REDUCING PRIMARY AND SECONDARY IMPACT LOADS ON THE PELVIS DURING SIDE IMPACT

#Allan F Tencer, #Robert Kaufman, * Phillipe Huber, #Charles Mock, Carole Conway+, and ML Routt

*Department of Orthopedics, Seattle CIREN team, #Harborview Injury Prevention and Research Center, University of Washington, Seattle, WA, USA, and + CIREN Team, San Diego, CA

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ABSTRACT

Pelvic fractures account for about 12% of injuries suffered in a side impact. Compared to patients in MVAs without pelvic injury, those with pelvic fracture have more severe injuries and higher mortality rates. LC-1 (lateral compression) unilateral fractures from direct contact with the door, are stable with little internal disruption and may be treated non-surgically. In contrast, LC-3 bilateral fractures also involve injuries to the pelvis on the side opposite that which contacted the door, are highly unstable, have significant hemorrhage and internal organ damage, and must be treated surgically. In several CIREN (NHTSA, Crash Injury Research and Engineering Network) crash investigations, it appeared that the occupant was trapped between the intruding door and a non-yielding center console, explaining the fracture to the pelvis on the side opposite the door.

In CIREN side impact crashes with 15-46cm of door intrusion, 29 occupants in vehicles with consoles and 9 in vehicles without consoles suffered AIS 2 and 3 pelvic injuries ($p<0.05$). Experimental testing with USDOT SID, a pendulum and pre-crushed door and a fixed and crushing seat, with a console, peak accelerations at the pelvis were 24.8g due to door contact, and -10.5g due to console contact. Removing the console decreased minimum acceleration to -3.3g. When the seat was mounted to a track allowing it to displace laterally during impact, into the space occupied by the center console, peak pelvic acceleration decreased to 15.3g. Using a MADYMO model of the pendulum drop experiment, with a finite element door and seat, USDOT SID positioned as the passenger, and a door peak velocity of 6.6 m/sec, initial nearside dummy lateral (+Y) door to pelvis contact force was about 10×10^3 N. As the door pushed the dummy against the console, this increased to about 20×10^3N. With no console and a laterally translating seat, peak pelvic load decreased to about 4×10^3 N, and only one peak was noted. A collapsible console and a seat track which allows lateral displacement of the seat may help to reduce pelvic injury in side impact crashes.

INTRODUCTION

Side impact crashes represented, in 2002, 26% of all fatal collisions (second only to frontal crashes) with an estimated total of 782,000 nonfatal and 9812 fatal injuries (1). Samaha and Elliott (2) reported, from a survey of NASS (National Automotive Sampling System) that injuries to the chest occurred in 39.7% of surviving occupants, followed by injuries to the head (25%), the pelvis (11.7%), and the abdomen (8.4%). In a study of the 119 crashes currently entered in the CIREN database (3), 71 (60%) of occupants had pelvic fractures of at least AIS 2 (Abbreviated Injury Score, (4)). The mortality rate from motor vehicle induced pelvic injury ranges from 8.6% to 50%, with 25%-35% of survivors having unsatisfactory results after treatment (5-8). Compared to patients in motor vehicle crashes without pelvic injury, those with pelvic injury were significantly more injured, had higher blood loss, longer hospital stays, more genitourinary injuries, and higher mortality rates.

LC-1 (lateral compression) pelvic fractures, involve structures in direct contact with the incoming door. LC-I fractures are stable, may be treated non-surgically and usually result in little internal disruption. In contrast, LC-III fractures involve not only injury to structures such as the sacrum or iliac wing and pubic ramus on the door side, but also structures on the opposite side. The LC-III fracture is highly unstable, involves rupture of pelvic area blood vessels, has significant associated internal hemorrhage, and damage to internal organs, and must be treated surgically by stabilization of both the anterior and posterior pelvic ring (9). Operative treatment of pelvic injuries, particularly open reduction and internal fixation is associated with significant surgical risk including deep infection, nerve injuries, and malreduction.

