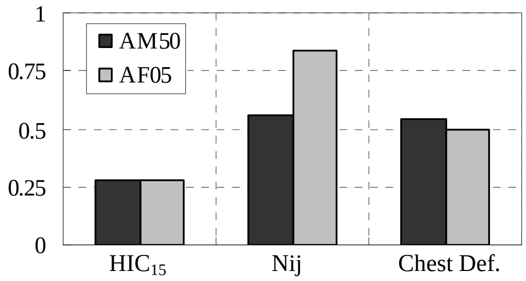
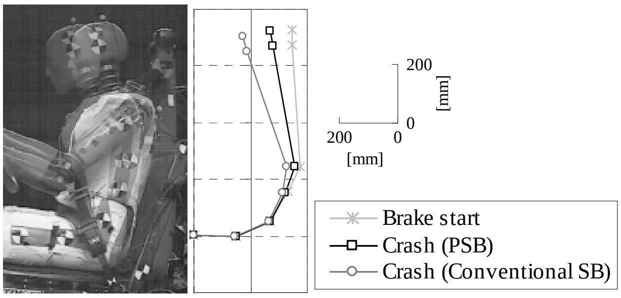


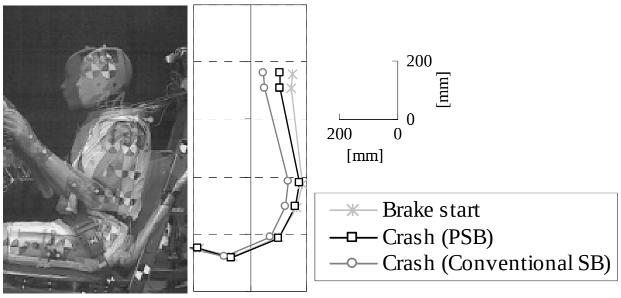
Figure7. Injury measures relative to injury criteria established by FMVSS208 (injury criteria = 1)

Average and small size occupant kinematics during pre-impact braking: effectiveness of the PSB's in-positioning function

Figure 8 shows a comparison of dummy body kinematics during braking for the PSB and the conventional SB for the AM50 dummy ((a) above) and the AF05 dummy ((b) below), respectively. The figure shows superimposed captures of the dummy at the end of the braking phase for the PSB and the conventional SB tests, respectively and a comparative schematic representation of the dummy posture at the beginning of the brake (light gray line with asterisks), in comparison to the posture at the beginning of the crash for the PSB test (black line with squares) and the conventional SB test (gray line with circles).



(a) AM50 dummy



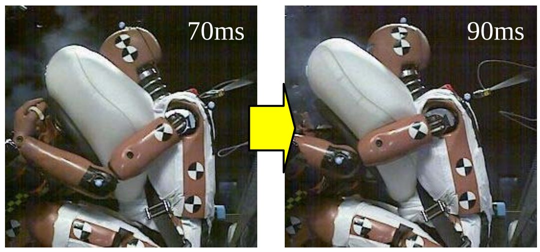
(b) AF05 dummy

Figure8. Comparison of pre-impact motion of the dummies with the PSB and the conventional SB

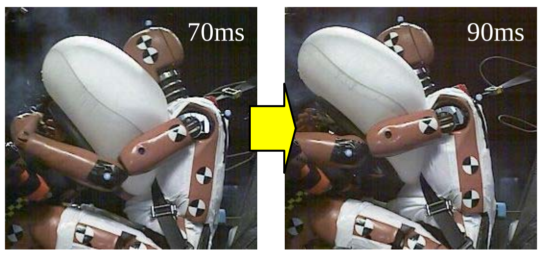
For both occupant sizes less body forward displacement and flexion were measured for the tests with the PSB, which confirms the correct functionality of the safety device.

Average-size occupant kinematics during crash: effectiveness of the PSB on optimized dummy-airbag interaction

Figure 9 shows images at 70 and 90 ms of the tests with the AM50 dummy. In the test with the conventional SB ((a) above), the head suffered from retro-flexion around 70 ms. The PSB alleviated the head retro-flexion ((b) below).



(a) Conventional SB



(b) PSB

Figure9. AM50 dummy motion during crash

Small-size occupant kinematics during crash: effectiveness of the PSB in combination with the widely deployment airbag on optimized dummy-airbag interaction

Figure 10 shows images from an anterior view of the AF05 dummy during crash for the baseline test with the conventional SB and the spec1 AB ((a) left) in comparison to the test with the PSB and the spec2 AB ((b) right). For the baseline test, the dummy head initiated contact with the airbag before full deployment. For the test with the PSB and the spec2 AB, the combined effect of the PSB delaying the approximation of the occupant to the steering wheel and the airbag widely deployed along the steering rim led to an optimized interaction between the dummy and the fully deployed airbag.

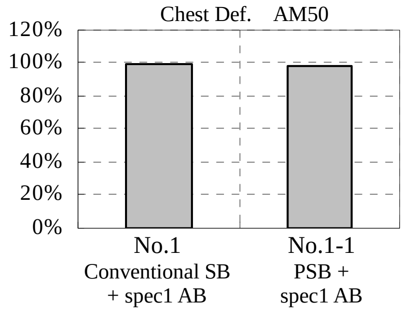
(a) Conventional SB & spec1 AB　　(b) PSB & spec2 AB

Figure10. AF05 dummy motion during crash

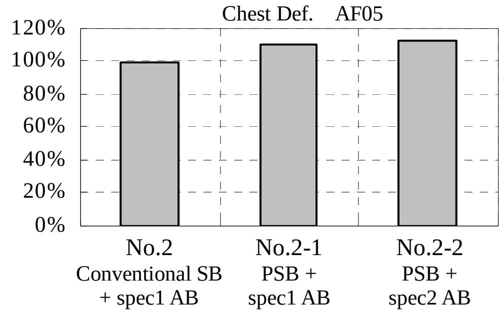
Potential safety improvements in terms of reduction of chest and neck injury values

Figure 11 shows chest deflection measurements normalized with respect to the baseline tests for the AM50 dummy ((a) above) and the AF05 dummy ((b) below). No significant differences were found concerning to chest deflections for neither the AM50 dummy nor the AF05 dummy.

In contrast, the Nij values normalized to the baseline values obtained with the conventional SB and the spec1 AB for each dummy were substantially reduced as shown in figure 12. In comparison to the baseline tests, the tests with the PSB alone resulted in a reduction of the Nij of an 18% for the AM50 dummy, and a 27% for the AF05 dummy. Moreover, for the AF05 dummy, a further reduction effect of 42% resulted from the test combining the PSB and the spec2 AB.

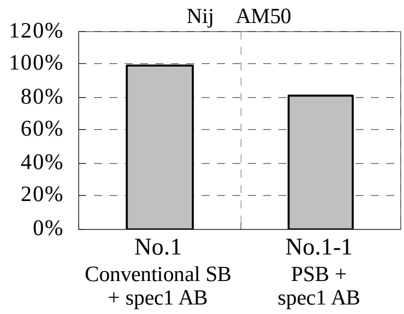


(a) AM50 dummy

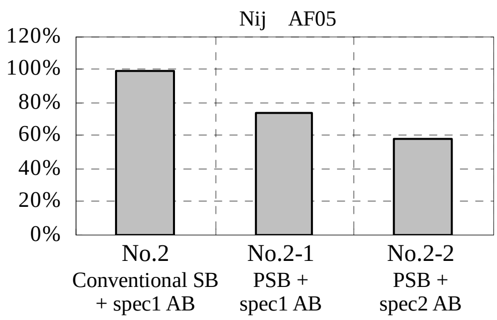


(b) AF05 dummy

Figure11 Chest deflection normalized to baseline values (100% corresponds with the value obtained at the tests with the conventional SB and the spec1 AB)



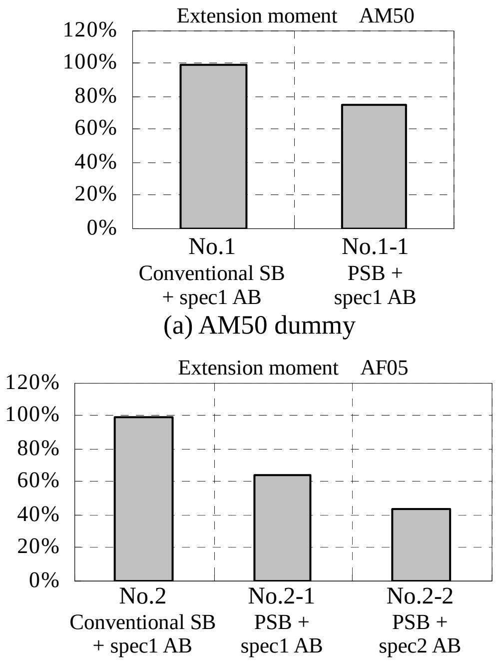
(a) AM50 dummy



(b) AF05 dummy

Figure12. Nij normalized to baseline values (100% corresponds with the value obtained at the tests with the conventional SB and the spec1 AB)

The Nij reductions were due to a reduction of neck extension moments. Figure 13 shows the extension moments normalized to baseline values. For the PSB alone, the moment was reduced by 25% for the AM50 dummy and by 36% for the AF05 dummy. Similarly to the Nij values, for the AF05 dummy, the PSB combined with the spec2 AB led to reduction of neck extension moment of 56%.



(b) AF05 dummy

Figure13. Neck extension moment normalized to baseline values (100% corresponds with the value obtained at the tests with the conventional SB and the spec1 AB)

DISCUSSION

The negative effects of posture change due to pre-impact braking in chest and neck injury outcome at crashes have been largely studied and demonstrated by means of experimental studies with out-of-position post mortem human subjects (PMHS) [12][13], ATDs [10] and computational models [14]. Our study stands on these observations, complements them with the confirmation of the correct functionality of the PSB for both average and small size occupants, and provides a quantified evaluation of potential safety improvements for the neck region as measured by the dummies at crashes.

The potential benefits of the PSB in terms of safety improvement have been shown for the AM50 and the AF05 dummies: figure 8 shows reduced dummy forward motion by the PSB during braking in comparison to the conventional SB. This additional retention of the upper body contributes to maintain the head of the occupant far from the steering wheel until the time of collision. This improvement achieved during the pre-crash phase will provide extra space and time so the airbag can completely deploy and work effectively in interacting with the dummy's head as shown in figure 9. These improvements were quantified in terms of the Nij reduction of 18% for the AM50 dummy and 27% for the AF05 dummy. In addition, this effect was more pronounced for the small-size occupant when the PSB was used together with the spec2 AB, as seen in figure 10. In this case, a further reduction effect of 42% was measured.

By modifying the abdomen-lumbar region of the dummies, improved biofidelity in terms of upper body motion was achieved. However, current studies with volunteers show that the neck region of existing dummies has different joint features and is stiffer than one of human. For further examination of detailed head-neck interaction with the airbag in general, and how it is affected by different pre-impact braking conditions in particular, it is necessary to further improve the dummies and to employ them in combination with biofidelic human computer models.

Tasks that remain to be addressed in future studies have been identified and include improvement of the biofidelity of current dummies in terms of head and neck kinematics to match human's, consideration of elderly and other vulnerable occupants, consideration of possible influence of occupant's muscle conditions at pre-impact and extension of our studies to other passenger-seat occupants.

CONCLUSION

In response to the demand of increased performance of restraint systems, pre-crash sled tests with modified dummies were carried out to evaluate potential driver protection enhancement with a PSB and a widely deployment airbag. The findings of this study show that:

1) The PSB effectively restrained the occupants, preventing them from forward traveling during pre-impact braking. This led to a reduction of neck injury values due to improved interaction with the airbag. This improvement was more pronounced for small-size occupants.

2) Additional neck injury values reductions were achieved when the widely deployment airbag was applied in combination with the PSB for small-size occupants.

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A study of the relationship between seatbelt system and occupant injury in rear seat based on EuroNCAP frontal impact

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Paper Number 13-0153

ABSTRACT

Front-row occupant protection in frontal crashes has benefited from restraint system development and vehicle crashworthiness improvements which have been driven partly by manufacturers' efforts to improve vehicle scores in consumer metric tests. Until recently, occupants in the rear seat have not been considered in most consumer metric tests. As a result, a rear occupant evaluation has been introduced in Europe as a part of the EuroNCAP. Occupant protection performance in the rear seat needs to be evaluated in order to perform well in this newly introduced market requirement. This study investigates the potential benefits of seat belt pretensioners and load limiters in the rear seat for the new EuroNCAP condition. A series of sled tests were conducted following the new EuroNCAP protocol for a 50 km/h full width rigid barrier test. A Hybrid III 5th percentile female (AF5) dummy was seated in the rear seat of a sled buck representative of a small-sized vehicle. A mathematical simulation study of rear seat restraint parameters was first performed to assess chest deflection, head excursion trend and neck injury using different belt load limiters and pretensioning stroke with the Hybrid III 5th percentile female dummy. The results suggest that the belt pretensioner and load-limiter studied here may improve performance to rear seat occupants in the EuroNCAP condition, although more study is needed to evaluate these restraints in other crash scenarios. This study is limited to the Hybrid III 5th percentile female (AF5) dummy in this load case. Restraint performance for larger and smaller occupants also needs to be considered.

INTRODUCTION

For many years, safety engineers have been working on ways to reduce the loss of human lives in high severity vehicle collisions. As a result, various advanced restraint systems were developed to reduce occupants' injury risk. Such endeavors were adopted by safety consumer metric programs such as EuroNCAP. It became very challenging to meet the consumer metric performance criteria without advanced restraint systems. These advanced restraints have focused more on front row occupants.

Recently, EuroNCAP announced the new barrier condition in which a 5th percentile female dummy is placed in the rear seat position in a full width rigid barrier test starting in CY2015. This paper focused on demonstrating performance benefit in this new EuroNCAP barrier test with rear seat 5th percentile female using a combination of a pretensioner and various load limiters (CLL: constant load limiter and PLL: progressive load limiter)[1][2]. Mathematical simulations using LS-Dyna were first conducted to determine the effect of the combination of a pretensioner and load limiter on the dummy's injury values and kinematics in the rear seat. Then, sled tests were conducted using a reinforced sled buck representing a small-size vehicle with a Hybrid III 5th percentile female dummy in the rear seat. The best performing restraint combinations identified in previous mathematical simulations were evaluated.

The load limiters decreased head acceleration and chest deflection of the rear seated dummy in the 50km/h full width barrier crash mode. However, load limiters tended to allow more excursions of the dummy head so that it contacted the front seat back. The pretensioner was applied to balance this increased excursion and as a result, the best performance in this EuroNCAP condition could be obtained through the combination of a retractor pretensioner and load limiter.

Method

A vehicle crash test was done for baseline test followed the European New Car Assessment Program procedure draft version for implementation in January 2015. Mathematical simulations using LS-Dyna were first conducted to determine the effect of the combination of a retractor pretensioner and load limiter on the dummy's injury values and kinematics in the rear seat. Then, sled tests were conducted with a reinforced sled buck of a small-size vehicle.

Vehicle Acceleration

The vehicle pulse selected represents a small-size passenger car in a 50km/h full width barrier impact. The acceleration and velocity-time histories are shown in Figure 1.

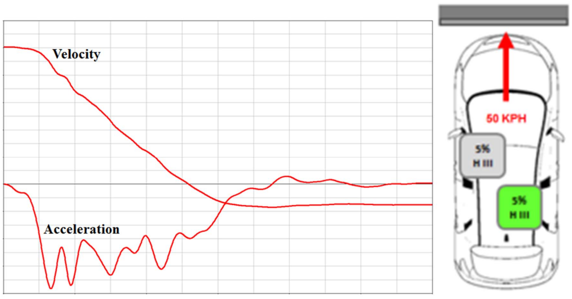


Figure1. Vehicle pulse

Dummy Positioning

A hybrid III 5th percentile female dummy was seated in the right side rear passenger seat. The dummy was seated in the rear right passenger seat by aligning the mid-sagittal plane of the dummy with the front seat centerline. A load cell was placed on the shoulder belt to monitor belt load. The initial positions of the head and H-point, as well as the pelvic angle, torso, femur, and tibia, were adjusted to match the initial occupant position from the baseline crash test.

Injury Criteria

Injury criteria of dummies were examined. In each body region, representative injury was measured and calculated.
The probability of injury was calculated based on the injury criteria of the crash dummy. Basically, injury risk curves were adopted from those used in the USNCAP to calculated scores. [4]
The probabilities of head, neck and chest injuries were calculated by AIS 3+ injury risk curves. Probability of femur injury was calculated by AIS2+ injury. Injury assessment reference value (IARV) was adopted from FMVSS208 to check the compliance. [5]

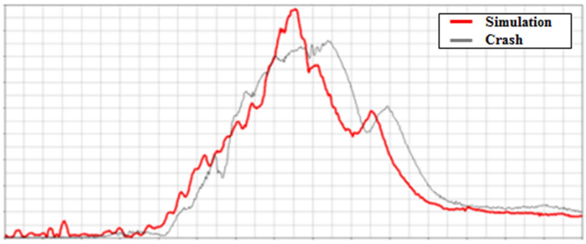
COMPUTATIONAL SIMULATION

Figure2. Pre-test (Crash test vs. Simulation)

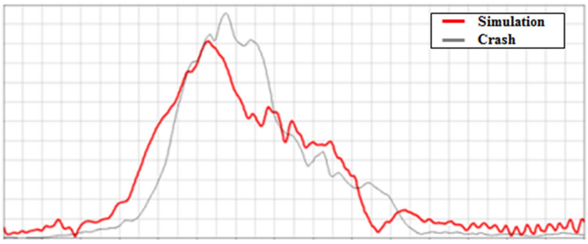
Injury Correlation (Simulation)

A seat belt with an emergency locking retractor (ELR) only (no pretensioner or load limiter) was applied as a restraint to the rear seat Hybrid III 5th percentile female dummy for the base correlated model in both the crash test and simulation. Figure 3 shows the crash test results in gray and the corresponding simulation output in red.

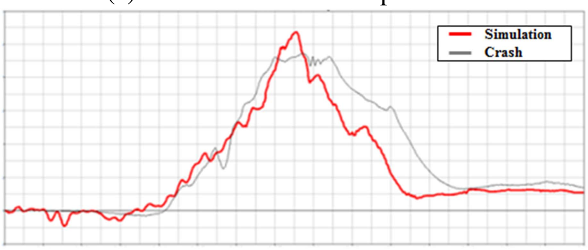
(a)Head acceleration (resultant)



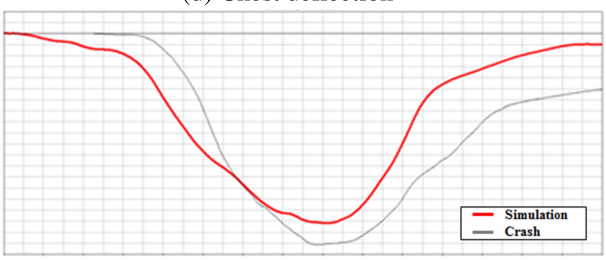
(b) Chest acceleration (resultant)



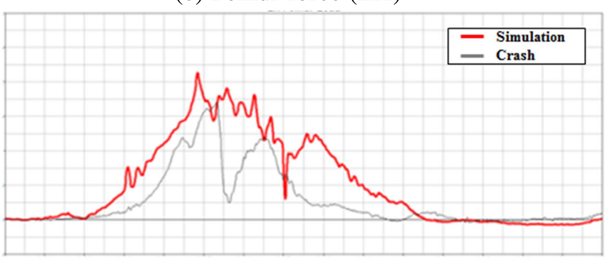
(c) Neck tension and compression



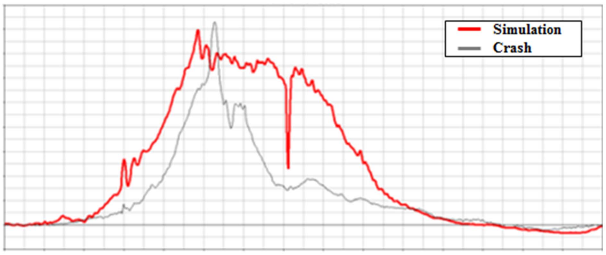
(d) Chest deflection



(e) Femur force (LH)



(f) Femur force (RH)



(g) Shoulder belt force

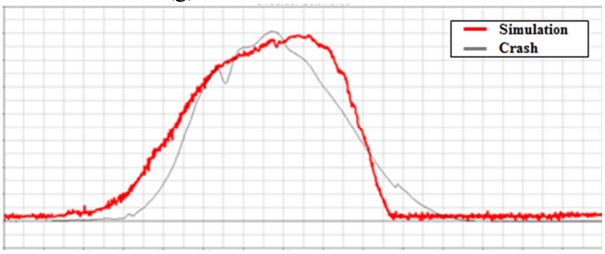
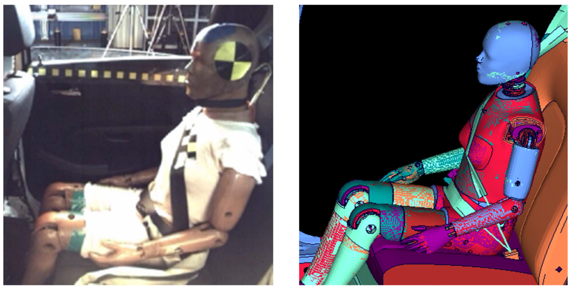


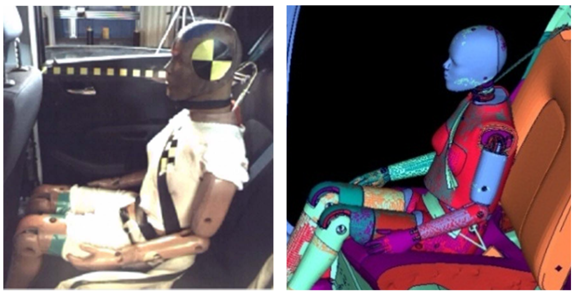
Figure3. Simulation correlation to vehicle test (x axis: time)

Kinematic Correlation (Simulation)

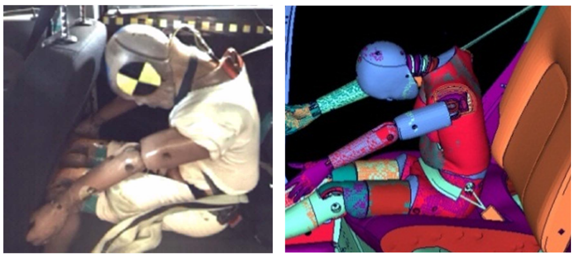
Correlation of the simulation to the test was shown with the head kinematics and lower leg contact to front seat back as shown in Figure 4.



0ms



40ms



80ms

Figure4. Dummy kinematic comparison (left crash and right simulation view)

Parameters of load limiters and pretensioners (Simulation)

In order to observe the effect of the various seatbelt systems on the rear seated female dummy in the EuroNCAP condition, several levels of load limiters were selected. Progressive load limiters were evaluated in addition to constant load limiters (CLL.) Also, two types of pretensioner - standard and high pay-in were added with the ELR and load limiters. Pretensioner deploy time (time to fire: TTF) was also varied. The TTF of a current small vehicle's front row pretensioner was used as nominal time; and 3ms earlier TTF was used to evaluate the influence of deploy time.

***Table1*.**
Study parameters

Load limiter		Retractor Pretensioner	Time to fire
Constant Load Limiter	Low	Standard	Nominal
	Mid		
	High		
	Hyper-high		
Progressive Load Limiter	Low+2kN	High pay-in	Nominal - 3ms
	Mid+1kN		

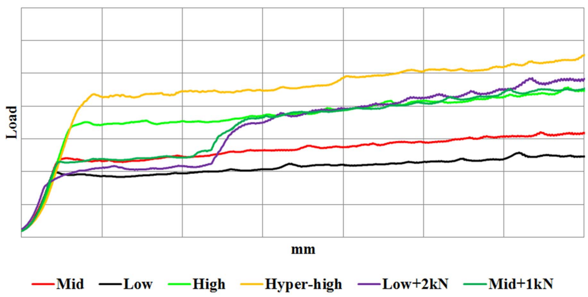


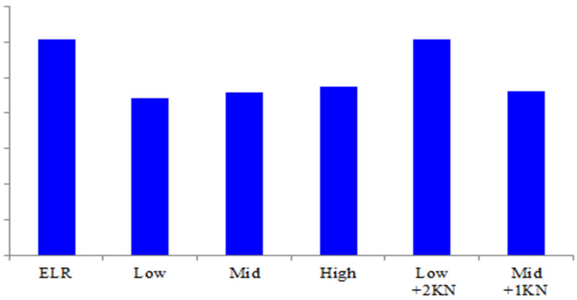
Figure5. Belt load versus displacement

1st study

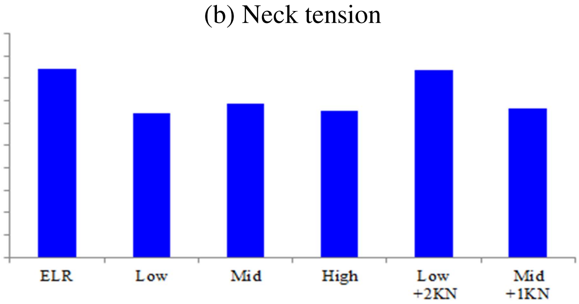
The first simulation study was done with various load limiters. Hyper high load limiter was not considered in this study.
According to the simulation results shown in Figure 5, the occupant injury values were reduced in the EuroNCAP condition. HIC15, neck tension and chest deflection were improved by 27%, 15% and 51% respectively with the low level CLL compared to the ELR (base) belt system. Chest deflection values tended to decrease as the load limiter levels were lowered. Dummy head excursion and neck injury criteria (N_{ij}), however, increased as load limiter

levels were lowered. All load limiters evaluated in this first study would have resulted in head contact to the front seat back. Figure 7 shows a schematic of the rear seat relative to the front seat, and Figure 8 shows the head excursion for the load limiters evaluated in this first study. The head could contact the front seat back if the dummy's head moves forward more than initial distance A between the dummy's head and the front seat back. Pretensioners were introduced in the second study to investigate whether head excursion could be improved through earlier belt restraint of the dummy.