Considering that in a near side impact collision, pelvic fracture is usually described as occurring from direct contact with the intruding door (2, 10, 11-18), it was of interest to study LC-III fractures since they include fractures on the side opposite the door, implying contact with some other structure in the vehicle. In several CIREN crash investigations, an example of which is shown in Figure 1, in near-side impacts, evidence was found of hard contact of the pelvis through the belt buckle into the center console. If the center console does play a role in some pelvic fractures, the secondary load from pelvic contact could be reduced by changing the console structure, so that it yields under loading by the pelvis. Further, extending this concept, if the seat were permitted to move laterally, in a controlled manner, into the space occupied by the crushed console, then primary impact loads on the pelvis from door contact might also be reduced. The involvement of the console in pelvic injury was explored using CIREN data and the effects of reducing console stiffness and allowing lateral displacement of the seat were studied using MADYMO modeling and experimental testing.

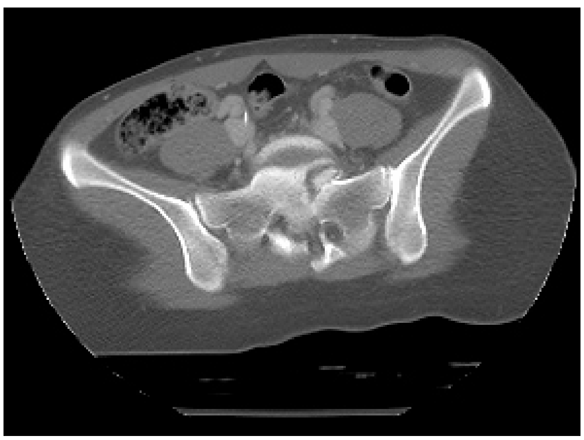

Figure 1 (upper) Example of CIREN crash investigation involving side impact showing locations of contact with the door and console (yellow tape), (lower), resulting sacral fracture.

METHODS

General approach

We compared the numbers of pelvic fractures, in vehicles with and without consoles from CIREN crash data. A pendulum impact subsystem experiment was performed using a USDOT SID dummy (US Dept of Transportation Side Impact Dummy), sitting on a vehicle seat and impacted with a pre-crushed door. Pelvic accelerations with fixed seat-no console, fixed seat-with console, and moveable seat-no console conditions were studied. A MADYMO (Mathematical Dynamic Modeling, TNO Automotive, version, 6.2, Livonia, Michigan) model of the pendulum apparatus was developed. Because of concerns about the low biofidelity of the USDOTSID (19,20), the MADYMO model was run using USDOT SID, SIDIIs, ES-2 (European side impact dummy) and BIOSID for comparison.

Field Studies of Vehicle Crashes

The motor vehicle crash and pelvic injury information included in this study was collected from several of NHTSA's CIREN Centers. Crashes in the CIREN database are sampled based on the fulfillment of several criteria. Among these are that the occupant must have been restrained and that at least one injury of AIS 3 or greater must have occurred. Each crash scene and vehicle investigation conducted by CIREN centers follow the data collection format established by NASS. Each case was reviewed by a multidisciplinary team consisting of a crash investigator, a bioengineer, a research nurse, and the treating physicians.

The crashes selected all involved side impacts with focus on injuries to the pelvis of the occupant. Each crash site had scaled documentation of the roadway, traffic controls, road surface type, conditions, and road grade at both pre- and post-impact locations. Physical evidence such as tire skid marks were located and referenced to establish the heading angle and post impact trajectory of the colliding vehicles. A scaled drawing with impact and final resting positions was completed to assist in calculation of the speed and force at impact. Exterior inspections of the vehicle were performed, which included detailed measurements of the direct and induced damage. For this study, all crash damage involved the side of the vehicle. With a contour gauge, a damage crush profile was collected and a specific Crash Deformation Code (CDC), which includes the principal direction of force (PDOF) was assigned. These measurements were entered into crash analysis software (Win SMASH, U.S. Dept of Transportation) to calculate the change in velocity (Delta V) of the vehicle during impact and the energy dissipated during the crash event.

An inspection of the interior of the vehicle from which the injured person had been removed was performed to determine points of occupant contact and restraint system use. An examination of the restraint system was performed including lap and shoulder belts and the air bag, if available, to confirm use by the injured occupant. An assessment of the integrity of the passenger compartment involved measurements of all intruding components, such as the door panels. Comparison measurements were obtained from exemplar vehicles or undamaged opposite seat positions to calculate the amount of component crush. With Institutional Review Board approval, the injuries were assessed by examining the patient's medical records and imaging studies.

For this study we identified 62 occupants in 54 crashes in vehicles between model years 1998 and 2004. The study was limited to drivers or front seat passengers, and only nearside occupants in crashes with a PDOF (principal direction of force) between 8 and 10 o'clock or 2 and 4 o'clock (approximately 30 deg from perpendicular to the side of the vehicle) which involved pelvic fractures. Field observations were made separately to determine whether or not the types of vehicles involved had center consoles. Center consoles did not include soft or fold down arm rests, only relatively rigid center structures protruding above seat level.

Experimental testing

SINCAP side impact tests performed by the National Highway Traffic Safety Administration (NHTSA) on vehicles from 1999-2003 were studied from data available at www.dms.dot.gov, docket 3835, where complete reports of each test are posted. A total of 165 separate tests were analyzed. From the data, mean time histories of door velocity and pelvic acceleration were generated to provide a comparison from our experiment and modeling to data from controlled crashes.

The experimental apparatus, shown in Figure 2 consisted of a pendulum carrying a pre-crushed door , a US DOT SID, a seat, and a mechanism to stop the motion of the pendulum after dummy impact. A door from a 1997 Toyota Celica was selected from wrecking yard vehicles (Pull-Apart, Lynnwood WA) that had sustained an approximately 90 deg side impact with predominant deformation of the door located in the rear half. A crushed door is necessary to simulate the actual door stiffness during contact with the occupant..

The apparatus consists of a simple pendulum composed of 2, 4.9 m long sections of 0.15 m x 0.15 m x 0.006 m (6" x 6" x ¼") aluminum angle bolted together. One end was mounted through a hinge to a frame bolted to the ceiling of the lab. The other end was pulled upwards by a winch and cable system. The door was mounted to the pendulum through an apparatus that could change its orientation both vertically and horizontally. The top of the arm rest was positioned level with the pelvis of the dummy at contact. Two springs which could be precompressed were used to stop the forward travel of the pendulum after contact with the dummy. From 165 US DOT NCAP (New Car Assessment Program) tests, the mean door peak velocity was 8.1 m/sec (range 2.8-13.4 m/sec) and maximum intrusion was 34.4 cm, with a mean initial door to dummy clearance of 15.1 cm giving a mean door-to-dummy contact stroke of about 19 cm (11). Our pendulum contact velocity was 6.3 m/sec with a door-to-dummy stroke of 15 cm.