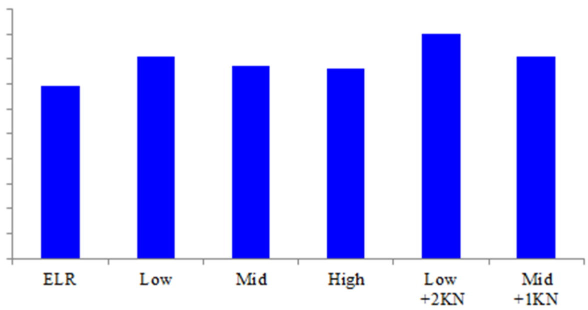
(a) HIC15



(b) Neck tension



(c) N_{ij}



(d) Chest deflection

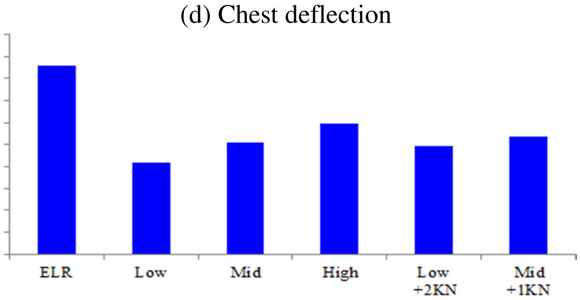


Figure6. Injury values versus load limiter type

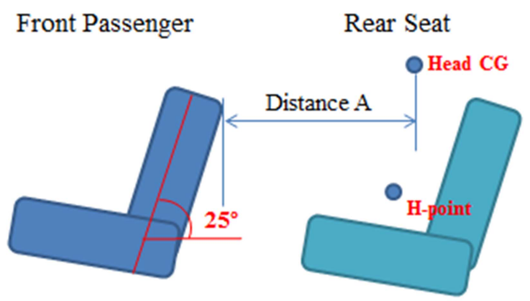


Figure7. Schematic of front and rear seat

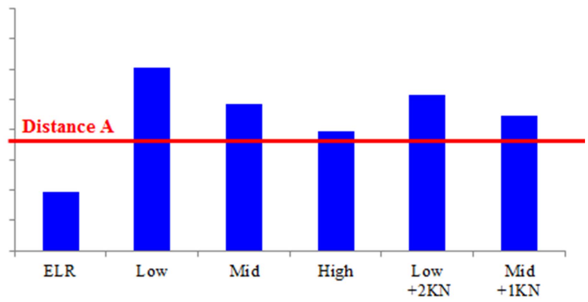


Figure8. Max. head displacement x-axis

2nd study

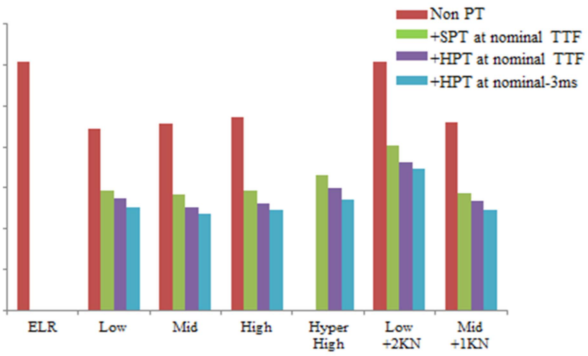
In the second simulation study, a pretensioner in combination with each level of load limiter was simulated. At the same time, two levels of TTF for the pretensioner were evaluated.

In the simulations with the standard pretensioner (SPT) in combination with a load limiter, the HIC15 value was reduced 33~38% in all cases compared to the HIC15 values produced in the first study without pretensioners. Neck tension and N_{ij} were reduced over 20%. Chest deflection increased over 20%.
In the simulations with the higher length pretensioner, 140% of the SPT retraction length was used. HIC15, neck tension and N_{ij} were decreased over 7%, 4% and 3% respectively compared with SPT. The higher length pretensioner results showed the same pattern as the SPT for chest deflection, which increased over 6% for all load limiter levels.

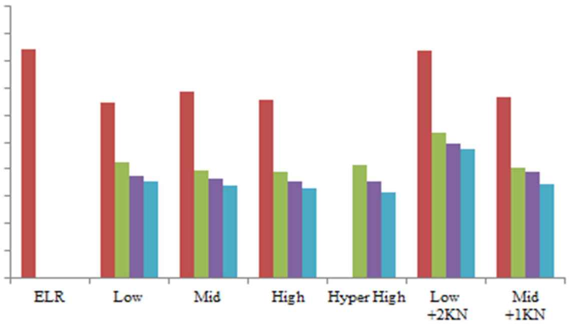
The pretensioner timing simulations showed decreasing injury values in all regions except chest deflection. HIC15, neck tension force and N_{ij} were decreased over 5%, 3% and 3% respectively for the 3 ms earlier TTF compared with the nominal TTF. Chest deflection increased over 6% in all load limiter levels with the 3 ms earlier TTF.

Head excursion relative to the front seat back is shown in Figure 9. All CLL levels without a pretensioner, and the SPT with the low+2 kN progressive load limiter, exceeded distance A. The mid or higher level of CLL, with any pretensioner evaluated, showed no contact to the seat back.

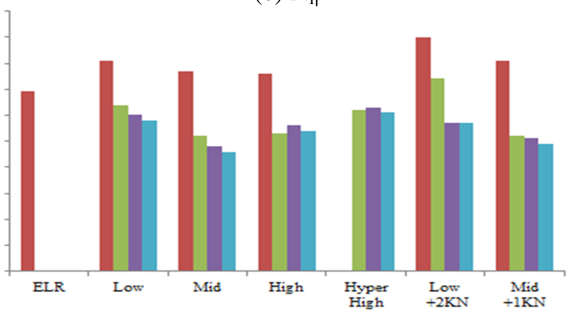
(a) HIC15



(b) Neck tension



(c) N_{ij}



(d) Chest deflection

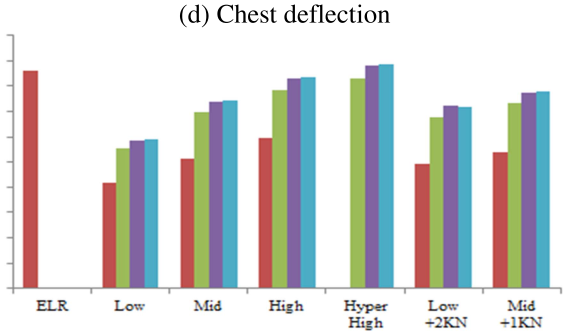


Figure9. Injury values versus load limiter, pretensioner, and TTF

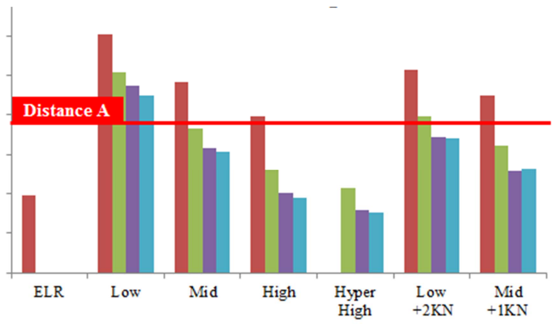


Figure10. Max. head displacement

SLED TEST

To verify the simulation results, the same vehicle acceleration pulse was used in sled tests representing a small-size passenger car undergoing the EuroNCAP 50km/h full width frontal rigid barrier crash test. The front passenger (right side) seat was installed and placed at its mid position of fore-aft travel, with the seat back angle set to 25 degrees, in order to assess potential rear seat dummy head contact. The test set-up (Figure 11) followed the latest EuroNCAP 50km/h full width frontal barrier test protocol. The baseline test was done with the ELR only belt for correlation between the baseline mathematical simulation and physical test.

Figure11. Sled test set-up

Sled tests were also conducted using the low and intermediate (mid) level constant load limiters with the ELR and standard powered pretensioner (SPT.) Since the EuroNCAP injury criteria for this condition had not been announced at the time of this writing, the test results relative to the injury risk limits according to FMVSS 208 were used as shown in Figure 12.

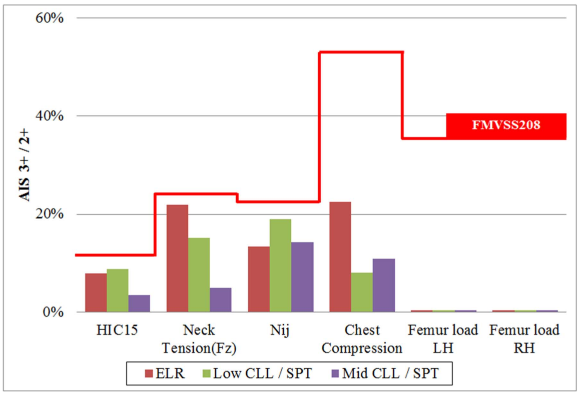


Figure12. Probability of injury

In the test with Low CLL/SPT combination, the chest deflection of AF5 dummy improved by 14% and neck tension improved by 6%, compared to the result of ELR only retractor. However, the dummy's head contacted the front seat back and HIC15 increased by 1% and N_{ij} increased by 5%. The test results of the mid load limiter (Mid CLL/SPT) also showed 11% improvement in chest deflection but 5% higher deflection than that of the low load limiter. The dummy's head did not contact the front seat with the Mid CLL/SPT. HIC15 improved by 4% compared to the ELR only test, and this HIC15 was lower than that of Low CLL/SPT test. Neck tension was also lower by 17% and chest deflection was increased by 11%, compared to the result of the low load limiter and ELR only.

To observe the effect of the increased pay-in amount of the higher length pretensioner on dummy injury in this EuroNCAP condition, sled tests were conducted with the three constant load limiters and the Mid+1 kN progressive load limiter , each in combination with a higher length pretensioner (HPT) [3]. Shoulder belt force is shown in Figure 13 and the dummy test results in Figure 14.

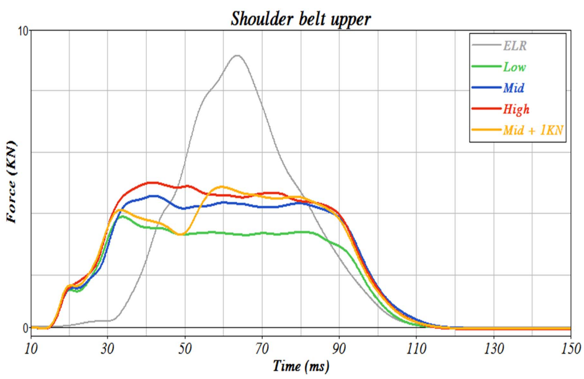


Figure13. Shoulder belt force

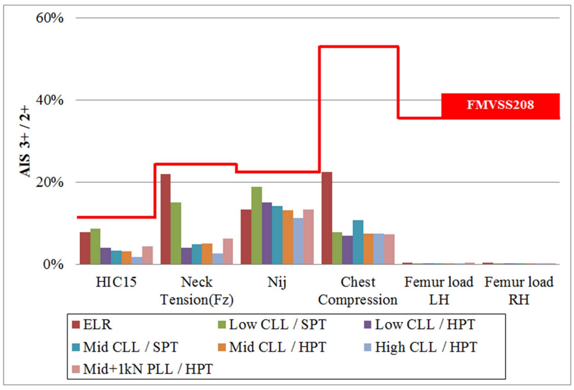


Figure14. Probability of injury

With the CLL/HPT combination, dynamic pay-in amount of belt webbing increased by an average of 50% or greater than that of CLL/SPT.

For the tests with the Low CLL/HPT, HIC15 was decreased by 4%; neck tension decreased by 18%; and chest deflection decreased by 16%. However, the dummy head contacted front seat back. In Mid CLL/HPT, HIC15 decreased by 4%; neck tension decreased by 17%; chest deflection decreased by compared to the SPT, the HPT showed the most decrease in the HIC, neck tension and chest compression by 0.1%, 0.1% and 3% respectively.

Test results showed that CLL High/HPT yielded lower HIC15 by 6% compared to the ELR only and neck tension also reduced by 19%.

The progressive load limiter(Mid+1kN PLL/HPT) showed little effect on dummy injury values compared to the Mid CLL/HPT.

DISCUSSION AND CONCLUSIONS

Simulations and sled tests were carried out for the EuroNCAP 50km/h rigid barrier condition with a belted Hybrid III AF5 in the rear outboard seat position. The conclusions may be summarized as follows:

1. The sled test results for the 50 km/h full width EuroNCAP condition showed that the current belt system (ELR) meets the dummy injury criteria of the FMVSS 208 regulatory requirements for the 5th percentile female dummy which apply in the US in the front outboard seat positions
2. With the load limiter level constant and pretensioner pay-in amount increased, dummy injury trends in the EuroNCAP condition showed a reduction in: HIC15, neck tension and chest deflection
3. As the load limiter level increased, dummy injury trends in the EuroNCAP condition showed a reduction in HIC15 and neck

tension, and an increase in chest deflection

4. Head excursion needs to be considered to determine the combination of pretensioner and load limiter which will prevent hard contact with the front seat back.

The results showed the possibility to improve the dummy injury values in the EuroNCAP full width barrier test when a load limiter and pretensioner are applied in the rear outboard seating positions.

The kinematics and injury values of the dummy in the rear seat could be affected by other factors, such as vehicle acceleration, direction of impact, space between front seat and rear seat and size of occupant, not investigated in this limited scope of study,

Even with the predicted improvement in the EuroNCAP full width barrier condition observed in the simulations and sled tests with the 5th percentile female dummy, protection of larger and smaller size occupants should also be considered.

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CHILD RESTRAINTS FOR CHILDREN WITH ADDITIONAL NEEDS

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ABSTRACT

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

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

INTRODUCTION

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

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

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

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

METHODS

CRS models

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

Impact test protocol

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

The test characteristics were based on:

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

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

The target sled impact pulses were:

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

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

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

ATD and instrumentation

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

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

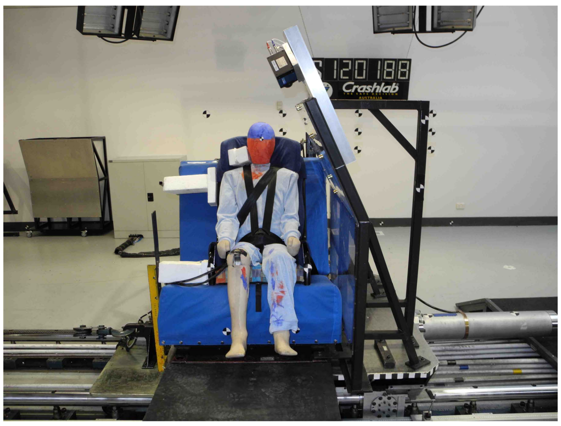

Figure 2. Sled, CRS and ATD side impact configuration.

The following instrumentation was used on the ATD:

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

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

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

Evaluation

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

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

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

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

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

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

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

RESULTS

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

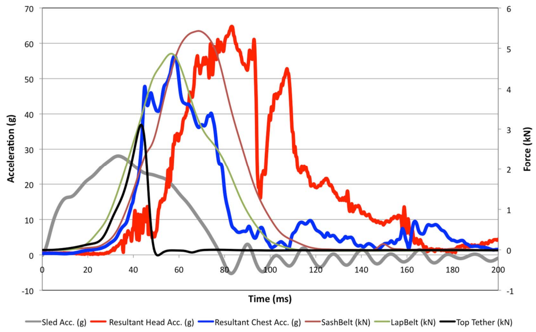

Figure 3. Time-histories from an exemplar frontal impact test (Test S120172)

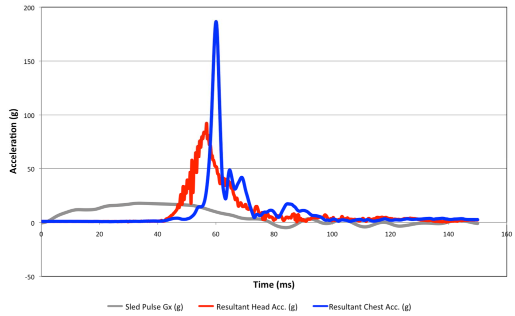

Figure 4. Time-histories from an exemplar side impact test (Test S120183)

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

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

Frontal impacts

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

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

Side impacts

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

Injury assessment

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

DISCUSSION

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

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

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

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

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

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

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

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

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DESIGN SENSITIVITY STUDY OF PASSENGER AIRBAG SHAPE TO MEET HEAD RESTRAINT PERFORMANCE FOR DIFFERENT OCCUPANT SIZE IN FRONTAL IMPACT

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ABSTRACT

Range of restraint performance needs to cover different occupant restraint conditions and occupant size in accordance to government regulation and NCAP tests. It should be effective in real-world safety also. There are several ways to accomplish the required safety performance. For example, adaptive system of airbag and belt load-limiter could be adjusted (i) depending on the occupant size, sensed by weight sensor and (ii) due to change in restraint condition, when buckle latch switch is introduced.
The present study focused on the sensitivity of the airbag shape on occupant head restraint performance and investigated the possibility to meet the required level of restraint performance by manipulating only the airbag shape with the help of airbag stiffness performance diagram.
In conclusion, to achieve the near optimum head restraint performance, by introducing S-shape in vertical direction at the center of the airbag instead of a Flat-shape airbag, the airbag stiffness can be tuned to meet performance requirements of two different size dummies AM50 and AF05 simultaneously.

INTRODUCTION

At present, a lot of NCAP and regulations tests are performed to improve the vehicle safety performance.
These evaluation procedures are not only based on vehicle structural deformation but also on the level of various types of occupant injuries at different body region such as head, neck, thorax, knee-femur, etc.
Further, in US, there are different test procedures based on the size of the occupant (AM50, AF05) and the restraint conditions (belted and unbelted).
To meet the required level of safety performance satisfying these variety of crash test conditions, not only the vehicle crash pulse and the amount of cabin intrusion but also the performance characteristics of the occupant restraint system (airbag, seatbelt) to be designed within the specified space around the occupant are very important factors [1]. Recently, following restraint systems are applied in vehicles to meet the different modes of crash with different occupants and restraint conditions.
Multiple operation level of an adaptive airbag and belt load-limiter system could be adjusted

(i) depending on the occupant size, sensed by weight sensor
(ii) due to change in restraint condition, when buckle latch switch is introduced

These procedures, using occupant sensing information, can control the characteristics of restraint performance of airbag and seatbelt.
The present study focused on the sensitivity of the airbag shape on occupant injury reduction possibility and investigated the possibility to meet the required level of restraint performance by manipulating only the airbag shape.

METHOD

STEP1: PRELIMINARY DESIGN STUDY

The amount of energy absorbed by an airbag changes due to many factors, for example the impact speed, the occupant size and the occupant restraint condition, such as belted or unbelted.
From the airbag performance requirement view point, the airbag should absorb sufficient amount of energy of the head and the thorax of the occupant as it moves towards the windshield from the start of the crash.
The layout of the interior of the vehicle and the relative initial position of the AM50 and AF05 occupants are shown in Figure 1.
The relation of the distance between the occupant head and the windshield is such that, the taller is the size of the occupant, the higher is the position of the restraint region on the airbag for the

occupant head which comes closer to the windshield.
On the other hand, the smaller is the occupant, the lower is the position of the restraint region for the head which remains further away from the windshield resulting in more head restraint stroke in between the head and the windshield (Figure 2). Again, so far as the level of energy absorbed by the airbag is concerned, it is more for the bigger occupants due to increase in mass of the occupant. Furthermore the amount of stroke is less for a taller occupant. Consequently the airbag should be stiffer. However, for lower region of the airbag, the required amount of energy to be absorbed is less due to the relative decrease in mass of the smaller occupant to be supported and consequently the required stiffness of the airbag should be low because the amount of stroke is more for a shorter occupant.
Further, if the level of the biomechanical tolerance related to AF05 population is usually lower than those for relatively bigger occupants corresponding to AM50 population [2], restraining at lower level airbag stiffness will be preferable.
Hence, if the degree of the restraint force and the stiffness of the airbag could be controlled, with respect to (i) the relative initial position, (ii) the target region of the airbag and (iii) the size of the occupant, a proper balance could be achieved (Figure 3).

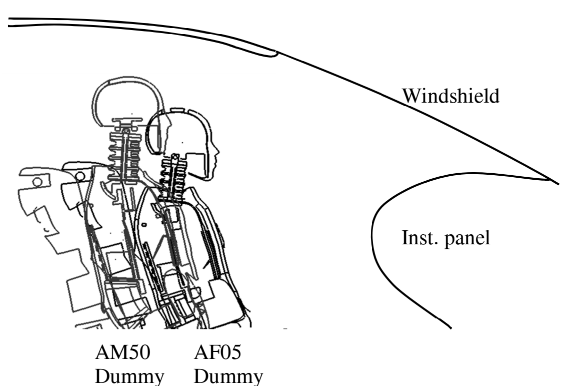


Figure1. Vehicle interior layout of a typical mid-size sedan with AM50 and AF05

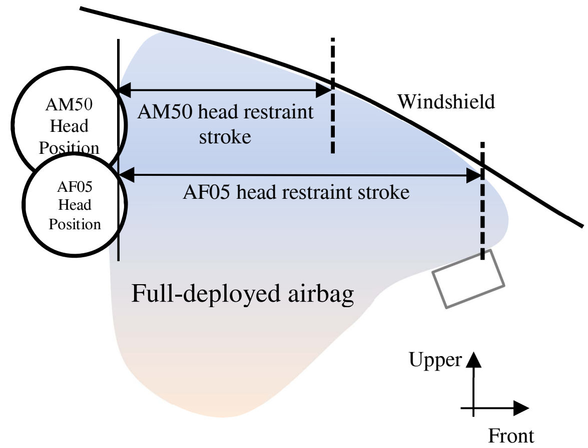


Figure2. Comparison of the head restraint stroke for AM50 and AF05 inside a mid-size sedan

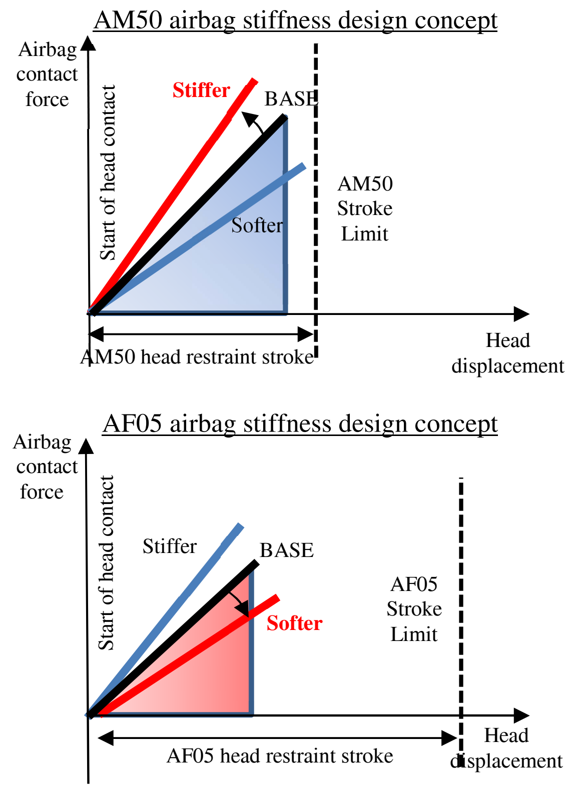


Figure3. Schematic diagram of airbag stiffness design concept to suit AM50 and AF05

STEP2: CAE SIMULATION

Simulation scenario

This section will describe about the simulation results to investigate the characteristics of the restraint force of the upper and lower halves of the airbag as mentioned in the previous section. In general, the vent-hole size, and inflator power are adjusted to manipulate the overall pressure inside

the airbag. Local airbag pressure is difficult to control with single chamber airbag.
However, incorporating a valley at the center of the airbag can partially control the local airbag restraint force [3].
The present study focused on the depth of the airbag at the center line. As the amount of head displacement of the AM50 and AF05 dummies can be adjusted by the depth of the valley at the center of the airbag, the degree of design flexibility to change the level of the restraint force acting on the head is investigated.

Simulation condition

Regarding FMVSS208 and US-NCAP test performance conditions among various other stipulated test conditions, the following two test cases are selected.
・56km/h belted AF05 (belted-AF05)
・40km/h unbelted AM50 (unbelted-AM50)
The layout, crash pulse and other related test conditions are based on the data of a typical mid-size sedan in US market. Explicit FE code PAM-CRASH™ solver is used.

Design parameter
Airbag design

CAE based parametric study is carried out to study the effect of the shape of the stitching at the central valley and the vent-hole size of the airbag.
The wavy stitching line (S-shape) , and the straight stitching line (Flat-shape) are the two design shape parameters at the center of the valley, as shown in figure 4 and 5.
In S-shape, in accordance with the position of restraint of the different size of the occupants, the depth of valley at the center of the airbag is varied to increase the level of head-restraint for the AM50 occupant and to reduce the same for AF05 occupant. To be more specific, the depth of the valley is varied with respect to occupant size to increase the degree of restraint, it is bulged out towards the occupant for AM50 and it is bulged away from the occupant for AF05.

The parameters that are changed in this study are shown below.
・Shape at the center of the valley
(Flat-shape, S-shape)
・Vent-hole size (V/H)
(S; Small, M; Medium, L; Large)

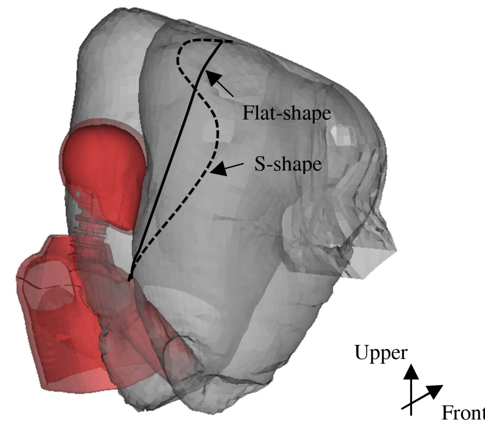


Figure4. Isometric view of present 3D airbag shape

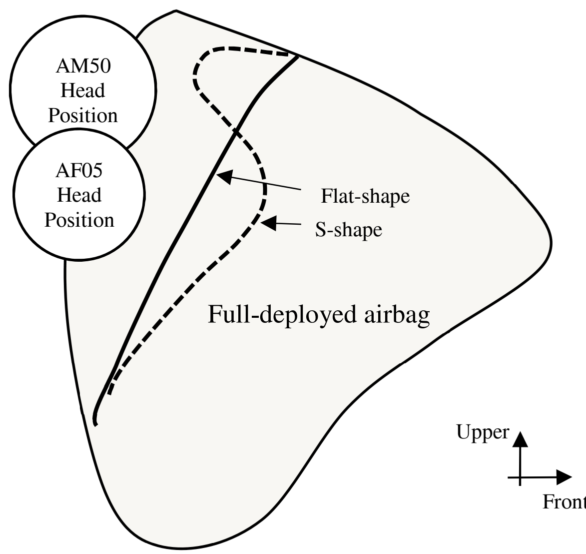
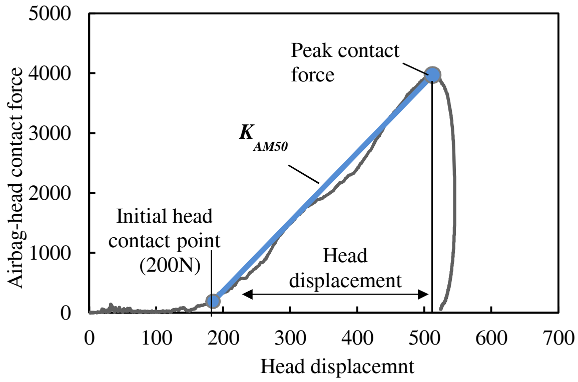


Figure5. Side view of the airbag shape showing relative position of the stitching line at the center of the valley

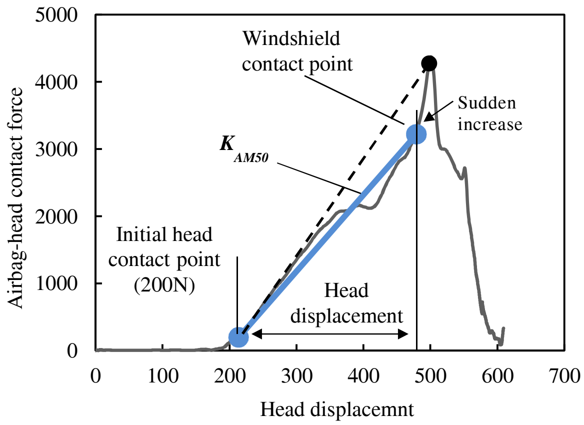
Airbag stiffness

The effect of variation of airbag stiffness, denoted by (K_{AM50}, K_{AF05}), is studied. In figure 6 a-b, the vertical axis shows the contact force of the dummy head with the airbag and the horizontal axis is the displacement of the head of the dummy.
The airbag stiffness (K_{AM50}, K_{AF05}) is defined as and calculated from the slope of the peak of the contact reaction force (Figure 6-a). The initial measuring point of the stiffness is defined as the point where the reaction force reached 200N level. Again, when the head almost contacts the windshield, in such cases, the final measuring point of the stiffness is defined at the point where the slope of the contact reaction suddenly increases (Figure 6-b).

$$K_{AM50,AF05} = \frac{Airbag\ contact\ maximum\ force}{Head\ displacement}$$



(a) Without head contact with windshield



(b) With head contact with windshield

Figure6 a-b. Definition of airbag stiffness

Result

(i) <u>Comparison of airbag shape</u>

In figure 7, F-S characteristics of the head-airbag contact force (F) vs. the head displacement (S) is plotted for belted-AF05 and unbelted-AM50 conditions. Comparing the results of AM50 and AF05, one can estimate the difference in the amount of energy absorbed due to the difference in mass of the dummies and the restraint conditions (belted and unbelted).

As shown in figure 7, comparison of the 2 airbag shapes (Flat-shape and S-shape) indicate that 14% reduction of the peak contact force for AF05 and 5% increase in contact force for AM50 respectively. As shown in figure 8 a-b, visualizing and comparing the amount of penetration of S-shape and Flat-shape airbag, the head penetrates deep into the S-shape airbag while head is stopped early at the stitching line of the Flat-shape airbag resulting in direct normal contact.

This direct contact for Flat-shape airbag resulted in some amount of increase in head-airbag contact force.

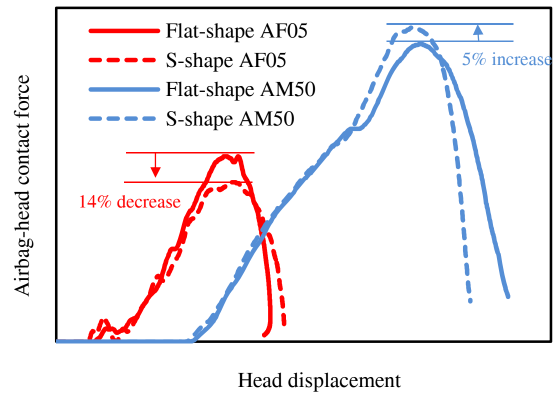
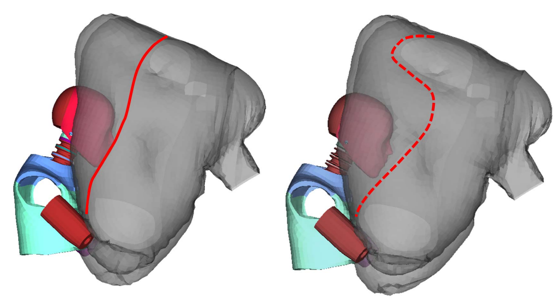
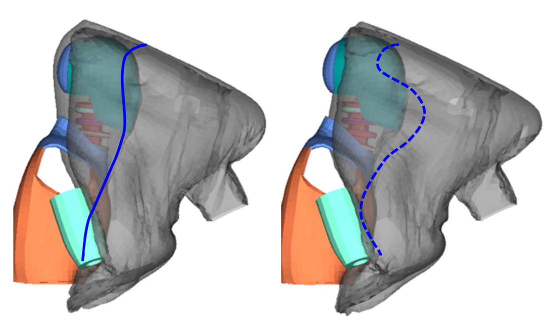


Figure7. Comparison of the head contact force (F) – displacement (S) characteristic for Flat-shape and S-shape airbag in belted-AF05 and unbelted-AM50 conditions



(a) Flat-shape *(b)* S-shape

Belted-AF05 condition



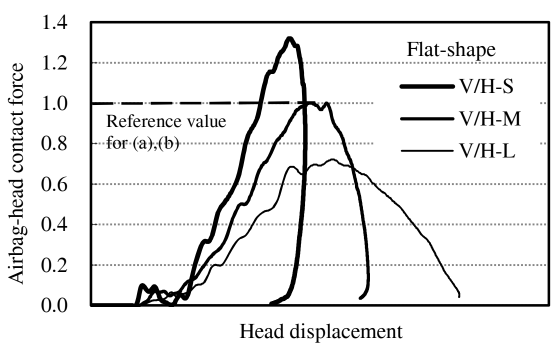
(c) Flat-shape *(d)* S-shape

Unbelted-AM50 condition

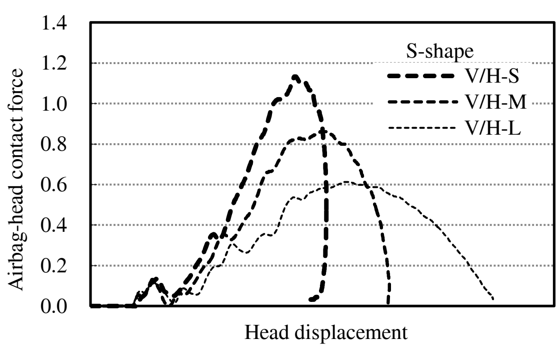
Figure8 a-d. Comparison of the head excursion inside Flat-shape and S-shape airbag in belted-AF05 and unbelted-AM50 conditions

(ii) Comparison of the vent-hole size

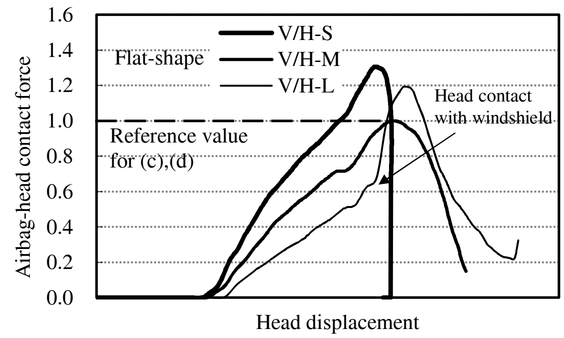
The comparison of the head contact force (F) – displacement (S) characteristic for Flat-shape and S-shape airbag for belted-AF05 and unbelted-AM50 conditions with V/H-S,M,L, are shown in figure 9 a-d. With the peak value of the airbag contact force of belted-AF05 and unbelted-AM50 in combination with Flat-shape of V/H-M airbags respectively as reference values (1.0), all the other airbag contact forces are normalized with respect to two reference values. As shown in figure 9 a-b for belted-AF05 condition, with the increase of vent-hole size, the peak value of the contact force becomes relatively low. As shown in figure 9 c-d for unbelted-AM50, the slope of the contact force decreases with the increase of vent-hole size before the start of bottoming out phase of the airbag between the head and windshield. As V/H-L, the airbag stiffness is too low at the initial phase of the head displacement, it resulted in hard contact of the head with the windshield at the final stage (Figure 10).



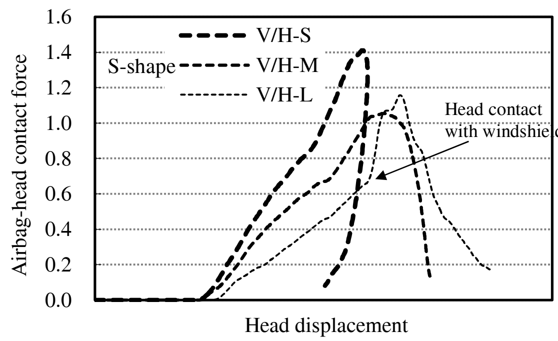
(a) Flat-shape (belted-AF05)



(b) S-shape (belted-AF05)



(c) Flat-shape (unbelted-AM50)



(d) S-shape (unbelted-AM50)

Figure9 a-d. Comparison of the head contact force (F) – displacement (S) characteristic for Flat-shape and S-shape airbag in belted-AF05 and unbelted-AM50 conditions with V/H-S,M,L,

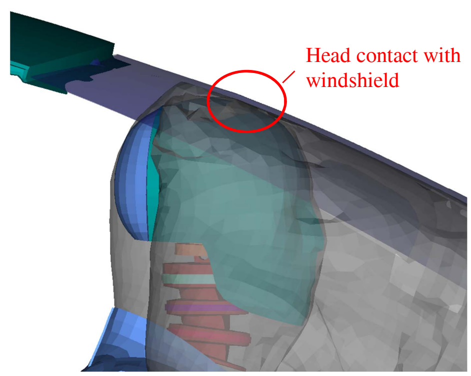


Figure10. Head contact with windshield with V/H-L airbag in unbelted-AM50 condition

(iii) Sensitivity study for airbag stiffness

Using the airbag stiffness estimation procedure as defined in the previous section, twelve simulation results are plotted in table1. With the stiffness of belted-AF05 and unbelted-AM50 in combination with Flat-shape of V/H-M airbags as respective reference values, all the other results are normalized with respect to two reference values.

Comparing the results for V/H-M with Flat-shape and S-shape airbags, the airbag stiffness is 17% lower for AF05 and 7% higher for AM50 in table1. Based on the CAE simulation results, the basic assumption that (i) the airbag stiffness will be low for AF05 and (ii) the airbag stiffness will be high for AM50, are verified.

In figure 11, the simulation results related to the variation of shape and the vent-hole size are plotted with two axes chosen as airbag stiffness, the vertical axis for unbelted-AM50 and the horizontal axis for belted-AF05.

Comparing the simulation results for different vent-hole size and airbag shapes, one can observe that the stiffness of the airbag increases both for AM50 and AF05 if the vent-hole size is made smaller for Flat-shape airbag. However, for S-shape airbag, the increase in relative stiffness is comparatively less for AF05 than compared to the amount of increase of airbag stiffness for AM50.

With V/H-L, in both of the S-shape and Flat-shape airbags, as the head hits the windshield, one can expect that, for AM50, there exists a lower bound of the airbag stiffness between the V/H-M, V/H-L airbag stiffness.

Again, to reduce the AF05 injury level, it is necessary to reduce the airbag stiffness. Therefore, an optimum region exits on the left side where AF05 stiffness tends to reduce and above the limit for AM50 stiffness due to stroke length as shown by respective vertical and horizontal arrows in the figure 11. The optimum region is shown in dotted circle at the left bottom corner in the figure 11.

In the present simulation result, it is decided that S-shape with V/H-M belongs to one of the optimum solutions, and sled tests are performed to verify it.

Table1. Comparison of airbag stiffness for different combination of airbag design parameters
(*Reference design: 1.00)

V/H	Belted-AF05		Unbelted-AM50	
	Flat-shape	S-shape	Flat-shape	S-shape
S	1.70	1.29	1.43	1.61
M	**1.00***	0.83	**1.00***	1.07
L	0.65	0.51	0.76	0.77

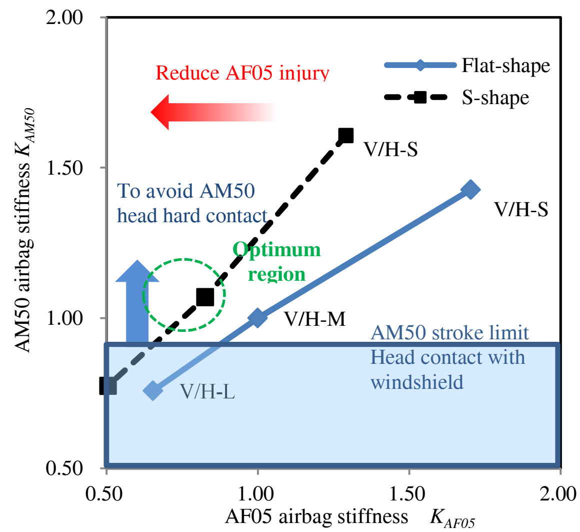


Figure11. Illustrated design procedure to achieve the optimum airbag stiffness solution

STEP3: VERIFICATION BY SLED TESTS

To confirm the findings from the CAE simulations, sled tests equipped with prototype airbag are carried out.

Test condition

Similar to the CAE simulations, the following two sets of experiments are carried out.

- 56km/h belted AF05
- 40km/h unbelted AM50

Airbag: S-shape with V/H-M

Results

In figure 12, the simulation and experiment results are plotted as G-S curves with head acceleration G (X-component) as the vertical axis, and head displacement S as the horizontal axis.

As good correlation is achieved between the simulation and experiment results for belted-AF05 and unbelted-AM50 conditions, the head of them are well restrained as expected.

G-S data for AM50 indicates that the head is well restrained without any hard contact.

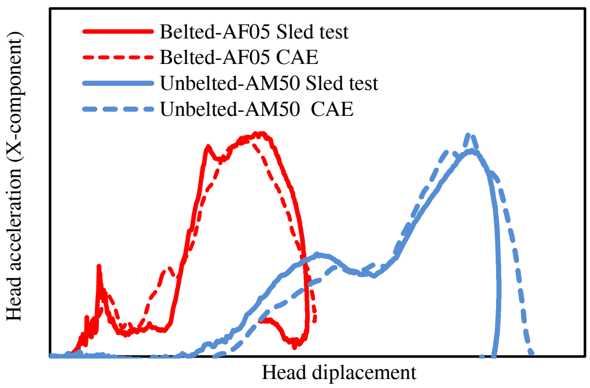


Figure12. Comparison of the X-component of head acceleration – displacement characteristic in belted-AF05 and unbelted-AM50 conditions

(a) Belted-AF05 condition

(b) Unbelted-AM50 condition

Figure13 a-b. Side view of sled tests

CONCLUSION

In the present study, with respect to difference size of occupant and the restraint conditions (belted and unbelted), in order to satisfy the head restraint performance requirement, CAE simulations and experiments are carried out.

The following conclusions are drawn to achieve the near optimum head restraint performance

(a) By introducing S-shape in vertical direction at the center of the airbag instead of a flat-shape airbag, the airbag stiffness can be tuned to meet performance requirement of two different size dummies AM50 and AF05 simultaneously.

(b) Design procedure to achieve the optimum airbag stiffness solution is illustrated with the help of airbag stiffness versus performance diagram.

Further studies are needed for the following main conditions and etc.:

(i) Type of vehicle (sedan, mini-van, SUV, etc.)

(ii) Crash configulations

(iii) Size of the occupant other than AM50 and AF05

ACKNOWLEDGMENTS

The authors would like to thank for Takata Corporation for their kind cooperation in this development work.

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The Development of Two panel Tucked Shape Passenger Airbag

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Paper Number 13-0358

ABSTRACT

Nowadays the most rising issues in the airbag industry are production cost and assemblability. Many car makers are considering applying low cost passenger airbag to their vehicle. In this paper, the inverse 'Ω' shape two panel passenger airbag was suggested to have cost competitiveness and good safety performance. The Sewing pattern that makes inverse 'Ω' shape, increases cushion depth and protects passenger more safely. This paper will introduce the advantages of the developed two panel passenger airbag and describe the superiorities of its performance through dynamic test results.

INTRODUCTION

As the installation of *PAB*(Passenger AirBag) has become mandatory, the developing airbag at low costs is getting more important. Therefore, in many other markets exept for the zone which puts relatively strict legal regulations depending on the regions, the specialized airbag with the low volume inflator and simple cushion is being widely used, achieving the cost competitiveness.

Figure 1. shows the application of the two panel *PAB* on *EURO-NCAP* official test vehicles. As of 2006, more than 60 percent of vehicles were installed with the two panel *PAB*, which makes it more important to apply more optimized and competitive two panel.

A typical *PAB* module, like shown on *Figure 2(a)*, consists of an inflator that produces gas, cushion that protects passengers, housing that stores the folded cushion and retainer that holds the inflator.

The current three panel *PAB* cushion, shown in *Figure 2(b)*, has two side panels and one main panel, which provides depth to protect passengers. But with its high costs and poor assembility, there has been an increasing need for a simple structured cushion. The two panel *PAB* cushion is produced with two panels, upper and lower one, which is a small structure that lightens an inflator and housing. This study intends to propose a more optimized structure by applying *TRIZ* tool to improve the current two panel *PAB*. Furthermore, it intends to prove the quality of a developed item with a collision simulation and dynamic test.

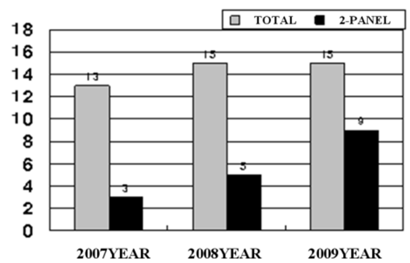
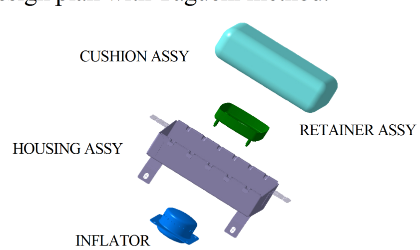


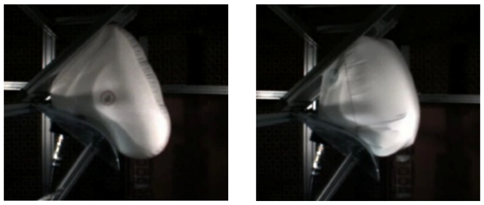
Figure1. Application of two panel *PAB* on *EURO-NCAP* test vehicles

TRIZ is the problem solving tool developed by Altshuller in 1964. Studies utilizing *TRIZ* tool are increasing today, and An Youngjun and his fellow researchers has described *TRIZ* as a concept design tool for an engineering application.

For the airbag collision simulation, Han Soonhong and other researchers in charge of an optimized airbag design, conducted a collision simulation with orthogonal array table and the parameter method that obtains an approximated solution by systemically changing design variables and proposed an optimized airbag design plan with Taguchi method.



(a) Component of *PAB*



(b)Three-Panel (c) Two-Panel

Figure 2. *PAB* component parts and cushion shape

CONCEPTUAL DEVELOPMENT

Determining a Concept for the Two panel tucked cushion

For the two panel to achieve the same or better quality than that of the current three panel, a new and detailed design needs to be adopted. *Table 1* illustrates the three panel *PAB*, two panel *PAB* and two panel tucked structure *PAB* proposed in this study. The two panel cushion has its limit in protecting passengers to the level of three panel cushion due to its low deploying depth. What is more, the two panel has an excellent assembility and low production costs, but does not provide adequate depth to protect passengers. To efficiently protect passengers, a frontal depth should be thick enough with adequate volume that suits the two-panel structure. To find an ideal final result, *TRIZ* theory has been adopted in this study. The basic two panel is one of the most basic concepts that are widely used at *DAB*(Driver Air Bag) and *SAB*(side airbag). For all its low unit price and excellent package, it is not suitable for a two panel *PAB* model as it is challenged by its technology limit. As a solution, the two panel tucked structure has been newly introduced. It is a tool to overcome the frontal depth limit, which gives an enough depth and reduced volume. Genrich Saulovich Altshuller's 40 principles have been used in this. *Table 2* shows the main problem solving factors to overcome the technology limit of the two panel. The item 4, 7, 16 of the *TRIZ* 40 principles were used at the two panel tucked structure development. *Table 3* shows the tucked structure of the two panel cushion as a solution for expanding the deploying depth. The tucked structure is the two-panel structure before folding process, but when deployed, it expands to the three-panel structure by adding an inverse Ω structure to the front panel.

Table 1
Main solution factor

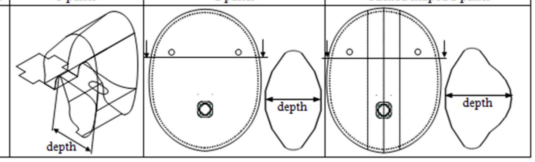
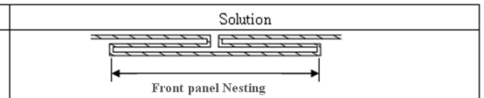
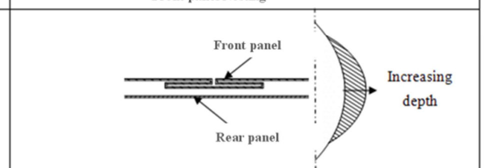
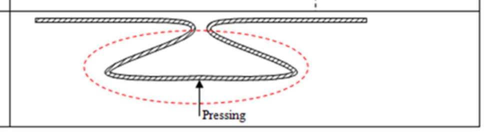
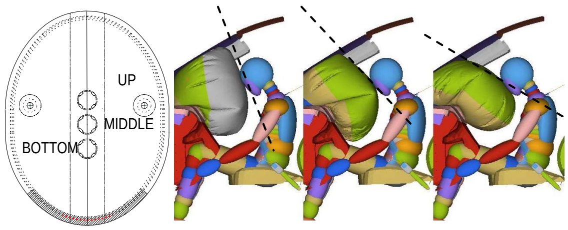
Classification	3 panel	2 panel	Tucked shaped 2 panel
shape			

Table 2
The concept for increasing the deploying depth

Classification	Solution
Nesting	
Asymmetry	
Partila or Exessive	

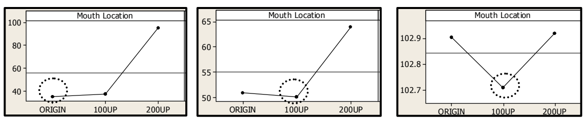
Determining the Best design through the analysis

The most critical aspect of this study is the deploying shape of the two panel tucked structure and the resulting level of injury. *Figure 3*. shows the deploying example after analyzing *EURO-NCAP* mode. In this analysis, the structure's tucked amount and vent size were fixed with the location of the mouth, into which gas is entered, varied. *Figure 3(b)* is the deploying shape of the two panel *PAB* that the mouth is located at the bottom. *Figure 3(c) and 3(d)* are the deploying shapes as the mouth was moved by 100mm from the original location at the bottom. Further analysis was conducted by varying the tucked amount by 100mm, 140mm and 180mm, and the vent size by 15mm, 25mm and 35mm. The *EURO-NCAP* dynamic analysis was conducted by varying the level of factors. Here, the noise also was considered by selecting vehicles that represent Compact, Midsize and SUV which are currently in mass production. This system also includes Smaller the Better Characteristics as it is advantageous to have a low injury level from the viewpoint of the robust design strategy.