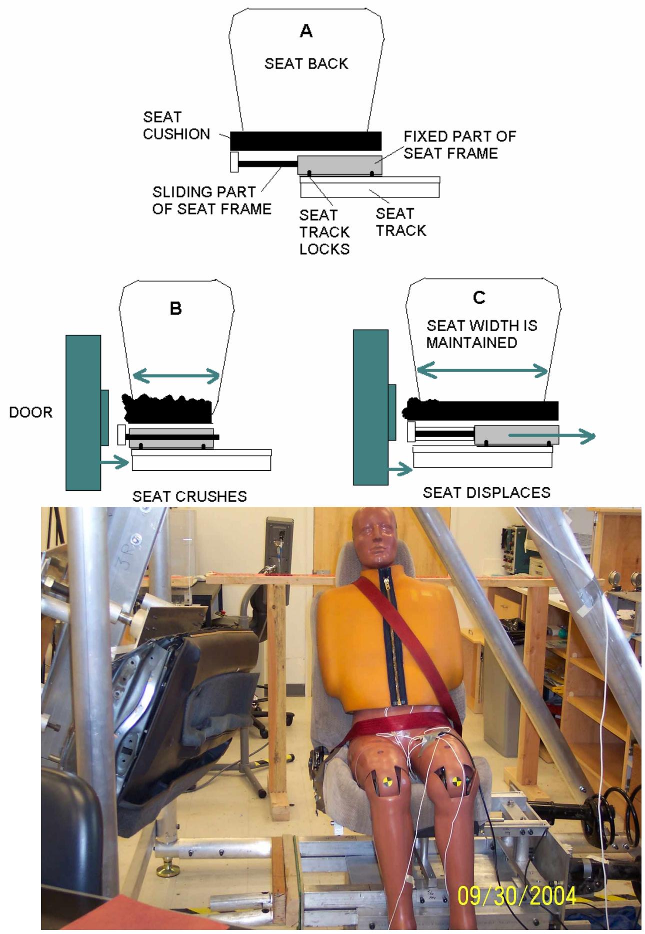

Figure 2 (upper) Schematic diagram of the function of the seat. The seat was designed to accommodate two conditions, remaining fixed and crushing to half its width, or remaining intact and displacing half its width (25 cm), with and without a center console plate mounted to the right side of the seat (not shown). (A) The seat frame has a rigid half (away from the door) and a sliding half (near the door). The whole seat is mounted on a track which allows lateral sliding (B) With the seat track locked and the sliding half of the seat frame free, the seat crushes under impact with the door. (C) With the sliding seat frame locked and the seat track free, the whole seat slides laterally without significant crushing. (lower) photo of the complete apparatus including the door, pendulum, DOTSID dummy, and the seat.

We selected a USDOT SID dummy (S/N 344 calibrated by Robert Denton, Inc, Michigan) for this part of the experiment because it is used in the SINCAP tests and therefore allowed a direct comparison of TTI and pelvic acceleration from this experiment to SINCAP full scale test results. The dummy was restrained with a lap and shoulder belt fixed to the seat. Accelerometers were fixed to the T4, T8, and T12 rib levels and at the pelvis in the standard mounting positions on the dummy.

The seat was designed to test the configurations of a (standard) fixed seat, which crushed during impact (see Figure 1) with and without a console, as well as a laterally translating seat with no console. The seat frame was constructed so the half away from the door was a rigid frame and the half towards the door was a moveable frame which could slide over the rigid half. This allowed the half of the seat frame closest to the door to simulate seat crushing during impact, as shown in Figure 1. The rigid part of the seat frame was mounted onto a slotted track which allowed lateral (Y) displacement. To simulate the fixed seat-no console condition, the seat was locked to the lateral track and the moveable half of the seat frame was allowed to slide into the rigid half frame. To simulate the fixed seat-with console condition, an aluminum plate, simulating the vertical plane of the console into which the hip might be compressed was bolted to the seat frame. Finally, to simulate the translating seat, the moveable seat half frame was locked in its outmost position, and the whole seat allowed to slide on the lateral track. In this configuration, the seat frame retains its original dimension and the whole seat slides laterally. This assembly is shown in Figure 2a. The seat track was designed to accommodate 25 cm of lateral displacement. This was the mean intrusion distance found from the CIREN crashes studied and also represents a common dimension between seats in many vehicles.

Data collection was performed at 10 KHz (National Instruments, Austin, TX). High speed video (Kodak Ectapro,, San Diego, CA) running at 1000 frames/sec was used capture each impact. Data from the accelerometers was filtered using the FIR 100 filter. Maximum and minimum accelerations from each test were determined from the time history and the three conditions were compared using a nonparametric Wilcoxon signed rank test small samples with a significant difference set at $p < 0.05$

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Development of a MADYMO model of the pendulum side impact

Since we were limited to using only the US DOT SID in the experiment because of availability, a MADYMO model was developed with consultants at TNO-MADYMO (Livonia, MI). A USDOT SID version of the model allowed direct comparison of the model, and the experimental results. ES-2, BIOSID and SIDiis versions of the model were used because of their reported greater biofidelity (19,20).

The door was modeled by first testing its local stiffness in the following manner. The door was mounted horizontally onto a cradle with its interior surface facing upwards. A grid, 2cm square, Figure 3, was drawn on the surface of the door and the center

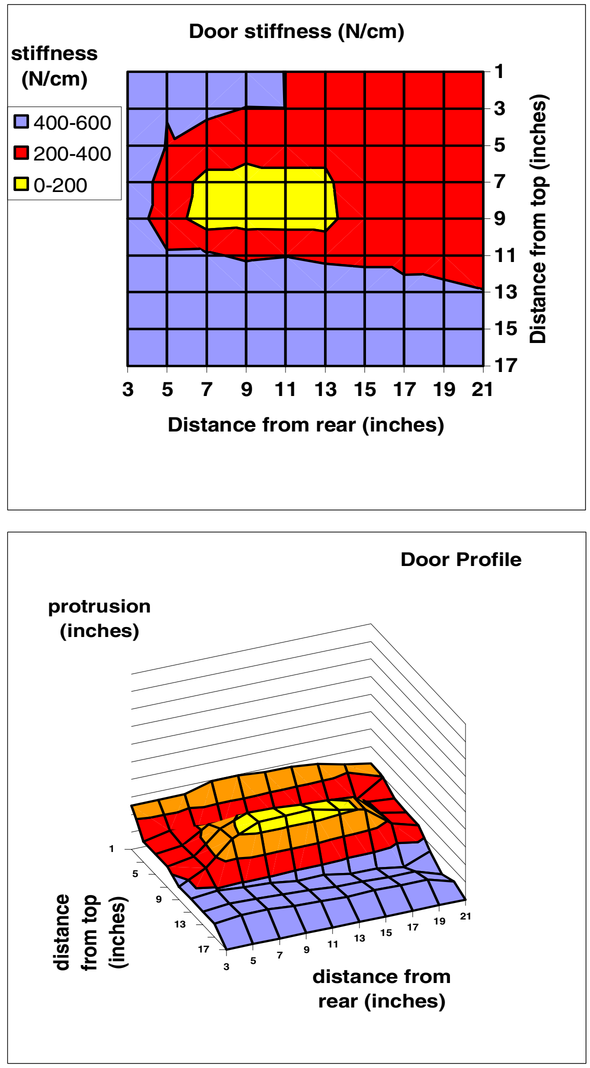

Figure 3 (upper) Stiffness map of the door used in the MADYMO model, (lower) geometric profile of the door.

point of each grid located at the crossing of diagonals on each square. The door and cradle was mounted to the table of a materials testing device. A 2.5 cm (1 inch) diameter cylindrical load tip was screwed to the base of the load cell. The door was tested nondestructively at low loading rate. Door interior panels, made of ABS, are relatively insensitive to loading rate and can be characterized by quasistatic or low rate loading (21). The tests were run under displacement control to a maximum displacement of 2 cm at all grid center point locations. The data was collected, at a sampling rate of 1000 Hz, force-deflection data were plotted, and a stiffness map of the interior door surface panel created. In addition, the displacement at which the load first increased from zero was defined as the contact point, from which a geometric profile map was plotted, Figure 3.

The door was represented in the model as a series of translational joints of prescribed stiffness based on the mechanical testing described above with a finite element mesh of shell elements as the door contact surface to the dummy. The door surface, being coarser, was selected as the master surface and finite element meshes were created to coat around the dummy's ellipsoid contact surfaces. The seat consisted of shell elements, with a center console plane, fixed to the reference space. The base of the seat was connected to the reference space by a joint allowing translation in the Y (lateral) direction, representing the seat track. The USDOT SID dummy was restrained by a finite element lap belt. The seat/dummy friction coefficient was set at 0.3. Both the model and experiment represented a passenger's side impact.

For the case of the (standard) fixed seat, the seat stiffness (for door contact) was 1x 10^2 N/mm, the seat joint was locked (no translation), a console plane was added, and the door configuration was as shown in Figure 3. For the translating seat, the seat stiffness was increased to 1 x 10^3, the seat joint was unlocked with a frictional coefficient of 0.3, along with a shear release load of 5000N, and the door panel was flat with a narrow arm rest. The pelvic contact forces were compared for the two cases studied.

RESULTS

CIREN data

For side impacted vehicles with consoles from the CIREN database, 41 occupants suffered pelvic injuries. The mean age was 40 years (range 15-89 years), 33 (80%) were female, 29 (71%) were drivers, and 36 (88%) were belted. The mean delta V for collisions in this group was 36 kph. Those suffered pelvic injuries in vehicles without consoles consisted of 21 occupants, with a mean age of 43 years (15-80 years), of which 11 (52%) were female, 13 (62%) were drivers, and 19 (90%) were seatbelted. The mean delta V in those crashes was 35 kph. There were no significant differences in age, percent drivers, percent belted, or mean delta V between the two groups. In crashes with between 15 and 30 cm of door intrusion, 14 occupants in vehicles with consoles and 5 in vehicles without consoles suffered AIS 2 and 3 injuries ($p<0.05$). In crashes with 30-46 cm of door intrusion, 15 in vehicles with consoles and 4 in vehicles without consoles suffered pelvic injuries ($p <0.05$), Figure 4.