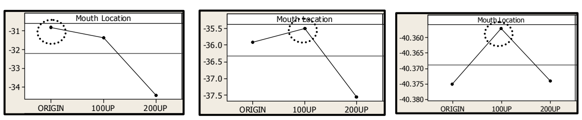


(a)Location (b) Bottom (c) Middle (d) Upper

Figure 3. Analysis result according to the mouth locations.

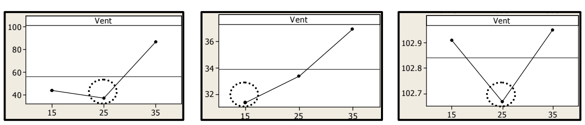


(a) HIC36(Mean) (b) Neck EXT(Mean) (c) Chest CD(Mean)

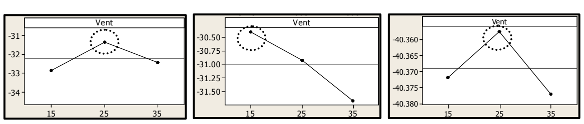


(d) HIC36(S/N) (e) Neck EXT(S/N) (f) Chest CD(S/N)

Figure 4. Analysis of the controlling factors(the mouth locatoin)



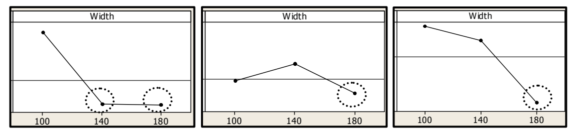
(a) HIC36(Mean) (b) Neck EXT(Mean) (c) Chest CD(Mean)



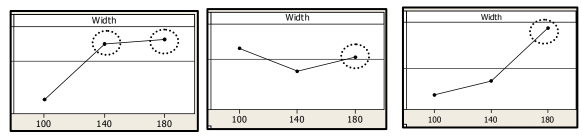
(d) HIC36(S/N) (e) Neck EXT(S/N) (f) Chest CD(S/N)

Figure 5. Analysis of the controlling factors (Vent diameter size(mm))

Figure 4., *Figure 5. and Figure 6*. show the Smaller the Better Characteristics results of the analysis for an optimized design. Generally, the ouput was the most robustic when the mouth was located at bottom (origin) or 100mm up and theirfore requires an appropriate tunnig according to vehicle types. And the analysis output showed the lowest level of injury when the diameter of the vent was somewhere betwen 15mm and 25mm. Meanwhile, the robustness level was the highest when the tucked amount was somewhere between 140mm and 180mm. In this analysis, the mount location up by 100mm, Φ15mm of the vent size and 140mm of the tucked amount for the Sled test were chosen, taking the test vehicle layout into account.



(a) HIC36(Mean) (b) Neck EXT(Mean) (c) Chest CD(Mean)



(d) HIC36(S/N) (e) Neck EXT(S/N) (f) Chest CD(S/N)

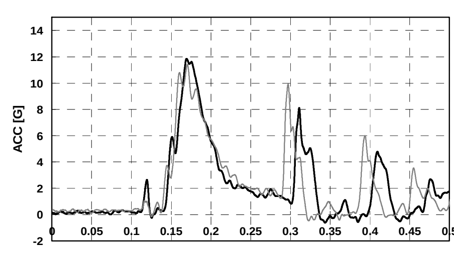
Figure 6. Analysis of the controlling factors (the tucked amount (mm))

CONCEPT EVALUATION

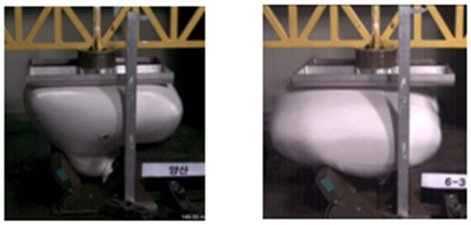
Sled test Result

The vent specification, the criteria for the Sled, was chosen after verification through the *DROP* tower test shown in *figure 7*. and the optimum analysis results. The black solid line in *Figure 7(a)* is the acceleration data of the three-panel drop and gray solid line is the acceleration data of the two-panel drop. *Figure 7(b) and (c)* are the illustrations of the drop tests conducted under the same condition (three8kgf, 19.6kph).

In this study, some relevant factors are reviewed and the collision performance proving test with the two panel *PAB* was conducted by utilizing the Taguchi method.



(a) test acceleration



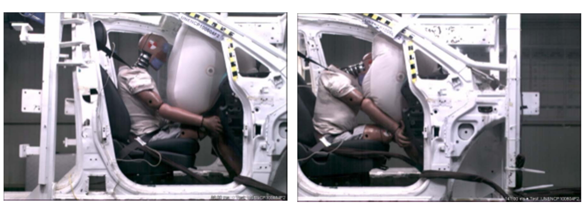
(b)3-panel(50ms) (c)2-panel(50ms)

Figure 7. drop tower test results

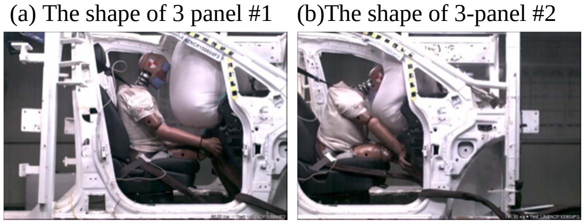
The main collision modes are *EURO-NCAP* offset frontal crash test (64kph) to evaluate injury at the passenger seat, the tree panel *PAB* of mass produced compact SUV vehicle, which has been the target of review. Other relevant parts except for the cushion have the same specification as the mass produced ones.

Figure 8. shows general deploying features of the three panel and two panel. The three panel cushion in *Figure 8*(a) and (b) deploys as a form of main side panel to protect the upper body of a passenger, and it's lower cushion gives enough protection to the chest. At the lower part of the chest, chest deflection or chest viscous, caused by the pressure of the seat belt and cushion, occur a lot.

In contrast, the two panel, as shown in *figure 8(c) and (d)*, protects a head and neck rather than chest, separating the restraining force of the belt and airbag, which minimize a passenger's upper body injury.



(a) The shape of 3 panel #1 (b)The shape of 3-panel #2



(c) The shape of the 2 panel #1 (d) The shape of 2 panel #2

Figure 8. The deploying comparison of the three and two panel *PAB*

Sled test Results Analysis

Table 3 shows the results of the *EURO-NCAP* three-panel Correlation Sled test and two-panel tucked structure Sled test. Airbag is a safety device that protects mainly the upper body of passengers and injuries on head, neck and chest are the most critical evaluation criteria. *Table 3* shows that occurrence of injuries decreased when the two-panel *PAB* was used, compared to the specification for mass production. In particular, the specification for mass production scored 3.2 points with 28.0mm at the injury evaluation, but the new two-panel model earned the perfect score with 4.0 and 22.1mm. This was possible due to the fact that the two-panel cushion came in contact with part of the head first, rested the head early, reducing chest injuries with the restraining force puts by the belt load only.

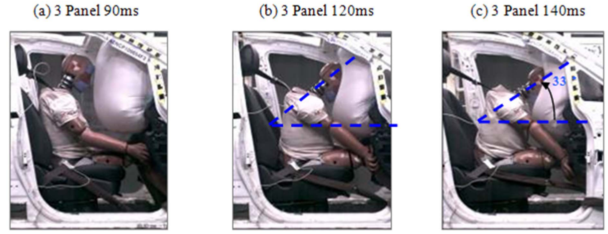
Table 3

***EURO-NCAP* vehicle and Sled injury**

UPPER BODY			3-PANEL (CORR.)	2-PANEL (SLED)	BELT
EURO-NCAP	HEAD	HIC36	127 (4.0)	100 (4.0)	SLL
		3ms G	28.3 (4.0)	24.5 (4.0)	
	NECK	Shear (N)	610 (4.0)	340 (4.0)	
		Tension (N)	984 (4.0)	525 (4.0)	
		EXT(Nm)	5.7 (4.0)	4.9 (4.0)	
	CHEST	C (mm)	28.0 (3.2)	22.1 (4.0)	
		V*C (m/s)	0.0 (4.0)	0.0 (4.0)	

Figure 9. shows that a passenger's head and neck are bent by 29° and 33°, smaller than the angle in the mass produced three-panel specification. It is considered that the overall injury performance enhanced thanks to the low load on the chest and the smaller bending angle on the head and neck.

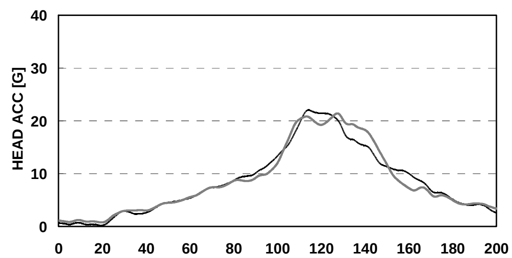
(a) 3 Panel 90ms (b) 3 Panel 120ms (c) 3 Panel 140ms



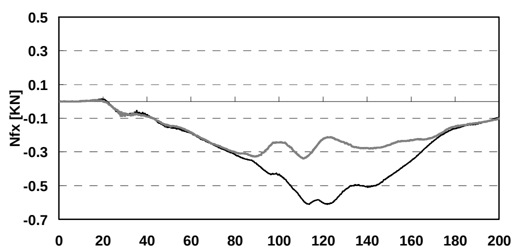
(d) 2 Panel 90ms (e) 2 Panel 120ms (f) 2 Panel 140ms

Figure 9. The deploying comparison of the Sled test.

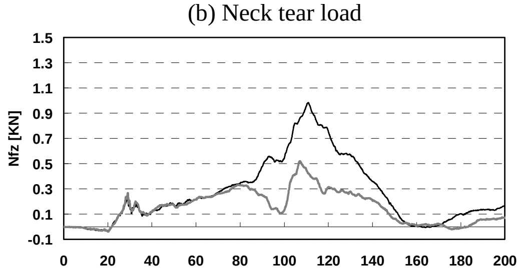
Figure 10. shows the results of the barrier test and injury graphs of the 64kph *EURO-NCAP* Sled test. The thick black solid line indicates the injury level of the mass produced vehicle, and grey is of the tucked two-panel Sled test. *Figure 10 (a)* show head injury characteristics of the 64kph *EURO-NCAP*. When the two-panel is applied, the head accelerations are distributed at low levels. *Figure 10 (b), (c) and (d)* show neck injury characteristics and *Figure 10 (e) and (f)* show chest injury characteristics. It is shown that the head and neck rotaition are lower than 3-panel cushion when the 2-panel is used.



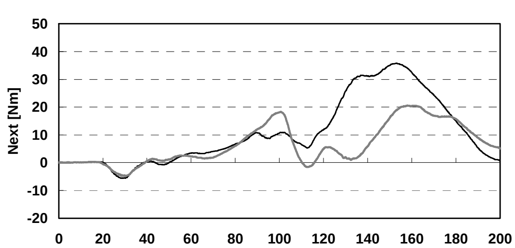
(a) Head acceleration X



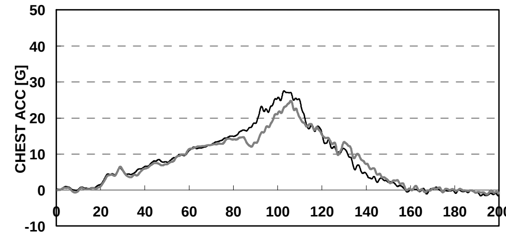
(b) Neck tear load



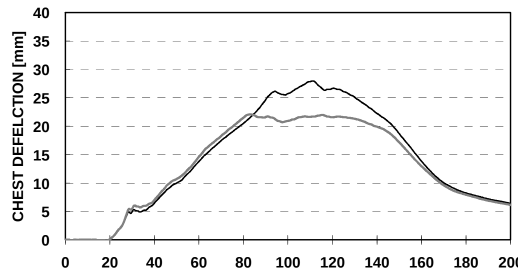
(c) Neck tension load



(d) Neck extension



(e) Chest acceleration X



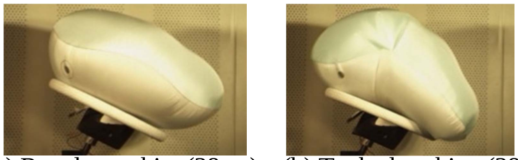
(f) Chest deflection X

Figure 10. The analysis of 64kph *EURO-NCAP* injury graph

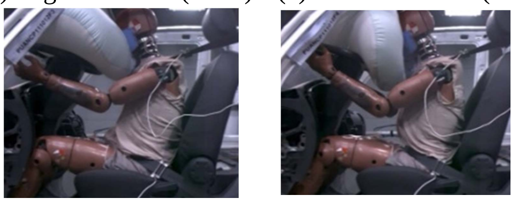
The load on chest was also reduced by lowering the load of pressure to chest. In addition, the vent sizes of the mass production specification and the two-panel were Φ25 and Φ15 respectively .

Application Examples of the Two-panel tucked structure

The commercial vehicle has its limit in protecting driver passenger as its steering wheel angle is larger than that of the regular passenger car or van. Furthermore, there has been no airbag developed so far that considers the layout feature of the commercial vehicle, leaving no choice but to install the airbag used in the current passenger/*RV* car. In this case, however, as the airbag deploys parallel to the steering wheel due to its installation angle, making it impossible to protect the upper body of a driver. Plus, the cushion gets stuck at throat, increasing the likelihood of chest or neck injuries. The tucked structure can solve this problem with an expanded upper deploying depth, which enables the early restraining of a driver's head and with lower part of cushion deploying to the area between the driver's chest and steering wheel, minimizing the driver's injury. Figure 11. Shows deploying features of specialized commercial vehicle *DAB*.



(a) Regular cushion(38ms) (b) Tucked cushion (38ms)



(c) Regular cushion (d) The tucked cushion

Figure 11. The deploying comparison of the static and dynamic test.

Unlike a passenger car/ban, the commercial vehicle has the middle seat, making it necessary to protect a passenger in the middle. In this type of vehicle, other components such as an audio are placed at the center fascia. Therefore, the protection area covered by the current airbag modules on each side should be expanded to protect a passenger in the middle as well. In addition, the tucked structure with an expanded deploying depth is used to cover possible injuries at the passenger seats. The protection area and the injury levels can be controlled by focusing on head protection for the middle passenger while keeping a similar protection performance to the current 3D cushion airbag for the passenger. Here, the air bag is developed in a way that only a passenger head is protected by minimizing passenger movement with the application of ELR(Emergency Locking Retractor) belt for the middle seat while sistemically satisfying the target performance to the level of the current passenger seat with Pre-Tensioner seat belt. Figure 12. Shows deploying analysis features of specialized commercial vehicle *PAB*.

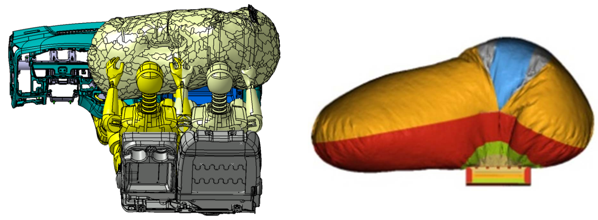


Figure 12. The expanded shape of the tucked structure

CONCLUSIONS

In this study, the main concept was determined for the two-panel tucked structure and the advantages of the determined model compared to the three-panel were analyzed through the comparison of the package, assembility and production costs. Moreover, the study proved the excellent collision performance of the two-panel *PAB* through the analysis of the current mass production barrier test and the two-panel Sled test results, reaching the conclusion as follows:

1) The technology limit has been overcome by the *TRIZ* problem solving method.
2) The robustness according to each factor and noise has been evaluated by adopting the Taguchi Robust Design concept.
3) It is proven that the two-panel tucked *PAB* has same or higher protection ability than the three-panel airbag through the *EURO-NCAP* tests.
4) Through the application of the tucked shape cushion, showed the possibiliy of new concept model airbags.

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SINGLE STAGE DRIVER AIRBAG MODULE DEVELOPMENT FOR OUT-OF-POSITION

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Paper Number 13-0494

ABSTRACT

A driver airbag module has been developed with single stage inflator in an attempt to determine the 05th% ATD measured dummy injury response ("MDIR") in out-of-position scenarios (two NHTSA positions). Through computer simulations, dynamic MDIRs for in-position 05th%ile and 50th%ile dummies were evaluated as well.

It typically takes many design iterations to finalize a driver side module configuration to meet FMVSS208 regulatory conditions. Some typical parameters are tear seam cover design, cushion folding pattern and inflator output. In this paper, a Taguchi design of experiments was used to evaluate the influence of module design parameters. A MDIR comparison between a proposed new driver airbag module with a single stage inflator and a baseline module with a dual stage inflator was made not only for out-of-position tests, but also in-position crash simulations.

Currently in the US market, a majority of driver airbag modules use dual stage inflators to meet the injury assessment reference value ("IARV") criteria set by federal regulation. This driver airbag module with single stage inflator will give car manufacturers an option to eliminate the seat track position sensor and to reduce the number of wire harnesses which are required to connect the dual stage inflator. An additional benefit would be a simplified airbag control unit involving both algorithm and hardware. This simplification should be accomplished while providing comparable MDIR for both in-position and out-of-position scenarios over a baseline module with a dual stage inflator.
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INTRODUCTION

The driver side airbag has played a significant role in saving the lives of occupants behind the steering wheel during a crash event [1]. However, there is a potential injury risk by the airbag when the occupant is located close to the airbag module [2]. One example of this is due to improper seating such as forced seating change by emergency braking called out-of-position ("OOP"). In an effort to provide more effective occupant protection and mitigate airbag induced injury, many different technologies have been developed. These technologies include cover tear seam design, cushion folding pattern [4, 7] and inflator output tailoring.

The advanced airbag rule made by the National Highway Traffic Safety Administration (NHTSA), in part [3], provides procedures and IARV guidelines to conduct low risk deployment ("LRD") airbag tests with a 05th%ile female dummy as well as the dynamic MDIR requirements.

To investigate the effects of module parameters and to find a combination that can reduce the risk of airbag induced injury, either a Design of Experiments ("DOE") [5] or an optimization tool can be used. As it is well known, a DOE full factorial method could increase the number of tests resulting in unwanted additional cost and a development timing increase. In addition, there is a need to secure a robust margin for the ATD MDIR in case of testing set-up change and/or variation [6]. Therefore, a Taguchi design was chosen because it is effective in reducing testing, and the variability caused by outside noise factors, while evaluating the influence of module parameters.

An active venting technology (TRW developed Self Adaptive Venting, "SAVe", US patent # 6773030 and 7954850) was incorporated in the Taguchi DOE to give MDIR margin for the OOP test conditions while retaining dynamic MDIR for the in-position, high speed crash modes.

Pendulum testing was used to evaluate the stiffness of each driver airbag module and to help correlate the component level simulation model. Later, this validated component model was inserted into the system level sled model to compare the indicated MDIR.

The new driver airbag module with single stage inflator showed MDIR levels below FMVSS 208 maximum IARVs for OOP tests. Simulation showed an equivalent and/or comparable dynamic MDIR over a dual stage baseline module for all size adult occupants (05th%ile and 50th%ile), belted or unbelted.

OOP TESTS WITH A BASELINE DUAL STAGE MODULE

Baseline dual stage module has a bag folding of multiple horizontal pleats. Bag diameter was 711mm (28") and the discrete vent size was 2×18mm. The cover tear seam pattern was "Y" type. (Figure 10) See the table 1 below for the module configuration. The baseline dual stage inflator was a hybrid type technology with a peak pressure of 215kPa for high output and 145kPa for low output. (Figure 1)

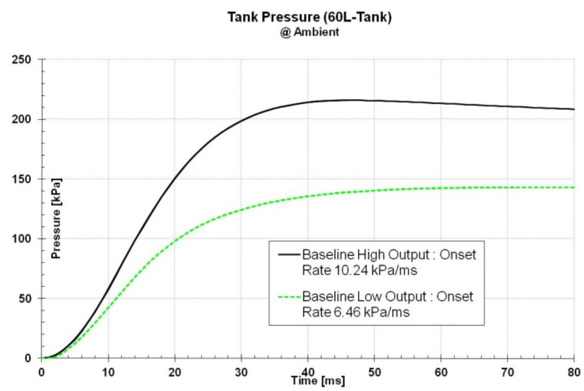


Figure 1. Inflator Pressure Curves from Baseline Module.

Table 1.
Baseline Bag Parameters

	Bag Diameter	Tether Size (3H/9H)	Discrete Vent Size	Adaptive Vent
Baseline	711mm	254mm/254mm	2×18mm	without

A test series evaluating the two positions specified by NHTSA was conducted with the baseline dual stage module. Low inflator output with 150ms delay between 1st stage and 2nd stage was used for all tests. These 2 regulated positions are called "Position #1 - Chin on Module position" and "Position #2 - Chin on Rim position". Two tests were conducted on each position to see the data variability as well as average MDIR. Figure 2 identifies the MDIRs from the tests for position 1. The major challenge to pass the OOP requirements is to reduce the initial punch-out force from the early airbag deployment. Neck tension variance was 20% of NHTSA's FMVSS208 regulatory value.

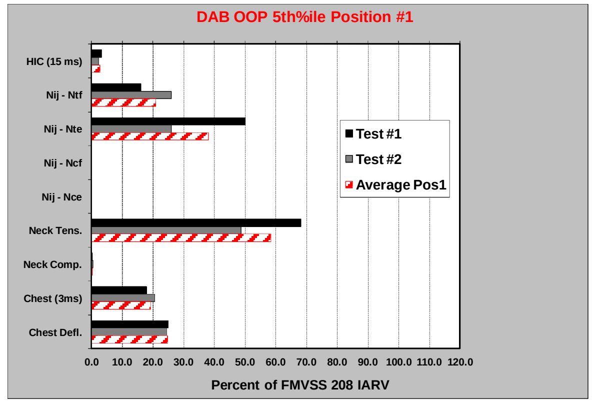


Figure 2. OOP Baseline MDIRs for NHTSA Position 2.

Two data points were obtained for "Chin on Rim" position test with the 05th percentile female dummy and Figure 3 shows the MDIRs from the test. This NHTSA regulated position usually puts the dummy's chest as close as possible to the steering wheel. This close proximity results in not only relatively high chest deflection, but also relatively getting high neck MDIRs due to airbag deployment under the chin. As shown in Figure 3 below, all MDIRs were within the regulation limits. 81% of chest deflection was the highest MDIR. Again, the neck tension force had 20% variation.

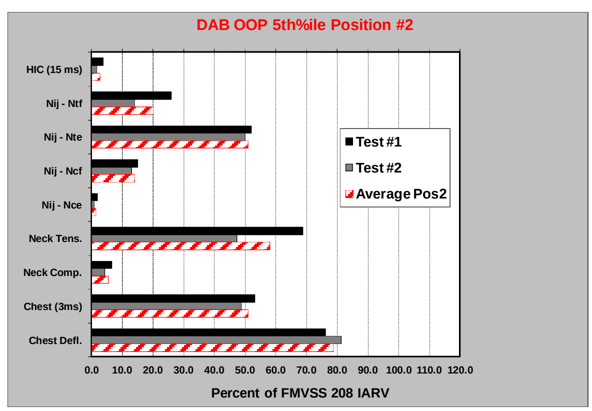


Figure 3. OOP Baseline MDIRs for NHTSA Position 2.

DESIGN CONSIDERATIONS FOR SINGLE STAGE MODULE

A self adaptive vent("SAVe") was designed in the rear panel. One end of the tether from adaptive vent technology was attached to the guide panel to cover the vents and the other end was attached to the rear panel (Figure 4). If the airbag fully deploys, the adaptive tether tightens, creating tension in the tether and pulling adaptive vent closed. The travel distance of adaptive tether to cover vents is 95mm. If the airbag deployment is obstructed, (i.e. by an OOP occupant) the tether does not tighten and the vents stay open. Thus, a portion of the gas is venting through adaptive vent (Figure 5).

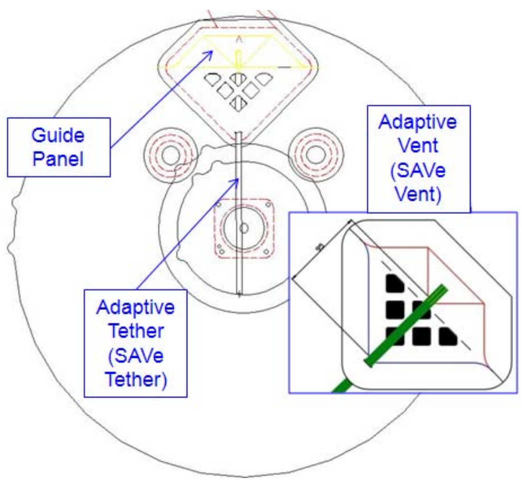
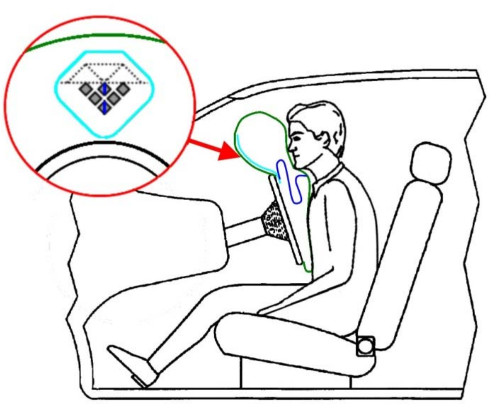


Figure 4. Self Adaptive Venting Schematic Diagram.