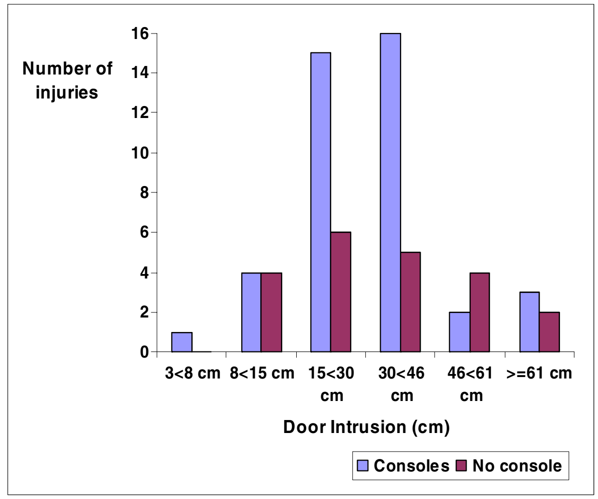

Figure 4 Number of AIS 2 and 3 pelvic injuries in sample of 62 occupants in CIREN nearside crashes, at different levels of door intrusion, in vehicles with and without center consoles.

Experimental testing

The pendulum tests were reproducible with a coefficient of variation in peak pelvic acceleration of 0.074 (standard deviation / mean). Figure 5 shows representative pelvic acceleration time histories.

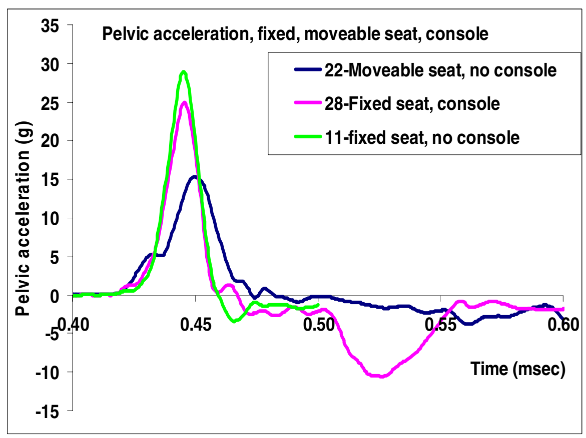

Figure 5. Sample pelvic acceleration-time histories from the experimental testing, with a laterally moveable seat and no console, a fixed seat with no console, and a fixed seat with a console.

With a fixed seat and no console, the maximum pelvic acceleration (due to contact from the door) was 28.5g and the minimum (due to the lap belt) was -3.3g. With a console plate added, the maximum acceleration was 24.8g (not significantly different) while the minimum acceleration (due to contact with the console) increased to -10.5g ($p <0.05$). With a seat allowing lateral movement upon impact, with no console, the maximum pelvic acceleration decreased to 15.3g ($p < 0.05$) and minimum acceleration remained at -3.8g.

MADYMO results

For this part of the study, focusing on pelvic loads, only results from USDOT are presented to show conceptually how the seat and the environment can be altered. Results with other dummies were similar. Figure 6 provides a comparison of pelvic accelerations between the model and experiment and with mean data from SINCAP tests. A small amount of drag was added in the model to reflect friction in the experimental apparatus. With this, the model and experiment were in very good agreement, both for door velocity and pelvic acceleration. SINCAP values were higher with mean peak door velocity of 11.1 m/sec (mean – 1sd = 8.4 m/sec). Pelvic acceleration was also higher. However, SINCAP test results had a very wide variation (2.8-13.4 m/sec for door velocity and 19-145g for peak pelvic acceleration.

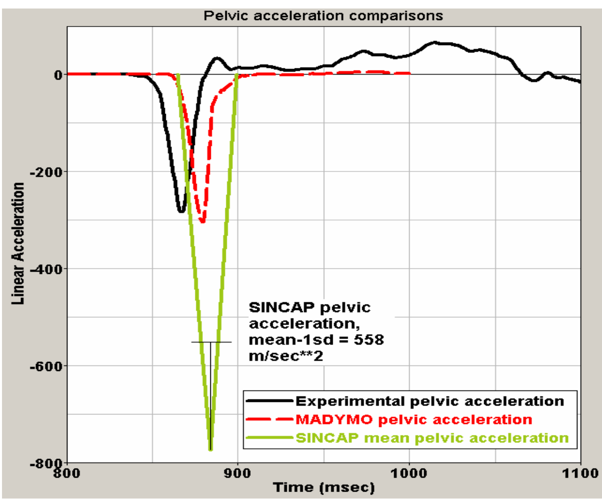

Figure 6 A comparison of pelvic acceleration from the experimental pendulum results and the MADYMO model of the experiment, both in relation to mean values from SINCAP testing.

Figure 7 demonstrates how the pelvis is trapped between the incoming door and the console in the case with a fixed, deformable seat and a rigid console (relative to the pelvis). The forces generated in the two cases are shown in Figure 8. The fixed seat results in high door to seat loads and the initial door to pelvis contact force (blue) was in the range of 10 x 10^3 N. When the pelvis contacted the console, the second force on the pelvis peaked at about 20 x 10^3 N. In contrast, with the stiffer translating seat and no console, the initial pelvic contact force was much lower, about 4 x 10^3 N and there was no secondary force since there was no pelvic to console contact.

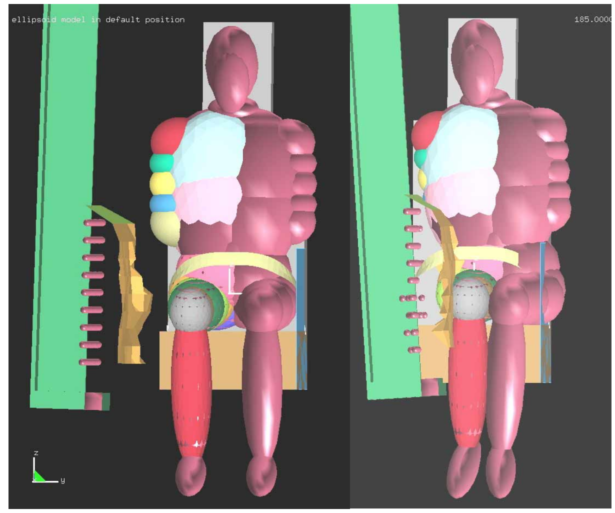

Figure 7 (left) MADYMO model showing (left) USDOT on seat with console plane on right side of seat (blue plane), door (gold) on left (attached to pendulum arm, (green) (right) pelvis trapped between intruding door and console.

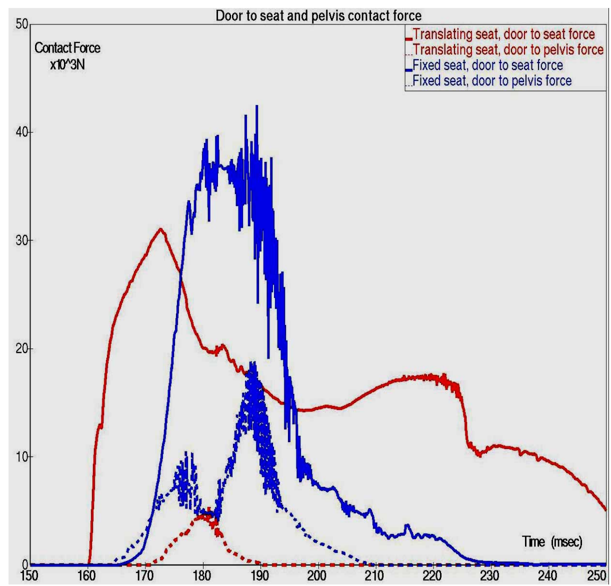

Figure 8 Door to seat (solid) and door to pelvis (dashed) contact forces, (blue) fixed seat, (red) translating seat.

DISCUSSION

In the CIREN database of side impacts, 60% of occupants suffered at least an AIS 2 pelvic injury (3). The most likely mechanism is direct contact of the intruding door against the pelvis (10-18). However, this mechanism does not explain the occurrence of pelvic injuries on the side opposite door-to-pelvis contact. We reviewed CIREN crashes and found that there were significantly more pelvic fractures to nearside occupants in vehicles with center consoles, and 15-46 cm of door intrusion. Experimental testing and modeling demonstrated a primary lateral pelvic acceleration due to door to pelvis contact and a secondary, opposite acceleration due to pelvis contact with the console. Removing the console eliminated the secondary acceleration and allowing the seat to displace laterally reduced the primary pelvic acceleration by about 50%.