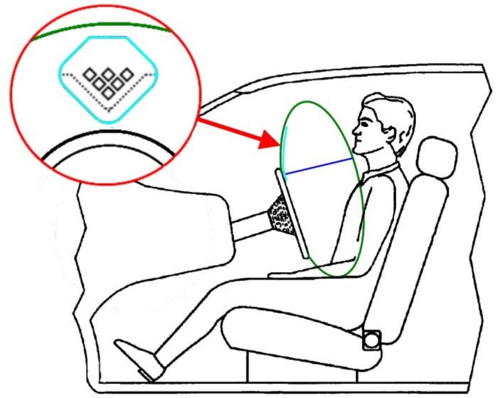


Figure 5. Self Adaptive Venting Working Mechanism.

Like stated above, adaptive vents have two main objectives. The first is being to remain open when an occupant is obstructing the deployment. The second is being to close and seal when the occupant is un-obstructed. Controlling these two functions begins with the tear stitch. It must be strong enough to keep the adaptive vent open during the assembly and folding process, and to tear during the lowest deployment conditions (i.e. a cold, low output deployment). A unique tear stitch design and thread combination provide that balance with minimal variation.

Another feature that drives the vent functionality is the tether length. It needs to be long enough to keep the vent open as long as possible to vent the gas in an out-of-position condition while being short enough to close and seal the vent for a normally seated condition. A series of static inflations helps determine a length that fulfills both requirements. But to help minimize the effect of variations in the length, a tether attachment location is found that has later contact with a normally seated occupant. This location is generally near the center of the bag, but may be need to be biased to the 12 o'clock position.

A Critical-to-Satisfaction (CTS) translation was used to identify critical functional factors influencing both dynamic crash MDIR and OOP MDIR. Four design parameters including adaptive vent design, inflator output, cover tear seam design and bag folding were identified to separate main parameters affecting OOP MDIR, while minimizing the influence on dynamic MDIR (Figure 6).

OOP Test ◎:9, ○:3, △:1			Priority	DAB Inflator: Inflator Pressure	DAB Inflator: Inflator Onset	DAB Cushion: Cushion Size	DAB Cushion: Tether Length	DAB Cushion: V/H Size	DAB Cushion: Cushion Material	DAB Cushion: Adaptive Vent	DAB Cushion: Tear Seam Pattern	DAB Cushion: Cushion Folding
Static	5th ATD	Position #1 (Chin on Module)	5	△	◎	△	△	○	○	◎	◎	◎
		Position #2 (Chin on Rim)	5	△	◎	△	△	○	○	◎	◎	◎
No relation between crash & LRD			5	○	○	○	○	△	△	◎	◎	◎
Cost			4	△	△	○	△	△	○	◎	△	○
Weight			4	△	△	△	△	△	△	△	△	△
Importance				33	113	41	33	43	51	175	143	151

Figure 6. CTS Translation Chart.

Figure 7 below shows the "P-Diagram" explaining the Taguchi DOE set-up to find a module configuration to meet FMVSS208 OOP requirements.

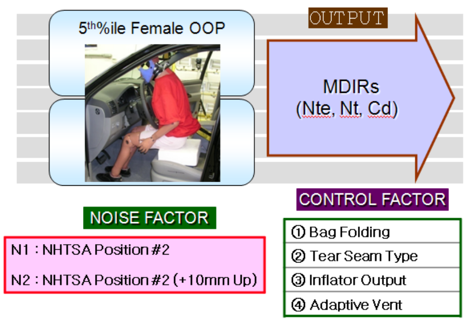


Figure 7. P-Diagram Set-up for OOP Tests.

From the baseline dual stage module OOP test series, NHTSA position 2 was chosen as the worst case dummy position based on higher MDIRs and airbag deployment variation. In addition to this, another dummy position was introduced. The head was raised by 10mm along vehicle z-axis to simulate test set-up variation. These two dummy positions were regarded as noise factors.
Neck tension ("Nt"), Nte and chest deflection("Cd") were chosen as output monitoring factors because these 3 MDIRs showed the highest values in the baseline tests.
Four different control factors from Critical-to-Satisfaction (CTS) translation were chosen to find a module configuration which would decrease the nominal MDIRs, while suppressing variation.
Figure 8 below shows two outputs of TRW DI10 pyrotechnic single stage inflator ballistic curve comparisons with baseline dual stage hybrid inflator. Star(intended to have radially deploying bag, TRW US patent # 6726615, 7090248 and 6086089) and tuck/roll were used for bag folding method as a control factor. (Figure 9) "I" type and "Y" type were used for cover tear seam pattern (Figure 10). Adaptive vent was also considered as a control factor.

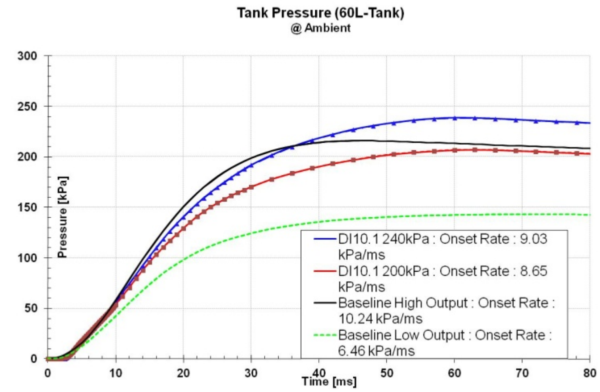


Figure 8. Control Factor: Inflator output.

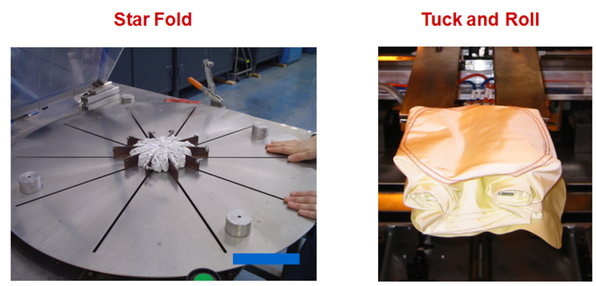


Figure 9. Control Factor: Bag Folding Method.

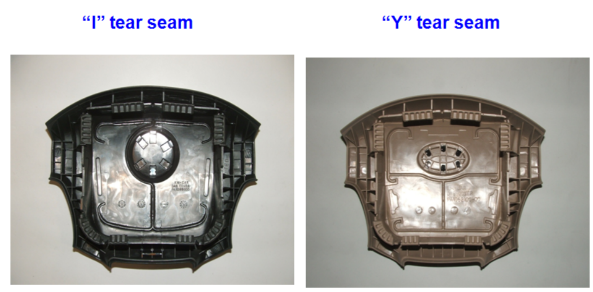


Figure 10. Control Factor: Tear Seam Design Pattern.

DOE ANALYSIS

Table 2 identifies the module configurations and test matrix for Taguchi method. The total number of tests would be 16 for each ATD position with the full factorial DOE method, but only 8 were tested with Taguchi method which reduced significant number of tests. The bag diameter and tether size were carried over from the baseline bag, but the discrete vent hole was changed to 2×30mm. The corresponding test results are shown in Figure 11 ~ Figure 13. Like explained in P-Diagram set-up, two data points were obtained for NHTSA position 2 (1st and 2nd in Figures) and one data point obtained for offset head location by 10mm (3rd in Figures). Since M5~M8 module showed consistently lower neck tension and Nij responses, star folding was chosen. The next focus was to minimize chest deflection with lower response variations.

Table 2.
Module Configurations for DOE

	Design/Control Factor			
	Bag Fold	Inflator	Tear Seam	Adaptive Vent
M1	T/R	200	Y	W/O
M2	T/R	240	Y	With
M3	T/R	240	I	W/O
M4	T/R	200	I	With
M5	Star	200	I	W/O
M6	Star	240	I	With
M7	Star	240	Y	W/O
M8	Star	200	Y	With

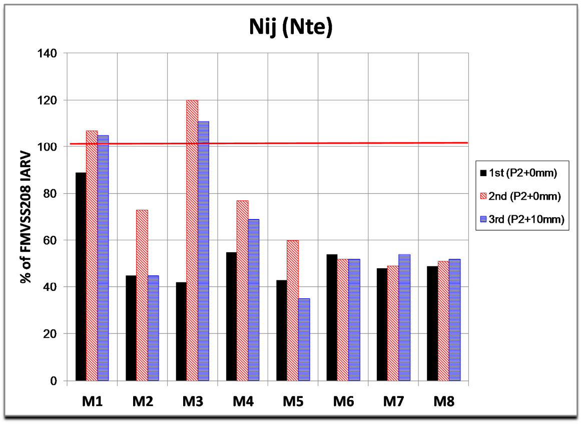


Figure 11. DOE Test Results (Nte).

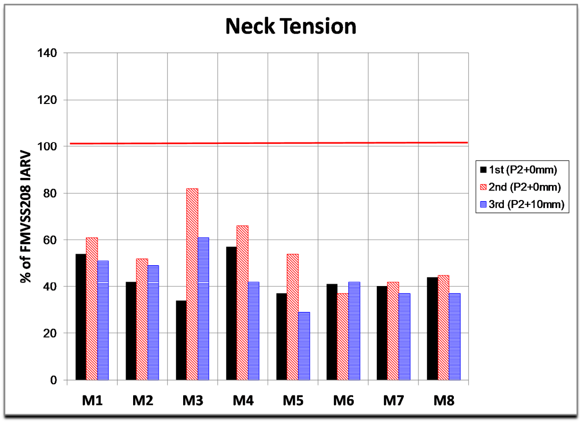


Figure 12. DOE Test Results (Neck Tension).

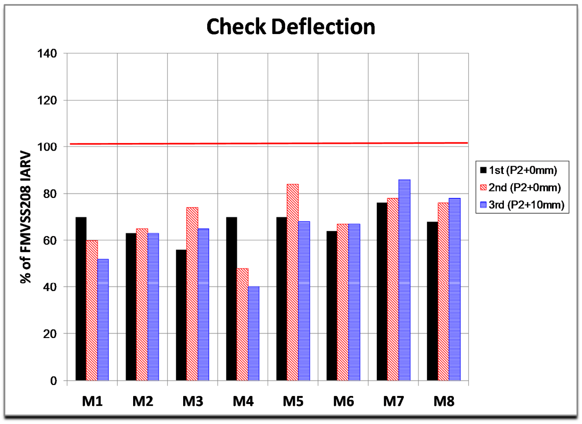


Figure 13. DOE Test Results (Chest Deflection).

Using the Taguchi method, signal to noise ratio (S/N ratio) and mean values were analyzed to evaluate trends in module parameters. Star folding and self adaptive vent were found to reduce Nij mean value while maintaining minimal response variations. (Figure 14 and 15) For chest compression, "I" tear seam pattern along with 200kPa inflator output showed lower injury values. (Figure 16 and 17)

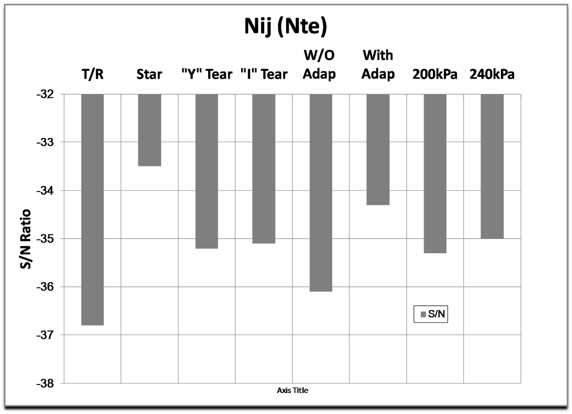


Figure 14. Robust Taguchi Analysis (Nte: S/N).

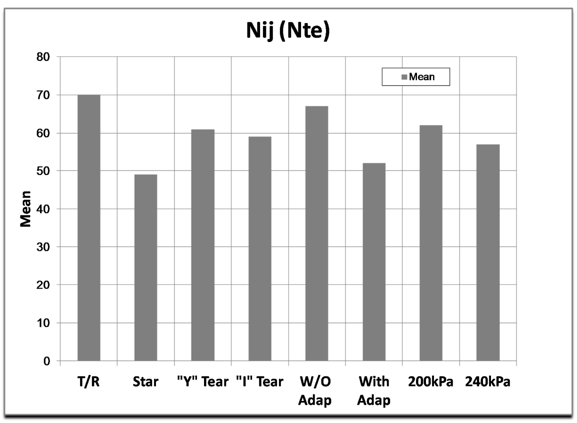


Figure 15. Robust Taguchi Analysis (Nte: Mean).

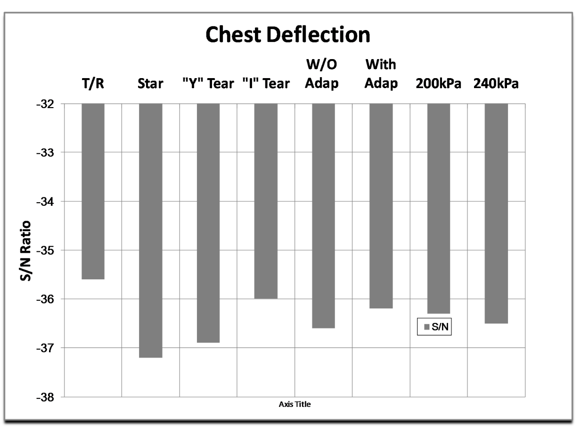


Figure 16. Robust Taguchi Analysis (Chest deflection: S/N).

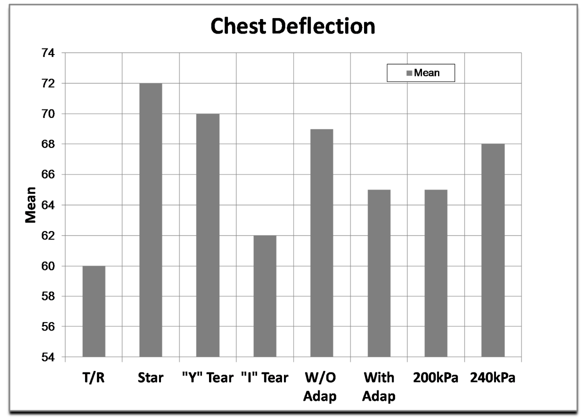


Figure 17. Robust Taguchi Analysis (Chest deflection: Mean).

Based on the DOE analysis and Taguchi robust design, star folding, Self adaptive vent, “I” tear seam and 200kPa inflator were chosen. However, 240kPa inflator was still considered as second solution in case of the necessity of more inflator output to attain desired dynamic MDIR (Table 3). Again, the bag diameter and tether size were the same as the baseline bag, except 2×30mm discrete vent.

Table 3.
Suggested Module Configurations

	Bag Folding	Inflator (DI10)	Tear Seam	Adaptive Vent
Suggestion 1	Star	200kPa	I	with
Suggestion 2	Star	240kPa	I	with

OOP CONFIRMATION TESTS

OOP confirmation tests were performed to evaluate MDIR of suggested modules. The testing environment (steering wheel, steering column position and angle, seat and dummy position) was exactly same as what was tested in the baseline OOP. Figure 18 and Figure 19 show MDIR percentage of FMVSS208 limits for each NHTSA position. Both modules showed lower MDIRs, along with less variation over the baseline dual stage module for neck tension and chest deflection. The highest percentage of MDIR from the suggested modules is below 70% of FMVSS208 limit. As shown Figure 20 through 25, airbags were consistently deployed behind the steering wheel. This reduced not only the MDIR, but also data variations from the repeated tests.

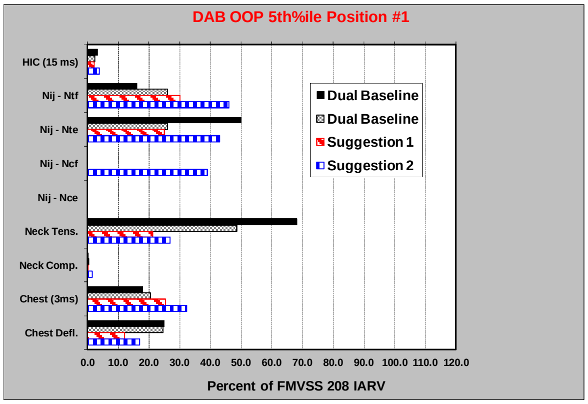


Figure 18. NHTSA Position 1 Confirmation OOP Test.

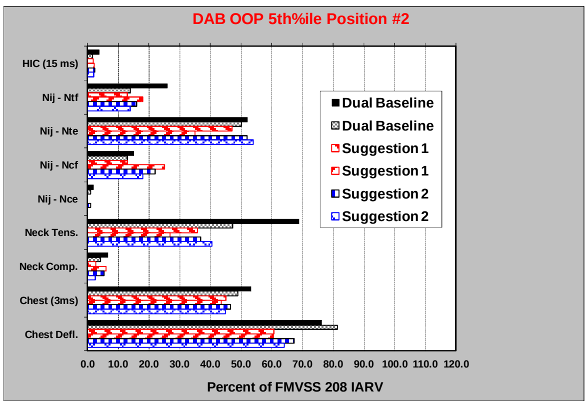


Figure 19. NHTSA Position 2 Confirmation OOP Test.

Figure 20. Confirmation OOP Test for NHTSA Position 1 at 15ms(Suggestion 1).

Figure 21. Confirmation OOP Test for NHTSA Position 1 at 15ms(Suggestion 2).

Figure 22. Confirmation OOP Test for NHTSA Position 2 at 15ms(Test 1 with Suggestion 1).

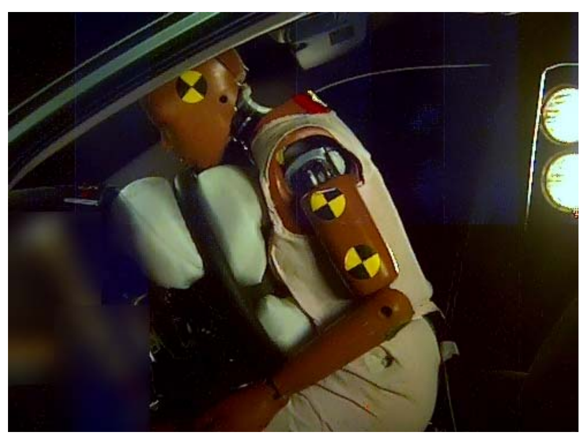


Figure 23. Confirmation OOP Test for NHTSA Position 2 at 15ms(Test 2 with Suggestion 1).

Figure 24. Confirmation OOP Test for NHTSA Position 2 at 15ms(Test 1 with Suggestion 2).

Figure 25. Confirmation OOP Test for NHTSA Position 2 at 15ms(Test 2 with Suggestion 2).

PENDULUM TESTS

A pendulum test series was completed to compare bag stiffness between baseline dual stage and proposed single stage modules. These were the same modules used in confirmation OOP testing. Figure 26 and 27 below show pendulum acceleration versus angle displacement curve for each inflator output. The -0.5 degree angle represents bag bottoming out and pendulum strike through. The suggested single stage modules showed earlier restraint force than baseline dual stage low output due to higher initial acceleration values. On the contrary, they showed slower loading along with higher peak acceleration than baseline dual stage high output. These characteristics are similar to inflator ballistic curves. (Figure 8) This pendulum data was used to correlate a component level airbag simulation model (MADYMO). The correlated model was used in a system level sled model to compare MDIR.

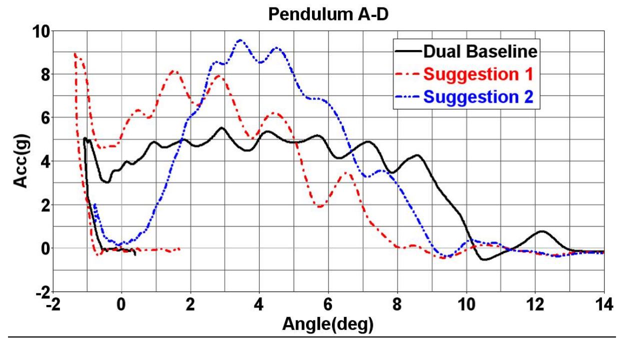


Figure 26. Pendulum Comparison (High Output for Baseline) : 90˚ Initial Angle.

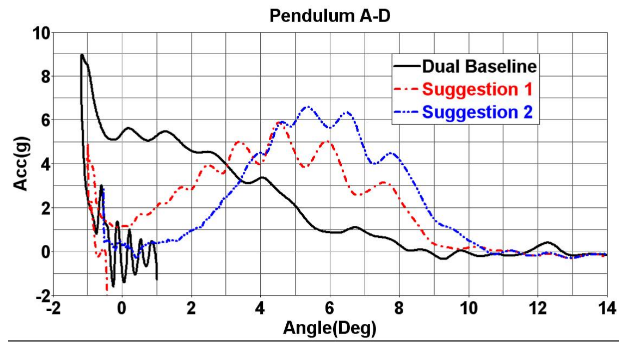


Figure 27. Pendulum Comparison (Low Output for Baseline) : 70˚ Initial Angle.

DYNAMIC MDIR COMPARISON

MADYMO simulation was used to compare the MDIR between the baseline dual stage and the proposed single stage designs. The vehicle pulse for 40kph and 56kph were shown in Figure 28. The vehicle environment information is shown in Table 4 below.

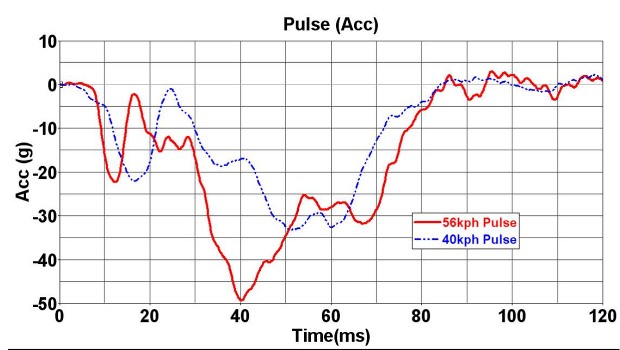


Figure 28. Dynamic Vehicle Crash Pulses.

Table 4.
Vehicle Environment Information

	Load Limiter	Belt Pretensioner	Airbag Fire Time	Speed
Belted	DLL	Retractor (14ms)	14ms	35mph
Unbelted	N/A	N/A	18ms	25mph

Four critical dynamic testing modes (40kph 50th%ile unbelted, 40kph 05th%ile unbelted, 56kph 50th%ile belted and 56kph 05th%ile belted) were evaluated (Figure 29). Low output was used for the baseline of 56kph 05th%ile belted and 40kph 05th%ile unbelted. High output was used for the remaining crash modes. MDIRs were compared in Figure 30~33. For both unbelted modes, the highest MDIRs were chest acceleration and chest deflection. The proposed single stage modules showed lower values than the baseline for these MDIRs. For the 56kph belted 05th%ile and 50th%ile ATD, suggestion 2 showed less performance on HIC, neck and chest response than suggestion 1. This is due to too much inflator gas from 240kPa peak output inflator. However, the overall MDIR with suggested single stage designs were comparable to the baseline dual stage for belted test conditions. This study was not focused on improving dynamic MDIR, but rather showing comparable MDIR to the baseline. Further, parameter tuning including vent size and steering column could help tune the system.

Figure 29. ATD Kinematics from Dynamic Simulations.

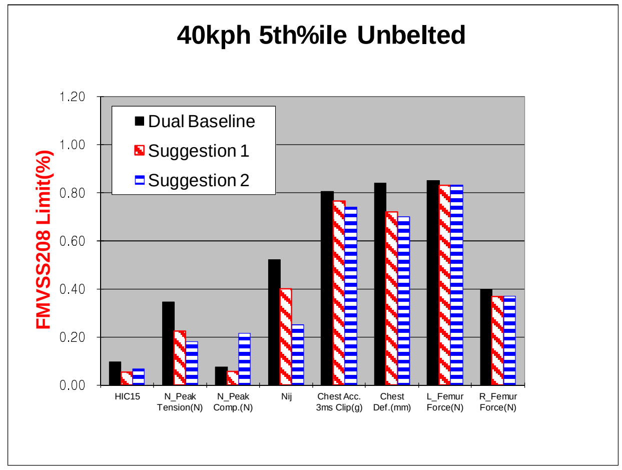


Figure 30. Dynamic MDIR Comparisons (40kph, 05th%ile Unbelted)

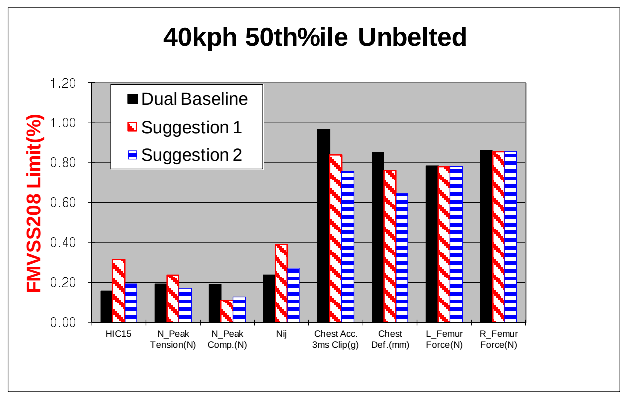


Figure 31. Dynamic MDIR Comparisons (40kph, 50th%ile Unbelted).

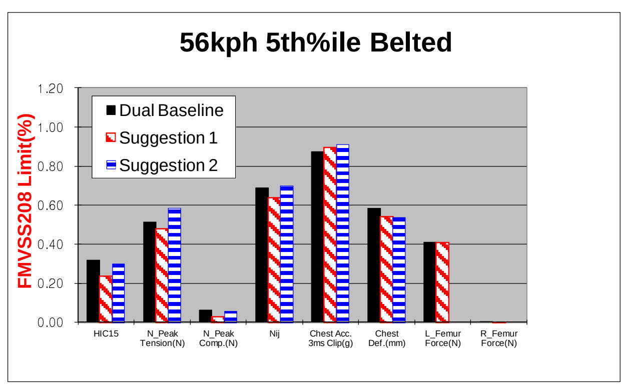


Figure 32. Dynamic MDIR Comparisons (56kph, 05th%ile Belted).

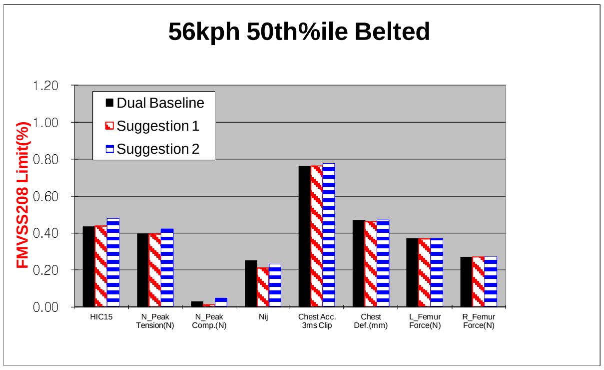


Figure 33. Dynamic MDIR Comparisons (56kph, 50th%ile Belted).

CONCLUSIONS

A baseline dual stage module showed MDIR variations on neck tension for NHTSA position 1 and 2.

Using the Taguchi method, signal to noise ratio (S/N ratio) and mean values were analyzed to determine robust single stage airbag module configurations. Star folding and self adaptive vent were found to reduce Nte mean value while maintaining minimal response variations. "I" tear seam pattern was chosen for chest compression. Two single stage module designs were suggested and showed lower MDIRs, along with less variation over the baseline dual stage module for neck tension and chest deflection through confirmation tests. Repeated confirmation tests showed the bag deployed consistently behind the wheel. The deployment variations with the baseline module were addressed with suggested modules.

A pendulum testing showed that the characteristics of suggested single stage designs were in the middle between the dual stage low output and high output in terms of early restraining force and bag stiffness. These characteristics were similar to inflator ballistic curves.

Comparable MDIR with the proposed module design with a single stage inflator was demonstrated for both unbelted and belted in-position critical crash modes through MADYMO simulations.

Suggested driver airbag module (Star folding, Self adaptive vent, "I" tear seam) with single stage inflator will give car manufacturers an option of a simpler and lighter module solution, along with simpler airbag deployment logic over dual stage designs. Suggested designs were based on the vehicle environments studied. Different solutions from the same development methodology could be applied for other vehicle environments.

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PRE-SAFE® IMPULSE –

EARLY INTERACTING OCCUPANT RESTRAINT SYSTEM

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ABSTRACT

The safety level in modern vehicles is extremely high. Restraint systems that are currently used, consisting of the classic seat belt and airbag system, feature a mature level of optimization. In the investigation examined here, we shall leave behind the "classic" restraint system approach and discuss the question as to whether and how occupant restraint could be initiated in a hazardous situation even before the seat belt and airbag system responds. Could the valuable milliseconds between the start of the crash and the response of the occupant restraint system be used for dissipating energy?

The purpose of this investigation is to design a system for early occupant impact protection that reduces the forces to which occupants are subjected during a crash. The focus is on frontal collisions. By inputting energy in a targeted manner, occupants are already restrained at the point in time when vehicle deceleration has still had only minor or no effects on the occupants. Methods for inputting energy as well as implementing this are examined. Furthermore, the paper describes the differences in occupant kinematics caused by the system and highlights the potential this technology holds for reducing the forces to which occupants are subjected.

Based on the results of the preliminary investigation, the predevelopment of an approach for implementing an early occupant impact protection system that is fit for production is described. At the end of the paper, we present this system, with all the advantages it holds, as well as an outlook with regard to the potentials still to be exploited.

INTRODUCTION

The safety level in modern vehicles is already extremely high. The restraint systems that are used, consisting of the classic seat belt and airbag system, feature an advanced level of optimization. In the investigation examined here, we shall leave behind the "classic" restraint system approach and discuss the question as to whether and how occupant restraint could be initiated in a hazardous situation even before the seat belt and airbag system responds. Could the valuable milliseconds close to the start of collision (t_0) up to the deceleration of the occupants be used to dissipate energy?

Mercedes-Benz model series already have restraint systems for preventive occupant impact protection. The reversible belt pretensioner is part of the PRE-SAFE® system and has been in use since 2002 (S-class). If a critical situation is detected and the PRE-SAFE® system is triggered, the electromotive pretensioner is able to reduce the slack in seat belts and fix the occupants tighter to the seat. The force of the reversible belt tensioner may not distract the driver from the ongoing tasks, as the accident may still be prevented at the point in time when the belt tensioner is triggered. Further measures, such as seat adjustment, can be carried out for the front and rear seat passengers.

The current power level of the reversible belt pretensioner does not, however, suffice for moving occupants in the event of a crash.

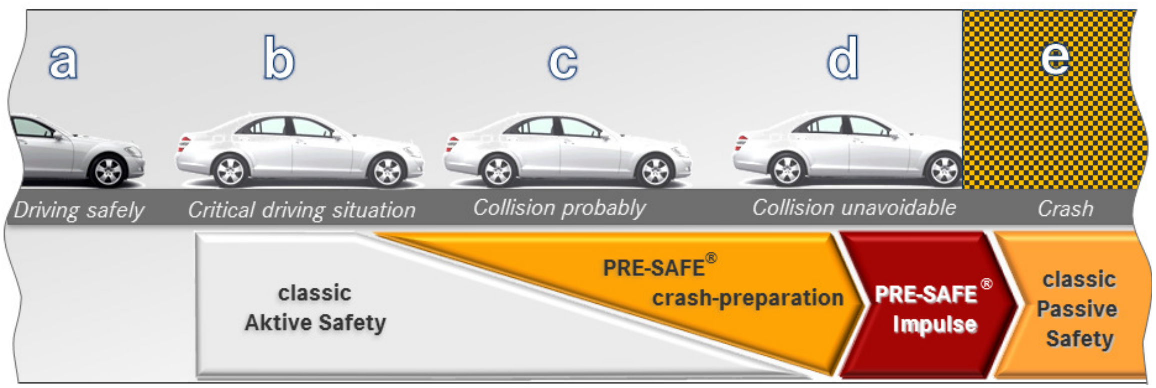

Figure 1: Head-on Collision – Chronological Sequence

HEAD-ON COLLISION – CHRONOLOGICAL SEQUENCE

In the classic description, a crash event starts when the vehicle comes into contact with the collision partner. Depending on the available sensor systems, today's vehicles already know the event history before a collision starts (e.g. driving condition, driver response, vehicle sensing electronics). For further consideration, it is helpful to organize the crash event into chronological phases and to classify the significance of the phases according to the crash event.

Before Start of Collision

A crash event passes through phases a through e as shown in Figure 1. However, the sensors and algorithms available in current vehicles for early crash detection purposes cannot associate these with the crash before the start of the collision in every case. The duration of the phases also differs from crash to crash. It is not currently possible to reliably detect every crash early on. Thus, an early interacting occupant restraint system must currently also function without detecting the crash early on.

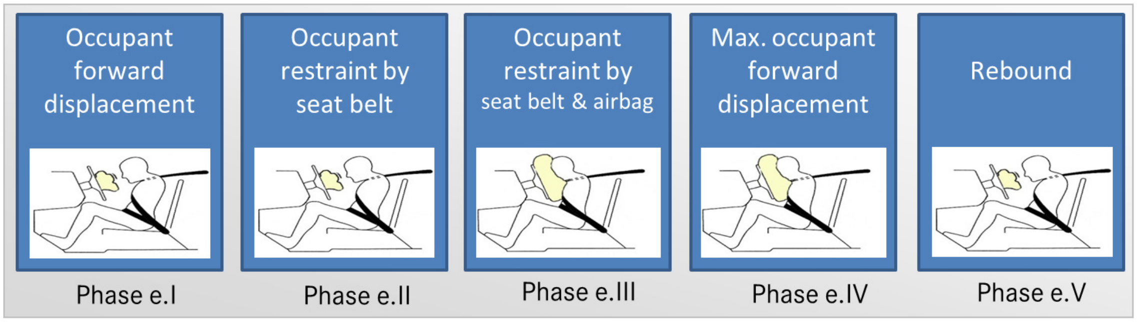

Figure 2: Phase (e) » Implementation of Restraint System over Course of Crash [2]

After Start of Collision

Phase (e) – the crash – starts when the vehicle comes into contact with the collision partner (t_0). At this point in time, the vehicle and occupant have the same speed. The vehicle starts to reduce its speed immediately afterwards. The occupant initially does not experience any deceleration (Figure 2, phase e.I) and is able to move forward. The deceleration of the occupant starts in a delayed manner, and he/she is restrained by the seat belt. Occupant deceleration commences (phase e.II). The occupant is restrained by the seat belt and airbag system over the further course of the crash (phase e.III). By means of airbag damping and belt force limiters, the available displacement path can be used to optimally reduce the kinetic energy of the occupant (phase e.IV).

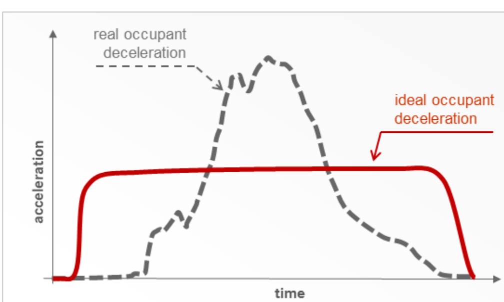

Figure 3: Idealized occupant acceleration curve

Based on the current restraint systems, the following approach applies for increasing the restraint system performance: The optimal restraint system load reduction can be achieved when the restraint system allows the occupant to participate in the vehicle deceleration as early as possible in the crash event and fully utilizes the available forward displacement path (see Figure 3).

BASIC IDEA OF EARLY INTERACTING OCCUPANT RESTRAINT SYSTEMS

The vehicle is in a phase in which it is already decelerating when the occupant restraint process starts. An uncontrolled forward displacement of the occupant is prevented by the seat belt and subsequently by the airbag (see Figure 2, phase e.I).

The chronological sequence is reversed in the theoretical consideration of the basic idea of an early interacting occupant restraint system. The occupant is jolted by the restraint system. The occupant perceives this as an acceleration impulse. This takes place in phase (e.I) of the accident, in which the vehicle deceleration has not yet acted on the occupant. This results in occupant deceleration; the occupant is briefly slower than the vehicle in which he is seated. The occupant is moved opposite the impact direction. The displacement path gained by the relative speed can be released again over the course of the accident via energy dissipation. This system is designated as an early interacting occupant restraint system in the following.

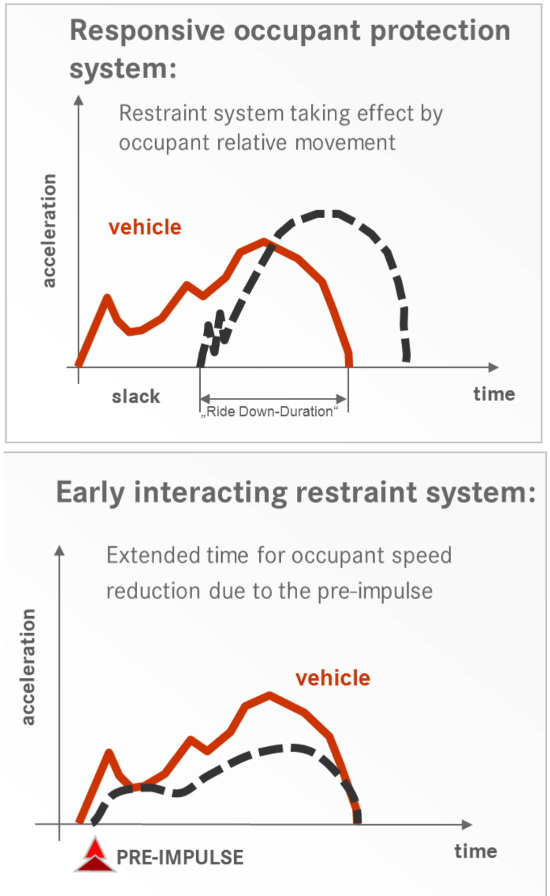

Figure 4:
Comparison of responsive occupant protection system and early interacting occupant restraint system [2]

Such a restraint system influences the ride-down effect and occupant kinematics and can reduce the occupant load values via the longer deceleration period. If you follow this train of thought, the potential arises for occupant kinematics that are fully decoupled from the crash impulse.

A demo test sled with two "occupants" with fastened safety belts was created to illustrate the theoretical approach. In the direct comparison, an "occupant" is pre-accelerated and has a longer displacement path available for deceleration. The difference in acceleration is shown using the mass heads mounted on deformable wires (see Figure 5).

FROM THE CONCEPT TO NEAR-STANDARD SOLUTION

Two central topics are important for the implementation of the basic idea. On the one hand, the following is required: A clear crash event detection, which occurs as early as possible. The sensors and algorithms must be suitable for this application. On the other hand, occupant protection components must be developed for an early interacting occupant restraint system.

Creation of the Infrastructure/Enabler

Even today, modern vehicles are already able to monitor their surroundings, detect possible collision objects and warn the driver and/or initiate partial and full brake applications (PRE-SAFE® BRAKE.) The prediction of the precise collision moment required for the ignition of the pyrotechnical protection systems and the determination of the required collision partner information represent a major challenge. Systems for faster crash severity detection as well as for improving the crash prediction capability are being developed.

An activation of the restraint system close to t_0 and the conventional restraint system response strategy were two approaches investigated during the design of the early interacting occupant restraint system components.

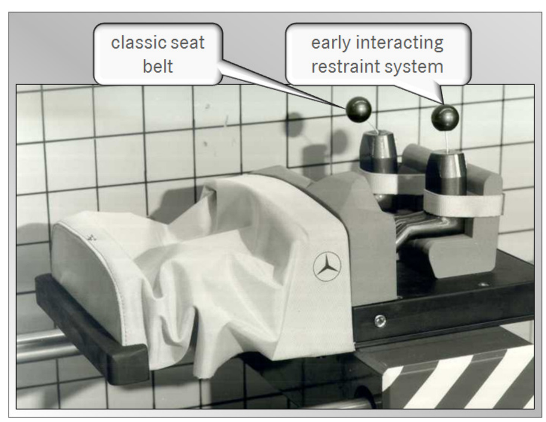

Figure 5: Demo test sled PRE-SAFE® Impulse

Components of an Early Interacting Occupant Restraint System

The components of an early interacting occupant restraint system must be able to appropriately respond to the acceleration impulse in a biomechanically compatible manner for the required duration.

Various approaches for an early interacting occupant restraint were examined during the design phase. This paper is focused on optimizing the existing restraint system components to satisfy the changed system requirements.

The airbag offers good preconditions for a low, local force introduction due to the large contact area. A "softer" airbag coupling is required in order to design an airbag as an early interacting occupant restraint system for head-on collisions. To do this, the precise seat position and occupant size must be known in real time. A very complex airbag size and damping control would be required in order to optimally address all load cases and occupant positions.

The 3-point seat belt, along with belt tensioners, presents itself as a basic system with regard to position and adaptivity. The current belt tensioner technology is able to reduce seat belt slack almost immediately. Due to its characteristics, an impulse via the belt tensioner is, however, only suitable as an early interacting occupant restraint to a limited extent. The force increase can be realized more "gently" in an early interacting occupant restraint system; it must, however, be possible to maintain the force for a longer period. The simultaneous use of all 3-point seat belt anchor points presents itself for a preferably homogeneous force application.

Using force limiter elements on the shoulder and lap belts, the maximum possible forward displacement path is made available while dissipating energy.

A numeric simulation was used to evaluate the concepts and the preliminary system design. Based on a vehicle-related generic surrounding, the occupant load reduction potentials through an early interacting occupant restraint system were determined for differing crash scenarios. A significant load reduction could be achieved with the currently available restraint system activation strategy due to the force application at the shoulder belt in combination with the two anchor points in the pelvic area (belt buckle and belt end fitting). Just a few millimeters of occupant displacement influence are enough to achieve a significant effect.

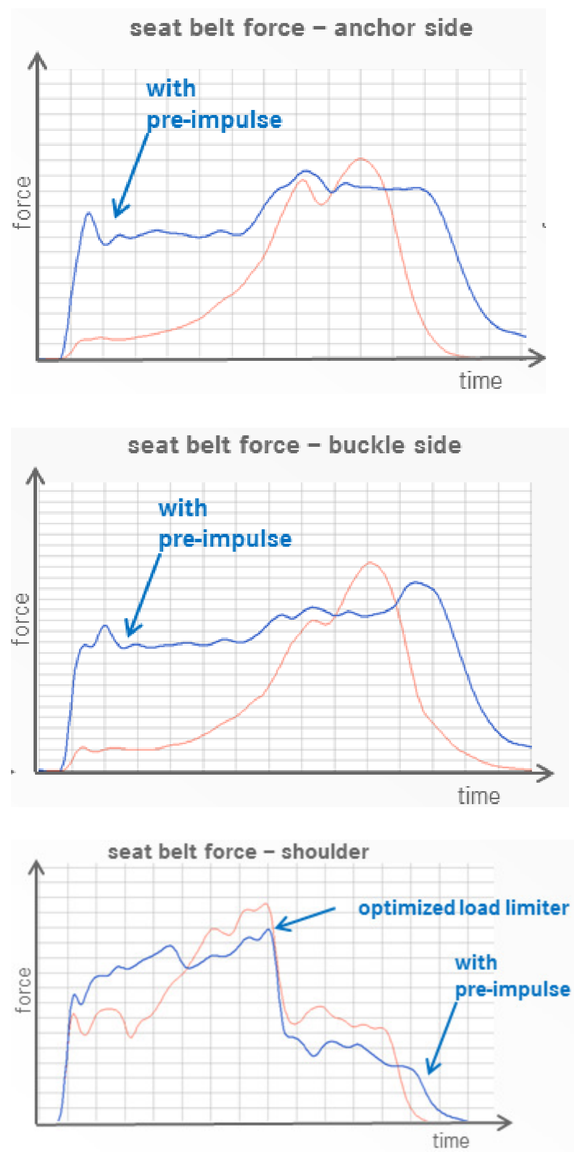

Figure 6: Comparison of belt forces with and without pre-impulse

Over the course of the development process, the preliminary investigation results served to concept components, which had to verify the theoretical potentials from the simulation in system tests of a substitute surrounding and in the basic vehicle. Based on the current pyrotechnical belt pretensioner, an actuator that has verified the theoretical potentials in testing has been developed via a design optimization. This actuator, designed as a pyrotechnical belt buckle- and anchor-pretensioner, is able to build up a force on the lap belt and maintain this over the duration of a head-on collision.

If the reaction force of the occupant during the crash is higher than the pretensioner force, the actuator is locking. In case of decreasing reaction force, the pretensioner will keep the force on the same level. When the defined maximum force level is reached, the load limiter provides forward displacement while dissipating energy.

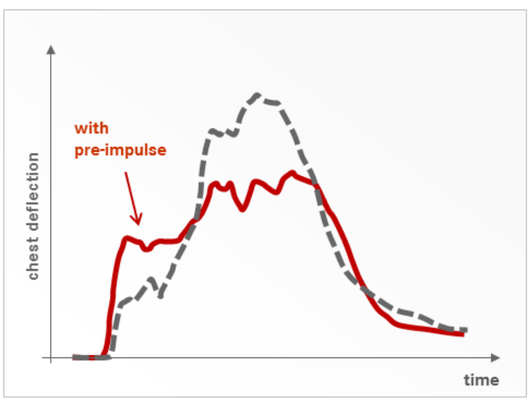

Figure 7: Reducing the chest load

Due to the homogeneous belt force load during the crash, the chest deflection can be reduced (Figure 8). The potential investigations for an early interacting restraint system are shown with conventional actuation strategy.

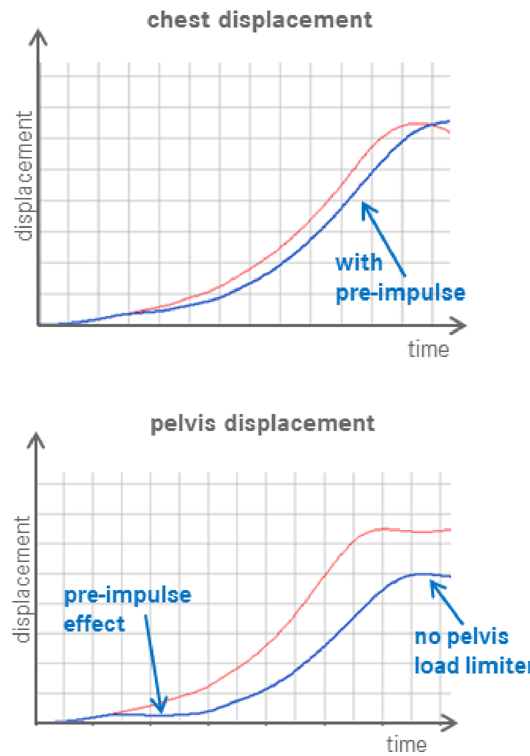

Figure 8: Comparison of chest and pelvis displacement with and without pre-impulse

The impulse of the new designed pretensioners pulls the occupant deeper into the seat. The seat cushion is compressed and the occupant is moved in the opposite direction of the impact. This is reflected in the chest and pelvic area forward displacement, shown in Figure 8.

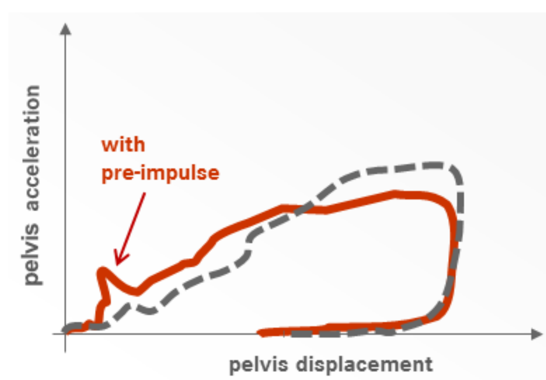

Figure 9: Potential of Early Interacting Occupant Restraint Systems

The reduced displacement of the occupant in the early crash phase (Figure 2, phase I & II) can be used in the phase of the maximum deceleration of the vehicle by a load limiter device that is optimized for an early interacting restraint system. This is illustrated in Figure 9, which shows the pelvic area forward displacement over the acceleration with and without an early interacting occupant restraint system with a conventional activation strategy. The forward displacement path gained in the first milliseconds of the crash can be released via the activation of a force limiter in the pelvic area and thus reduce the maximum loads with approximately the same forward displacement path.

CONCLUSION AND OUTLOOK

The results of the developments tests show that the basic concept of an early interacting occupant restraint system can be implemented in the vehicle. Occupant impact load reductions of over 20% in individual body regions (chest, lower extremities) could be achieved with conventional activation times in standard load cases with early interacting occupant restraint system components in the near-standard vehicle environment.

In the case of an actual accident, the event history before the crash is used in order to activate the system directly after a definite detection of the impact load case. For this purpose, the activation algorithm is sensitized based on the previous PRE-SAFE® activation via the Mercedes-Benz PRE-SENSE system [6].

Higher potentials can theoretically be achieved if the actuators could be activated before t_0. The possible timeframe here is the phase before a collision when the driver cannot prevent the collision either by a steering maneuver or brake application up to the collision with the predetermined collision object (see Figure 1, phase (d)). Development work is still required for the activation of pyrotechnical protective systems based on vehicle environment data. The current hurdle in development is to identify, on the one hand, the largest possible number of impact load cases, and at the same time reduce the number of incorrect system activations to an acceptable amount. A sensor system redundancy is, at least, required to achieve this according to the current as-is configuration. It is, in the meantime, already possible to interpret the vehicle environment data due to a merger of radar- and camera-based systems.

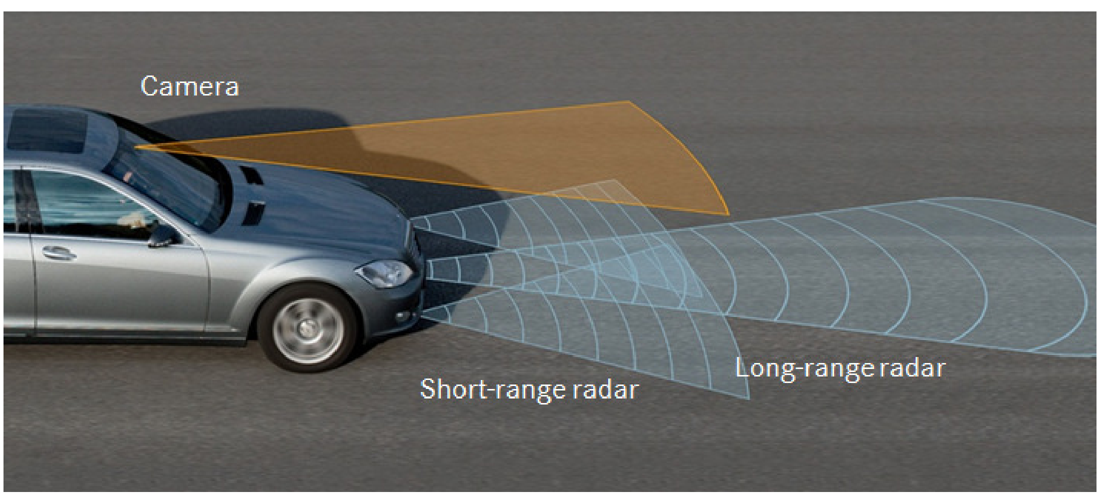

Figure 1: Vehicle environment detection systems [5]

In this connection, the systems "learn" the vehicle environment and situation evaluation based on sample situations and movement profiles.

The algorithms must also be able to clearly forecast the crash severity and collision time for a situation-appropriate activation of the early interacting occupant restraint systems. This is currently also a field of action, as information about the "collision partner" cannot be fully determined by these systems. The vehicle front and rear end profiles can thus be "taught-in" via a camera-based system; the collision energy information (among other things, the collision object weight) can, however, only be roughly estimated. This information gap could be closed by systems focused on data exchange between the vehicles. Vehicle communication shortly before a collision (achieved, for example, by wireless transmission or RFID tags and which provides information about the vehicle type, mass, rigidity, geometry, speed and direction of travel of the collision partner) would be conceivable. These systems are, however, still in an early development stage.

A further challenge is a concept consisting of the restraint system and vehicle components that can make the required displacement paths (against the crash direction) available to the occupants in order to exploit the potential of an early interacting occupant restraint system and a corresponding adaptivity in terms of the involved restraint system component design (such as airbag-size and -damping, belt force limiters) in order to cover the resulting variation options.

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FRONTAL IMPACT PROTECTION: APPLICATION OF AN UPGRADED CHEST INJURY CRITERION - THE EQUIVALENT DEFLECTION (DEQ)

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ABSTRACT

The equivalent deflexion (Deq) is a new criterion foreseen to be used in Euro NCAP to better assess the chest protection in frontal impact. It has the particularity to discriminate the contribution of two parameters on chest deflexion:

- contribution of the seat-belt (with a small surface of load application, which is damageable for the occupant),
- contribution of the airbag (with a larger surface of load application, which is more acceptable for the occupant).

Such a criterion will help car manufacturers to design adequate restraint systems with an appropriate combination of airbag and seat-belt to better protect the vulnerable occupants.
To better understand this new criterion, PSA Peugeot Citroën launched a study to quantify the performances of its current vehicle platforms with respect to the Deq.

Physical tests were analysed on different car platforms with several restraint systems characteristics. Each time, the Hybrid III rodpot and the shoulder belt load were recorded and analysed.
This analysis shows that the sensitivity and reproducibility of the Deq measurements are equivalent than the Rodpot ones.

Because the Deq criterion needs the chest deflexion measured on the Hybrid III rodpot and the shoulder belt load, there are some questions raised by other researchers about sensitivity of Deq and about the pertinence of Deq with respect to Rodpot.

This question is investigated for a nominal restraint system as proposed in Peugeot and Citroën cars. This was done via Design of Experiments made with HIII 50th and HIII 5th models respectively in ODB 64 km/h and Full-width rigid test 50 km/h.
The outcome is that for good restraint systems already built to be protective (load limitation less than 5kN), Deq would prevent to use combination of relative high load limitation with very soft airbags, contrary to Rodpot.
But this study is just at its initial phase because of time constraints, because not all the biomechanical criteria were analysed (eg. neck load and moments) and because only one vehicle was investigated. Therefore, we would suggest carrying out the same analysis for restraint solutions widely different than ours.

INTRODUCTION - AIM OF THE STUDY

Self-protection of car occupant is a crucial topic all over the world. Restraint systems have to be designed to protect various sizes of occupants involved in several type of crash and therefore several types of crash pulses.
Frontal impact on a rigid obstacle are the most severe impacts with respect to change of velocity (deceleration) sustained by the occupants.
This test configuration will be used worldwide in the near future (already in China, Japan, Korea, USA [1] + possible new regulation on frontal impact and Euro NCAP 2015[2]). It will also be used with a more demanding level of protection in order better protect vulnerable users.
One of the crucial body segments is chest, with the injury coming from chest compression. But the current dummies in use (Hybrid III 50th and Hybrid HIIII 5th) are criticized because of two main reasons:

- chest compression is measured via the rodpot sensor that is sensitive to seat belt path
- injury thresholds were built on old restraint systems (belt only, no airbag loading) and therefore they do not represent the actual risk sustained in case of a combined loading

Indeed, the seat-belt is a restraint offering a small surface of load application, which is more damageable for the occupant that the airbag and its load application spread on a larger surface. For a same level of force, a localized loading is more damageable that a spread one.

To overcome these critics and because the next generation of frontal impact dummies is not available yet, a new criterion, called equivalent deflection (Deq) was designed [3] and recently upgraded [4].

This criterion, Deq, is foreseen to be used by Euro NCAP for its new full-width rigid frontal test (0°, 50 km/h) that will be applicable from 2015 [2].

The purpose of our research is to better understand how Deq works and what would be the consequence of designing a restraint system with Deq compared to a restraint system designed with Rodpot only.

Before going into the details of this research, it is worth to define the formula that will be used throughout the paper.

PARAMETERS DEFINITIONS AND THRESHOLDS

As presented in [4] Deq formula (Deq linear) is somewhat complex and needs to be computed via a macro to exactly reflect its scientific origin. But as a first order approach Trosseille et al. [4] also proposed a simplified formula where Deq is simply a combination of maximum seat belt force and maximum Rodpot deflection. This is the formula used in this research

Deq definition and formula as used in this research

The simple equation used for Deq, as given in [4], is:

$$Deq = 3.5*USBF + 0.84*Rodpot \qquad (1).$$

Where:

- « USBF » is expressed in kN and is the maximum seat belt load measured on the upper part of the diagonal strap.
- « Rodpot » is expressed in mm and is the maximum chest deflexion measured by the rodpot on the Hybrid III dummy.

Thresholds used to compare the performances of Rodpot and Deq

Even if we talk about "deflection" for Rodpot as well as Deq, we cannot say that both are directly comparable. Indeed, the 1 mm of Deq is not equivalent to 1 mm of Rodpot. Therefore, to compare the two criteria, we decided to use the performance thresholds that are currently discussed within the Euro NCAP Frontal Impact Working Group. The following tables (Table 1 and Table 2) present the thresholds used respectively for Rodpot and Deq.

Table 1.
Performance thresholds used to calculate a chest score – Rodpot thresholds for the 2 dummies

Rodpot thresholds	HIII 50th	HIII 5th (Hypothesis)	Score
Lower performance	50	41	0pt
Higher performance	22	18	4pts

Table 2.
Performance thresholds used to calculate a chest score – Deq thresholds for the 2 dummies

Deq thresholds	HIII 50th (Hypothesis)	HIII 5th (Hypothesis)	Score
Lower performance	61	50	0pt
Higher performance	32	26	4pts

Between the lower and higher performance thresholds, the score is calculated via sliding scale. Therefore, if we want to target a 3 points score on chest we should aim at the following values (see Table 3).

Table 3.
Rodpot and Deq target for a 3pts performance for each of the 2 dummies

Criteria value to reach 3pts	HIII 50th	HIII 5th
Rodpot	29	23.75
Deq	39.25	32

Now the main parameters and thresholds have been defined, we will start the analysis with an assessment of the scattering and the reproducibility of the two criteria.

SCATTERING AND REPRODUCIBILITY OF DEQ AND RODPOT MEASUREMENTS

Method

Using our database of Euro NCAP type test (frontal ODB test 64 km/h with HIII 50th driver and passenger), we compared tests carried out on the same car model. Some tests were carried out at the same crash test lab, and others were carried out in a different lab. Therefore we can assess the overall reproducibility of the measurements.
Several car models were analysed.
Finally, to compare the Deq results with the Rodpot ones, we used the sliding scales as described in Table 1 and 2.
Again, Deq is computed via Eq 1.

Results

Figure 1 presents the results. Each colour represent a car model coupled to an occupant (driver or passenger) and the rodpot score (in colour) is compared with the associated Deq score.

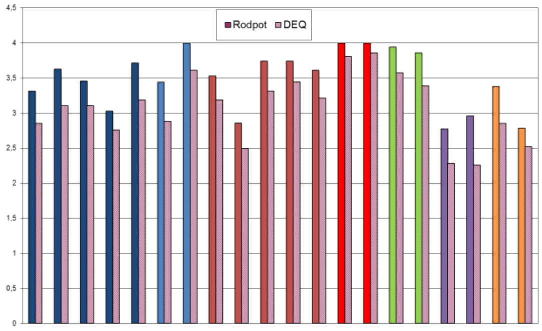

Figure 1. Comparison of Rodpot score and Deq score on several car models and occupant.

Comparing the results of a same colour provides an assessment of reproducibility.

First of all, looking at the average score of each car model/occupant (Figure 2) allow us to show that the assessment was made on cars having a wide variation of performance but always at the level of good cars (we are not looking at poor performers, but at current cars designed to be good (5 stars) in Euro NCAP). The Rodpot score goes from 2.9 pts to 4 pts.

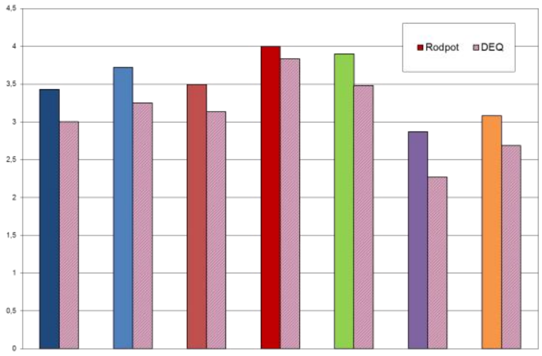

Figure 2. Average score for Rodpot and Deq for each couple car model / occupant

Now, in order to look at the scattering, we can have a look at the delta of measurement for each couple car model / occupant. Figure 3 presents the average scatter for each couple, for Rodpot and for Deq score.

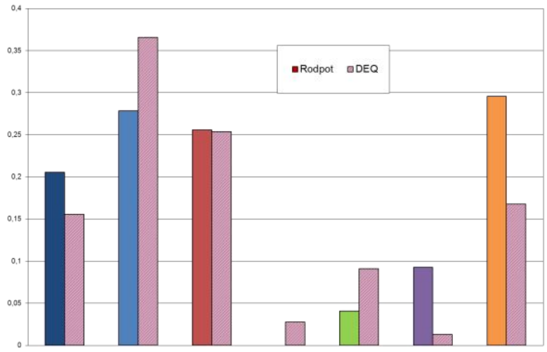

Figure 3. Average scatter in the Rodpot and Deq scores for each couple car model / occupant

It is good to recall our aim: is the Deq more scattered than the rodpot? With this set of data, no clear conclusion can be made. Both seem to be scattered in the same way.

Looking at the absolute scatter (max score - min score) for each couple under study, as shown in Figure 4, there is no additional trend to highlight.

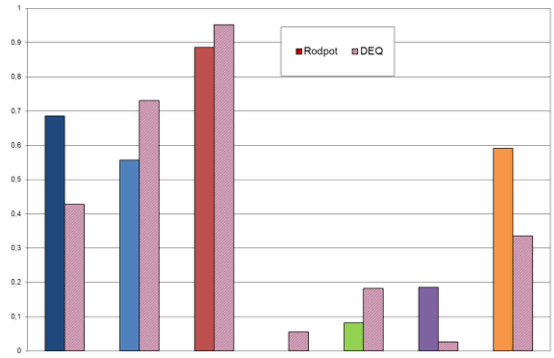

Figure 4. Absolute scatter (max score – min score) for Rodpot and Deq scores for each couple car model / occupant

A final check could be to look at the relative scatter, in order to erase the fact that lower score will give by definition lower scatter. This is presented in Figure 5. The relative scatter is reckoned as the absolute scatter (figure 4) divided by the average scatter (figure 3).

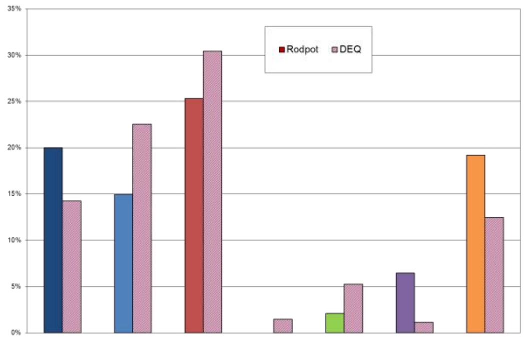

Figure 5. Relative scatter for Rodpot and Deq scores for each couple car model / occupant

With Figure 5 we can say that whatever the performance of the car, both Rodpot and Deq are scattered by about the same amount.

Conclusion on scattering

We analysed a set of results taking current car models tested in the Euro NCAP ODB test, using driver and passenger dummies, and using tests carried out in different labs, or in the same lab but with different dummies. Looking at the scatter of these results, one can conclude that the overall reproducibility of Deq is of the same magnitude than the Rodpot one. Nothing shows than Deq is more sensitive to scatter than Rodpot, even if some people were stressing this problem because of the external measurement needed to reckon Deq (upper diagonal belt load).

Even if it was not the main purpose of the assessment, it is interesting to stress that the score reached by the Rodpot is always better than the one reached with the Deq. This is shown in Figure 1 and Figure 2. But Figure 6 show it even more obviously.

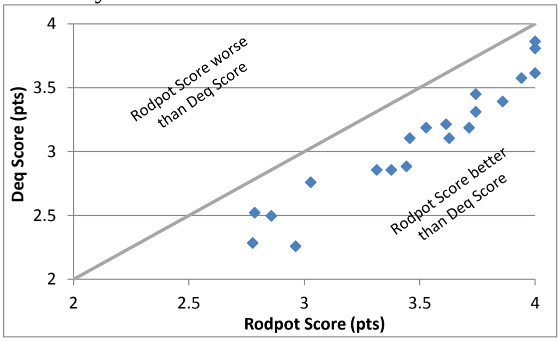

Figure 6. Deq Score as a function Rodpot Score

We already recalled that Deq was made to discriminate seat-belt only loadings from seat-belt + airbag loadings. This should give incentive to lower load limitations that will be beneficial for vulnerable occupants.
In order to highlight this fact, we can analyse our set of results (measured on current cars) with a last point of view: we can look at the seat-belt score with respect to chest score measured with Rodpot or with Deq. This is given in Figure 7.

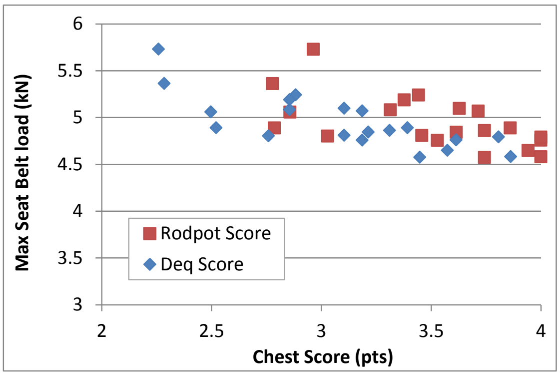

Figure 7. Maximum seat belt load measured in our set of results expressed as a function of chest score reckoned respectively via Rodpot or via Deq

For sure we have cars that reaches good results (chest score >3 pts) but they are assessed only in ODB 64 km/h test and with the HIII 50th dummy. The question is now to know if there would be other restraint systems characteristics that would get the same level of score, but taking into account full-width test and HIII 5th and 50th.

This is what is presented in the next part of our research.

DESIGN OF EXPERIMENTS TO COMPARE DEQ AND RODPOT AND TO STUDY THE PARAMETERS INFLUENCING THESE TWO CRITERIA

Method

The purpose of this chapter is to quantify the restraint system characteristics that could influence Rodpot and Deq.
For this study, we used numerical model (Madymo) widely used to design restraint systems.
The model was correlated on physical tests (full scale and sled tests).
The model of reference is the model with the actual driver restraint system currently fitted on a brand new vehicle.
Then we made a Design of Experiments (DoE) to assess the influence of several restraint characteristics on Deq and Rodpot.
This DoE is made with 2 dummies, 2 values of column collapse, 4 values of seat belt load limitation and 4 values of airbag vent diameter (in fact 3 for each dummy, 2 being common to both dummies).

The dummy positioning fulfils the current Euro NCAP ODB protocol for HIII 50th and the foreseen Euro NCAP Full-width rigid test:

- HIII 50th is set-up in mid rails, fully down position
- HIII 5th is set-up in fully forward, mid height position

HIII 50th is tested with an ODB 64 km/h pulse. Its kinematics and the restraint system are shown in Figure 8.

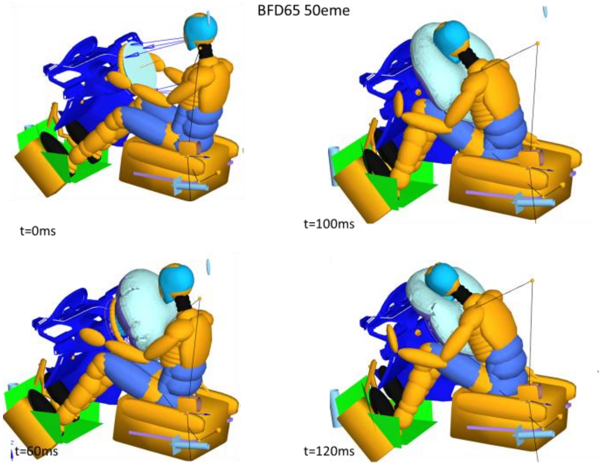

Figure 8. HIII 50th kinematics and restraint system behaviour in an ODB 64 km/h

With the same restraint system as for HIII 50th, the HIII 5th model sustained a Full-width 0° 50 km/h test, as shown in Figure 9.

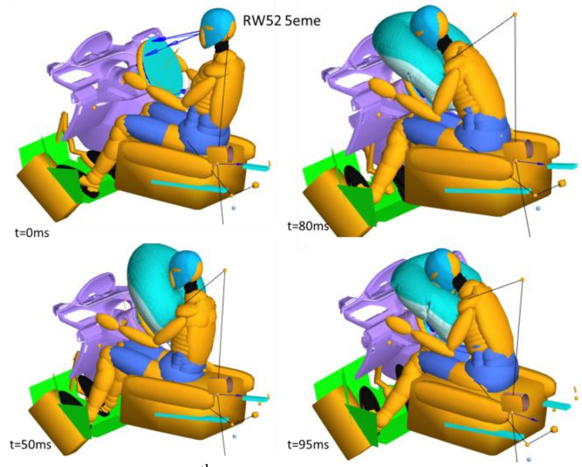

Figure 9. HIII 5th kinematics and restraint system behaviour in a Full-width 0° 50 km/h

As already stated, 3 main parameters of the restraint will be varied, to assess their influence of Rodpot and Deq:

- seat belt load limitation
- airbag vent diameter
- length of column collapse

The DoE for HIII 50th is made with the variations presented in Table 4.

Table 4.
Parameter variations for HIII 50th DoE

Parameter	Value
Load limitation (N)	2640 / 3300 / 3960 / 4620
Vent diameter (m)	0.040 / 0.0475 / 0.055
Length of column collapse (mm)	0 / 100

This gave a 24-cases DoE.

The DoE for HIII 50th is made with the variations presented in Table 5.

Table 5.
Parameter variations for HIII 5th DoE

Parameter	Value
Load limitation (N)	2640 / 3300 / 3960 / 4620
Vent diameter (m)	0.0475 / 0.055 / 0.0625
Length of column collapse (mm)	0 / 100

This gave a 24-cases DoE.

Direct output criteria were:

- HIC36
- Head resultant acceleration 3ms
- Chest deflection (Rodpot)
- Head clearance
- Chest clearance
- Pelvis displacement
- Upper seat belt load

Head and chest clearance are the remaining distance between head (respectively chest) and steering wheel when the dummy is at its maximum excursion. To avoid any bottoming-out of the airbag, a minimum value of clearance should be kept.

Deq is then reckoned via Eq 1. The purpose of this study is to try to define a relationship between chest deflection and the restraint parameters.

HIII 50th results

Restraint systems parameters influencing Deq

The variation of pelvis displacement is very low, whatever the DoE case (3 mm only). Therefore, we did not take it into account in the remaining part of the study.

This statistical study of the DoE highlighted a strong relationship between Deq and the 3 varying parameters. Table 6 presents the full set of results. It can be noticed that R^2 is close to 0.99 !

Table 6.
Weighting factors and correlation level for Deq expressed in terms of the 3 restraint systems parameters

Deq (mmDeq)	Estimation	Std. Error	t-value	Pr(>|t|)	Quality
Constant	26.435123	0.4558055	57.996494	0	***
Column collapse (mm)	19.047882	1.0018858	19.01203	7.971D-14	***
Load limitation (N)	0.0046527	0.0000667	69.77047	0	***
Vent size (m)	-111.69385	7.9989577	-13.963551	1.926D-11	***
Incertitude	0.2399687				
R	0.9965445				
R² ajust	0.9959989				
F-stat	1826.4793				
p-value	0				

After rounding the weighting factors, we can write the following equation that allows us to approximate the Deq value.

Aprx_Deq=26.4 +19*CC+4.65*LL-0.11*VD (2).
where :

- CC is the Column Collapse, in mm
- LL is the Load limitation, in kN
- VD is the airbag Vent Diameter, in mm

Figure 10 presents the comparison between the Deq as measured in equation 1 (Deq is a function of USBF and Rodpot) and the approximated Deq (Aprx_Deq) as defined thanks to the DoE and equation (2).

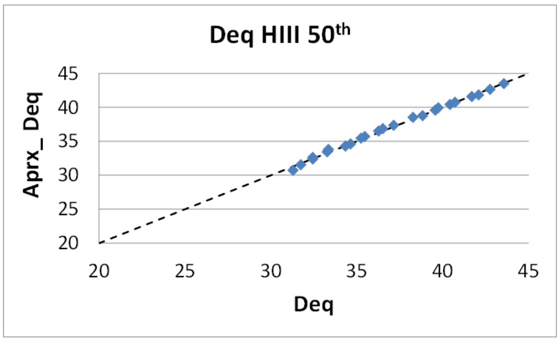

Figure 10. Comparison between actual Deq calculation and approximation made thanks to DoE

It could be interesting to apply the same analysis to the Rodpot to check if the same restraint systems parameters contribute to the rodpot measure and to which extent.

Restraint systems parameters influencing Rodpot

Via the statistical study of the DoE, we highlighted a second strong relationship; this time between Rodpot and the 3 varying parameters. Table 7 presents the full set of results. Here again, R^2 is close to 0.99 !

Table 7.
Weighting factors and correlation level for Rodpot expressed in terms of the 3 restraint systems parameters

Rodpot (m)	Estimation	Std. Error	t-value	Pr(>|t|)	Quality
Constant	0.0289546	0.0005346	54.164454	0	***
Column collapse (m)	0.0256216	0.0011750	21.805474	6.439D-15	***
Load limitation (N)	0.0000022	7.821D-08	27.530502	2.220D-16	***
Vent size (m)	-0.1450788	0.0093812	-15.464911	3.214D-12	***
Incertitude	0.0002814				
R	0.9874674				
R² ajust	0.9854886				
F-stat	499.01552				
p-value	0				

Here again, after simplifying the weighting factors, we can write the following equation that allows us to approximate the Rodpot value.

Aprx_Rodpot=29 +25.6*CC+2.2*LL-0.14*VD (3).
where :

- CC is the Column Collapse, in mm
- LL is the Load limitation, in kN
- VD is the airbag Vent Diameter, in mm

Figure 11 presents the comparison between the Rodpot as directly measured in the test and the approximated Rodpot (Aprx_Rodpot) as defined thanks to the DoE and equation (3).

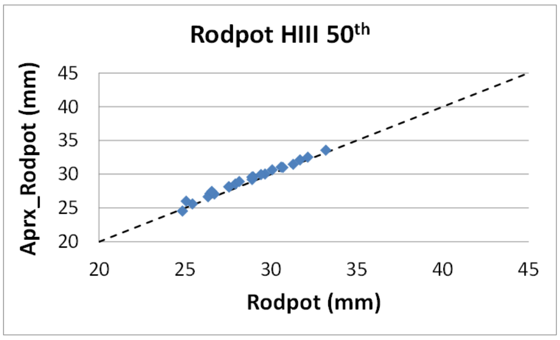

Figure 11. Comparison between actual Rodpot calculation and approximation made thanks to DoE

Comparison between Rodpot and Deq: relative contribution of the restraint systems parameters

Now that we have the two relationships between the chest deflection and the 3 restraint systems parameters, we can compare the weighting factors. This will allow us to highlight the sensitivity of Rodpot and Deq to the restraint system characteristics.

Indeed, if we use the generic formula

$$\text{Aprx\_deflection} = \lambda_i + \alpha_i * CC + \beta_i * LL + \gamma_i * VD \quad (4).$$

where :

- CC is the Column Collapse, in mm
- LL is the Load limitation, in kN
- VD is the airbag Vent Diameter, in mm

we can express (λ_D, α_D, β_D, γ_D), the weighting factors of approximated Deq in terms of (λ_R, α_R, β_R, γ_R) the weighting factors of approximated Rodpot.

Then, we are able to say that when the Rodpot sustains 1 unit of variation from CC, LL or DD, the Deq sustains x% of the Rodpot unit of variation. This is an assessment of the relative weight of influence of the restraint systems characteristics on the Deq value, with respect to the Rodpot one. This will be illustrated in Table 8 and Figure 12.

The following table recalls the weighting factors presented in Eq (2) and Eq (3) (so the (λ_i, α_i, β_i, γ_i)) as well as the relative factors of Deq expressed in percentage of Rodpot – that is to say the (λ_D/λ_R, α_D/α_R, β_D/β_R, γ_D/γ_R).

Table 8.
Simplified weighting factor used to approximate Rodpot and Deq as a function of restraint systems parameters and relative weight

	Aprx_ RodPot	Aprx_ Deq	Deq factor as a percentage of Rodpot factor*
Constant (mm)	29	26.4	91%
Factor for Column Collapse when expressed in mm	25.6	19	74%
Factor for Load Limitation when expressed in kN	2.2	4.65	211%
Factor for Vent Diameter when expressed in mm	-0.14	-0.11	79%

* Deq / Rodpot, that is to say the (λ_D/λ_R, α_D/α_R, β_D/β_R and γ_D/γ_R)

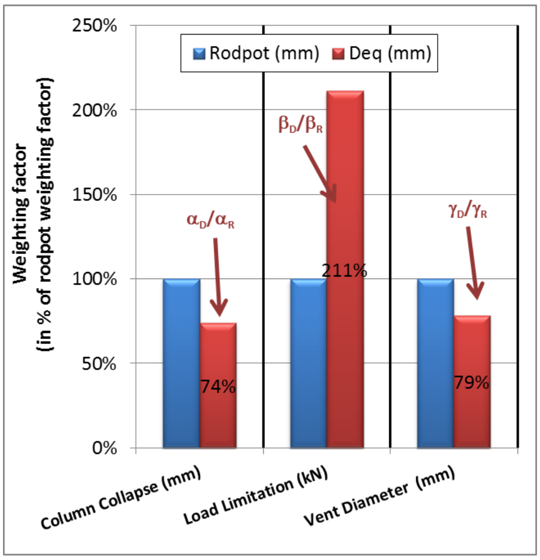

Figure 12. Relative factors of Deq expressed in percentage of Rodpot – that is to say the (λ_D/λ_R, α_D/α_R, β_D/β_R, γ_D/γ_R).

Thanks to this analysis, we can state that Deq is more sensitive than Rodpot to Load Limitation and less sensitive to Column Collapse and the airbag Vent Diameter. This will definitely give incentive to design restraint systems that have a lower load limitation. This is good for elderly occupants that are more fragile on chest and shoulder. It will also do not prevent the design of stiffer airbag. That was the case with the rodpot and that was not good for real occupant protection. Indeed, accident analysis and biomechanical studies already stressed that restraining the occupant by an airbag and its widely spread load is better than using only a seat belt load.

<u>Design of restraint system: what are the new possibilities? What are the forbidden ones if Deq is chosen?</u>

Another way to analyse the data is to draw the graph shown in Figure 13. It is derived from the DoE results and shows the Deq values in function of their Rodpot ones.

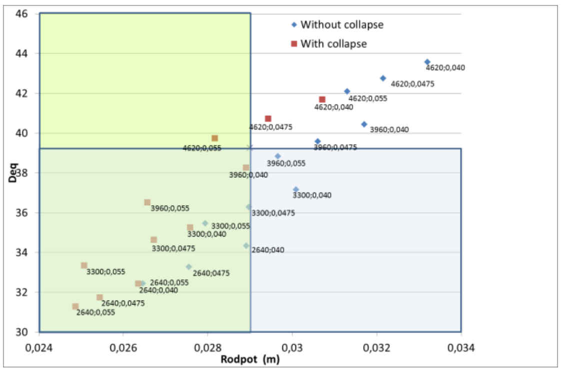

Figure 13. Deq measure in function of Rodpot – from HIII 50th DoE

The green rectangle (a vertical rectangle) represents the loading cases for which the Euro NCAP score of the Rodpot is 3 points or above.
In the same philosophy, the blue rectangle (an horizontal rectangle) represents the loading cases for which the Deq score is 3 points or above.
The red dots represent the DoE cases with 100 mm of maximum column collapse allowed. The blue dots represent the cases with no column collapse. For each dot, the other DoE parameters values are recalled (seat belt load limitation and airbag vent diameter).
The dots that are in the common zone (green+blue) are the load cases where whatever the chest deflection criterion, the score will be above 3 points. The pure green zone concerns load cases where Rodpot score is above 3 points but Deq score would be lower than 3 points. The pure blue zone concerns load cases where Deq score is above 3 points but Rodpot score would be lower than 3 points. Finally, the white zone concerns cases where nor Rodpot, neither Deq would score 3 points.

But we also need to look at the other injury criteria to filter the results. This is made by several steps.

Figure 14 presents Deq in function of head clearance for all the DoE points collected. In addition, the lower performance foreseen for Deq is shown in red (max Deq) and the upper performance foreseen for Deq is shown in green (min Deq).

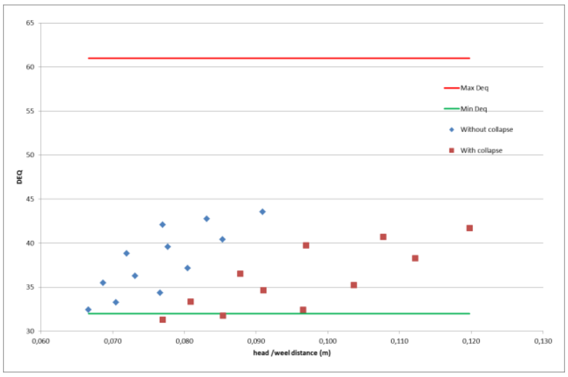

Figure 14. Deq in function of head clearance for DoE – from HIII 50th DoE

No case would be removed from HIII 50th DoE when looking at head clearance. This means that head clearance is not a limiting factor for a good Deq score.

The second step is to look at chest clearance. Figure 15 presents Deq in function of chest clearance for all the DoE points collected. Here again, the lower performance foreseen for Deq is shown in red (max Deq) and the upper performance foreseen for Deq is shown in green (min Deq).

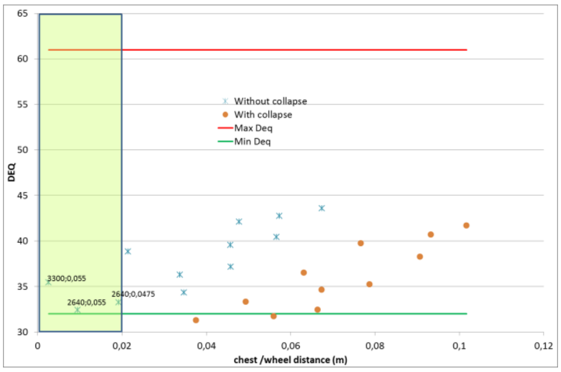

Figure 15. Deq in function of chest clearance for DoE – from HIII 50th DoE

In the case of chest clearance, some load cases have to be excluded because the value was too low (below 20 mm). These excluded cases are the ones located in the green zone of Figure 13. And they all belong to the “no collapse” cases. Their Load Limitation (LL) and Vent Diameter (VD) characteristics are:

- (LL 3300 ; VD 0,055)
- (LL 2640 ; VD 0,055)
- (LL 2640 ; VD 0,0475)

Removing these 3 cases from Figure 13 will give the following results, as shown in Figure 16.

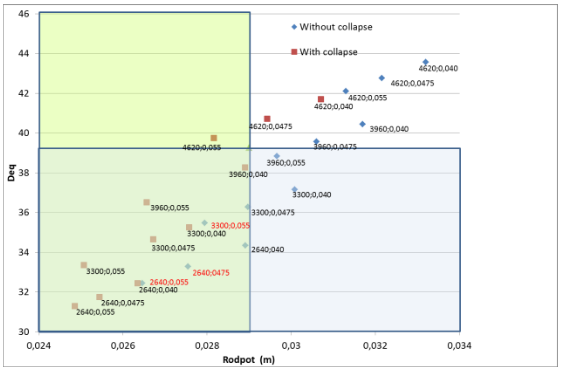

Figure 16. Deq measure in function of Rodpot with the three load cases to be removed because fo chest clearance – from HIII 50th DoE

When designing a restraint system targeted to reach 3 points with the Rodpot, all the loaded cases included in the green rectangle would be possible. This means that load cases with 4600 N load limitation or less would have been possible. But on the other hand, almost no case without collapse would have been allowed.
Indeed only two blue dots are close to 29 mm (the 3 points limit for Rodpot for HIII 50th).

On the other hand if we have to design a restraint system targeted to reach 3 points with the Deq, all the loaded cases included in the blue rectangle would be possible. This means that load cases

above 3960 N load limitation would have been forbidden. But on the other hand, some cases without collapse would have been allowed. Indeed some blue dots are in the blue zone, the ones with stiffer airbags.
There is a common zone where load cases answer to both Rodpot and Deq 3 points target.
Because of Deq, seat belt with too high load limitation would be excluded, but additional points with stiffer airbag become possible.
The danger would be to stiffen to much the airbag and therefore increase too much the head acceleration and HIC. But looking at HIC and head acceleration collected in the DoE, there is no point exceeding 80g.

Using only Rodpot would allow us to design a restraint system with a column collapse + 4620 LL and 0.055 VD - that is to say a case with a high load limitation compensated by a soft airbag (high vent diameter). This case would not be allowed with Deq, which is good for occupant protection. On the contrary, using Deq would allow us to design restraint system without a column collapse + 3960 LL and 0.055 VD or without a column collapse + 3300 LL and 0.0475 VD.

HIII 5th results

<u>Restraint systems parameters influencing Deq</u>

The same philosophy is applied to HIII 5th.

Here again, the statistical study of the DoE highlighted a strong relationship between Deq and the 3 varying parameters. Table 9 presents the full set of results. It can be noticed that R² is close to 0.99 !

Table 9.
Weighting factors and correlation level for Deq expressed in terms of the 3 restraint systems parameters

Deq (mmDeq)	Estimation	Std. Error	t-value	Pr(>|t|)	Qualité
Constant	22.948772	0.5176913	44.329064	0	***
Column collapse (mm)	18.404334	1.0015762	18.37537	5.396D-14	***
Load limitation (N)	0.0039661	0.0000679	58.440457	0	***
Vent size (m)	-89.477628	8.1777539	-10.94159	6.824D-10	***
Incertitude	0.2453326				
R	0.9948621				
R² ajust	0.9940914				
F-stat	1290.8865				
p-value	0				

Rounding the weighting factors leads to equation (5).
Aprx_Deq=22.9 +18.4*CC+3.97*LL-0.09*VD (5).
where :

- CC is the Column Collapse, in mm
- LL is the Load limitation, in kN
- VD is the airbag Vent Diameter, in mm

Figure 17 presents the comparison between the Deq as measured in equation 1 (Deq is a function of USBF and Rodpot) and the approximated Deq (Aprx_Deq) as defined thanks to the DoE and equation (5).

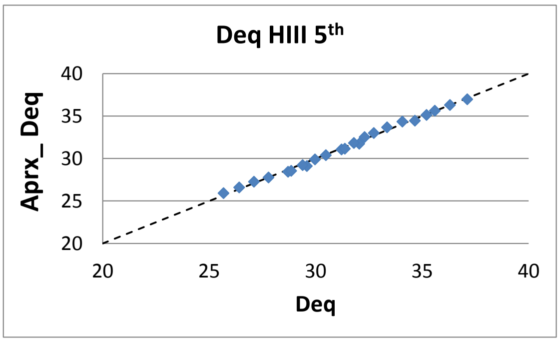

Figure 17. Comparison between actual Deq calculation and approximation made thanks to DoE

Applying the same analysis to the Rodpot is given below.

<u>Restraint systems parameters influencing Rodpot</u>

Table 10 presents the full set of results for Rodpot and HIII 5th. R² is close to 0.98 !

Table 10.
Weighting factors and correlation level for Rodpot expressed in terms of the 3 restraint systems parameters

Rodpot (m)	Estimation	Std. Error	t-value	Pr(>|t|)	Qualité
Constant	0.0241555	0.0005723	42.204518	0	***
Column collapse (m)	0.0231688	0.0011073	20.923386	4.441D-15	***
Load limitation (N)	0.0000015	7.503D-08	20.315348	7.994D-15	***
Vent size (m)	-0.110853	0.0090411	-12.261022	9.286D-11	***
Incertitude	0.0002712				
R	0.9804082				
R² ajust	0.9774694				
F-stat	333.61136				
p-value	0				

Rounding the weighting factors leads to equation (6).
Aprx_Rodpot=24.2 +23.2*CC+1.5*LL-0.11*VD(6).
where :

- CC is the Column Collapse, in mm
- LL is the Load limitation, in kN
- VD is the airbag Vent Diameter, in mm

Figure 18 presents the comparison between the Rodpot as directly measured in the test and the approximated Rodpot (Aprx_Rodpot) as defined thanks to the DoE and equation (6).

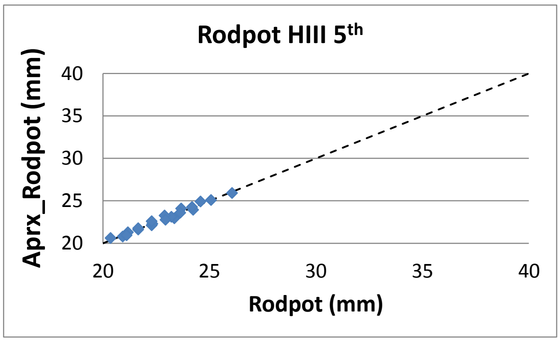

Figure 18. Comparison between actual Rodpot calculation and approximation made thanks to DoE

Comparison between Rodpot and Deq: relative contribution of the restraint systems parameters

For HIII 5[th], Table 11 recalls the weighting factors presented in Eq (5) and Eq 63) (so the (λ_i, α_i, β_i, γ_i)) as well as the relative factors of Deq expressed in percentage of Rodpot – that is to say the (λ_D/λ_R, α_D/α_R, β_D/β_R, γ_D/γ_R).

Table 11.
Simplified weighting factor used to approximate Rodpot and Deq as a function of restraint systems parameters and relative weight

simplified weighting factor	RodPot	Deq	weighting factor (Deq / Rodpot)
Constant (mm)	24.2	22.9	95%
Column Collapse (mm)	23.2	18.4	79%
Load Limitation (kN)	1.5	3.97	265%
Vent Diameter (mm)	-0.11	-0.09	82%

* Deq / Rodpot, that is to say the (λ_D/λ_R, α_D/α_R, β_D/β_R and γ_D/γ_R)

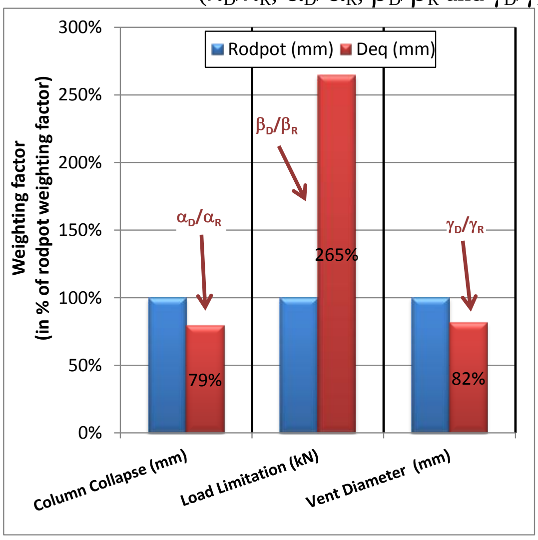

Figure 19. Relative factors of Deq expressed in percentage of Rodpot – that is to say the (λ_D/λ_R, α_D/α_R, β_D/β_R, γ_D/γ_R) for HIII 5[th].

Again, for HIII 5[th] as well, Deq is more sensitive than Rodpot to Load Limitation and less sensitive to Column Collapse and the airbag Vent Diameter.

Design of restraint system: what are the new possibilities? What are the forbidden ones if Deq is chosen?

Figure 20 presents Deq in function of head clearance for all the DoE points collected for HIII 5[th]. The lower performance foreseen for Deq is shown in red (max Deq) and the upper performance foreseen for Deq is shown in green (min Deq).

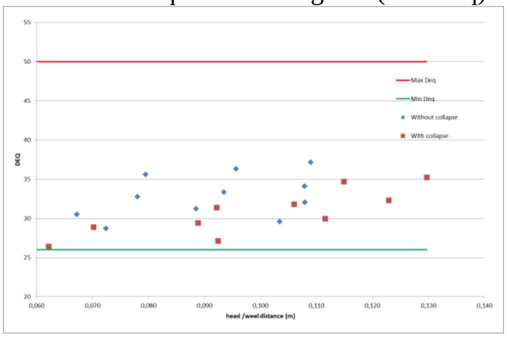

Figure 20. Deq in function of head clearance for DoE – from HIII 5[th] DoE

Again, no case would be removed from HIII 5[th] DoE when looking at head clearance. This means that head clearance is not a limiting factor for a good Deq score.

Figure 21 presents Deq in function of chest clearance for all the DoE points collected.

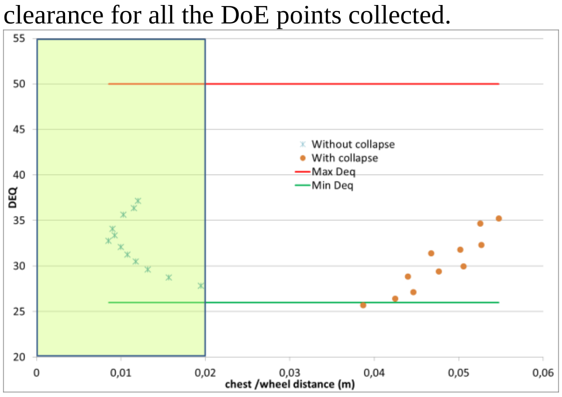

Figure 21. Deq in function of chest clearance for DoE – from HIII 5[th] DoE

The chest clearance will therefore force us to remove all the load cases without collapse.

Applying this analysis to the DoE results for HIII 5[th] would give the following results, as shown in Figure 22.

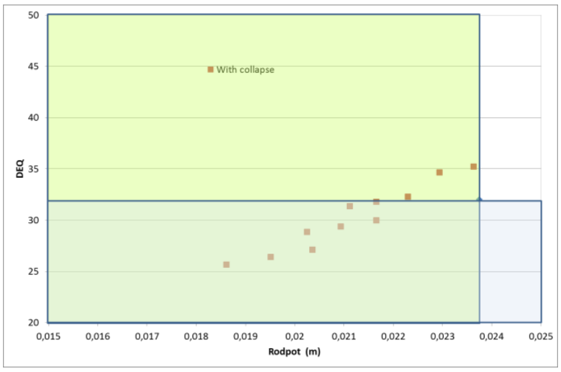

Figure 22. Deq measure in function of Rodpot with the load cases removed because fo chest clearance – from HIII 5th DoE

When designing a restraint system targeted to reach 3 points with the Rodpot, all the loaded cases included in the green rectangle would be possible. This includes all the remaining cases (all the ones with column collapse.
On the other hand, if we have to design a restraint system targeted to reach 3 points with the Deq, all the loaded cases included in the blue rectangle would be possible. This means that 3 load cases would have been forbidden.

Using Deq would prevent us to design restraint system with a column collapse and with the following characteristics:

- 3960 LL and 0.0475 VD
- 4620 LL and 0.055 VD
- 4620 LL and 0.0475 VD.

DISCUSSION AND LIMITATIONS OF THE STUDY

To summarize our findings before starting the discussion we can say that the first part of the research was the assessment of scattering in actual measurements of chest deflexion (Rodpot and Deq). This has already been discussed in the partial conclusion on the scattering and reproducibility.

Then we decided to study numerically restraint systems that should give better results when combining 50th and 5th percentile protection i.e. with load limitation lower than the one tested in the reproducibility analysis. For this purpose, we carried out numerical Design of Experiments changing the restraint systems parameters from an actual car to see the consequences on biomechanical results.

This first output of this numerical study was to define the Deq and Rodpot maximum values as a function of restraint systems characteristics (column collapse, airbag stiffness and seat belt load limitation). This way, we saw that Deq is more dependent to load limitation than Rodpot. And on the other hand, Rodpot is more dependent to column collapse and airbag stiffness than Deq.

But this analysis is made by varying the restraint systems characteristics for one unique vehicle model. Our research is not finished and we have planned to study other vehicles to see if the equations would be similar.

Concerning the main outcome of the study, we found that varying the restraint system characteristics allows us to find satisfying cases where some occupant protection principles are fulfilled. But looking at chest deflection via Rodpot or Deq would not give the same selection of cases. At this stage, we should also warn that the analysis did not look at other biomechanical parameters such as neck forces and moment.

In order to decide if one chest deflection criterion is more appropriate than the other, the last thing to do is to combine the results got for the HIII 50th to the ones obtained with the HIII 5th. This is presented in Figure 23 where we kept all the cases selected for Rodpot scores > 3points or for the Deq Scores > 3 points.

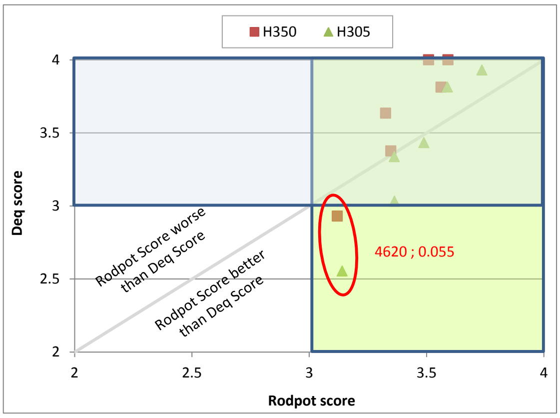

Figure 23. Deq score in function of Rodpot with for HIII 50th HIII and 5th Design of Experiments – Cases selected for Rodpot scores > 3points or Deq scores > 3points

From these figures, we can conclude that 5 restraint cases would be allowed by Deq for HIII 50th and HIII 5th dummies. They are all with column collapse and with:

- 2640 LL ; 0.0475 VD
- 3300 LL ; 0.0475 VD
- 2640 LL ; 0.055 VD
- 3300 LL ; 0.055 VD
- 3960 LL ; 0.055 VD

where LL = seat belt Load Limitation and VD = airbag Vent Diameter.

A 6th one (circled in red in Figure 23) would be allowed by Rodpot and not by Deq. This is the 4620 LL ; 0.0055 VD with column collapse. This means a restraint with a load limitation not very low combined with a soft airbag. In terms of occupant protection, this combination is not desired if we want to protect the elderly.

These five sets of parameters allowed by Deq for the car restraint system should be cross-checked with the other biomechanical criteria not studied here (such as neck criteria) to be sure they are all compatible with a good level of occupant protection on all body segments.

CONCLUSION

One part of our study was to analyse the overall reproducibility of Rodpot and Deq measurement based on current cars tested in the Euro NCAP ODB 64km/h test with HIII 50th. No significant difference or trend was found between the scatterings of the two ways of measuring chest deflection. But we saw that for the restraint systems tested in this analysis, Deq score was always lower than Rodpot score. The score was calculated according to one of the hypotheses of chest deflection thresholds currently manipulated by Euro NCAP.
In order to see how we can get better results, we carried out a numerical programs based on ODB 64 km/h test with HIII 50th and Full-width 50 km/h test with HIII 5th where we varied the restraint systems characteristics (column collapse, airbag stiffness and seat belt load limitation). We looked at the results in terms of biomechanical criteria as well as restraint criteria, such as head and chest clearance. The purpose was to see whether or not Rodpot would allow different restraint systems solutions than Deq. With the set of parameters investigated, we saw that Rodpot would allow one case in addition to the one allowed by Deq, but it is the one with the highest load limitation investigated and the softest airbag investigated. Using a chest criterion preventing from choosing this solution would be good. The limits of the study are that some other biomechanical criteria were not studied in details, such as neck load and moments because their lower quality in numerical correlation. It may limit the number of solution retained in the final selection of restraint parameters.

We also investigate the sensitivity of the two criteria with respect to the restraint systems characteristics.
For HIII 50th as well as for HIII 5th, we found that Deq is more sensitive than Rodpot to Load Limitation and less sensitive to Column Collapse and the airbag Vent Diameter.

As a summary, we can say that Rodpot and Deq are equivalent in terms of scatterings. But using Deq will definitely give incentive to design restraint systems that have a lower load limitation. It will also prevent the design of restraint systems made of higher load limitation combined with soft airbag. This is good for elderly occupants that are known to be more fragile on chest and shoulder.

ACKNOWLEDGMENTS

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