Unstable pelvic ring fractures are life threatening, due to their associated injuries. Bilateral pelvic fractures and dislocations are more difficult to treat than unilateral injuries with a greater rate of complications. Considering the severity of the resulting injury, it seems reasonable to maintain the useful function of a center console, but simply construct it so that it would yield with pelvic contact during a side impact. Further protection can be gained by allowing the seat to displace towards the center of the vehicle. In this way pelvic force, produced from contact with the door, and the center console on the opposite side of the pelvis, can be reduced.

Several studies have provided information related to biomechanical criteria for pelvic injury. Bouquet, et al (12), based on 11 post mortem human subjects (PMHS) tests, proposed for a 50% probability of AIS 2 pelvic injury, a deflection criterion of 46 mm, a viscous criterion (VC) of 0.62, and a force criterion of 7600N. Tests by Zhu, et al (13), on 17 PMHS, showed that for impacts against a flat wall at 9 m/sec, criteria resulting in 50% AIS pelvic injury probability were, pelvic peak acceleration of 65.5g, VCmax of 1.57, maximum force of 8780 N, and average force (which they felt was the best criterion) of 5430 N. In SINCAP tests we reviewed, mean pelvic acceleration was in the range of 80g, well above the estimated thresholds for pelvic injury (11).

Morris, et al (14) and Allan-Stubbs (15) used data from SINCAP tests as a basis for an input door velocity and comparison of resulting dummy accelerations in their models. Although we used a pre-crushed door to simulate the increased stiffness of the door during a side impact where the outer panel is first deformed against the inner panel, our pelvic accelerations, with a peak about 31g, were 62% lower than those in SINCAP testing. The pendulum velocity of 6.3 m/sec in our experiment was 43% lower than the 11.1 m/sec mean SINCAP absolute door velocity, from the 165 tests analyzed. The model and experimental results were in very close agreement. While the maximum pendulum velocity is limited, we were able to run the model at greater impact velocities and show comparable results to the SINCAP tests. Also, it should be recognized that individual SINCAP tests produced wide variations in both peak door velocity (2.8-13.4 m/sec) and pelvic acceleration (19g-145g).

All of the methods of analysis used in this study have some limitations. CIREN data, at higher door intrusions, supported the role of the console in bilateral pelvic injury. However the CIREN data is a relatively small sample considering all the confounding variables, such as striking vehicle speed, vehicle mass, front end rigidity, height of impact, and variations in occupant characteristics which occur in actual crashes. The USDOT SID used in the SINCAP test itself has a reported biofidelity rating for the pelvis of only 2.5 (out of 10) (20). The MADYMO model was used to study the responses of more biofidelic models such as ES-2, BIOSID and SIDiis. Since trends were similar, they were not reported here.

Several strategies have been employed to reduce side impact injury. Door side impact beams have been required on all vehicles since 1997. Stiffening the door reduces both door intrusion velocity and overall intrusion distance. Increasing occupant-to door distance results in lower door velocity at the time of contact (14,15), but there is a limit to the allowable increase in vehicle width, with trade-offs such as compatability of vehicle size to widths of existing roadways and the additional vehicle weight that comes with increasing width. Door padding reduces overall pelvic acceleration (13), however, at the expense of earlier contact and greater energy transfer and compression of the pelvis. Airbags have been installed for head and thoracic protection during side impacts but not for reducing pelvic loading. Modifying the structure of the console is a simple design change. If this change can reduce the incidence of bilateral, highly unstable pelvic fractures in side impacts, it would be of considerable benefit. There is a significant difference between a highly unstable bilateral pelvic fracture which compromises internal organs, involves significant blood loss, and must be treated by major surgical intervention, and a unilateral, stable pelvic fracture which may be treated without surgery.

Allowing the seat to displace laterally invokes the strategy of using the space available between the seats to move the occupant away from the intruding door. Several issues which must be resolved include, the design of a seat frame which can absorb door impact without significant deformation, and which can retain the occupant during lateral movement. In addition, the interaction between the nearside and farside occupants with such a system has not been studied, although if the seat is angled slightly backwards during its lateral movement, the nearside occupant may be made to contact the back of the farside seat instead of the farside occupant.

Preliminary test results documented in this report do suggest that further study of this concept should be undertaken.

Acknowledgement and Disclaimer
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INTRODUCTION TO FEASIBLE INNOVATIONS IN SIDE IMPACT SAFETY

Eng. Gustavo Zini
School of Engineering – University of Buenos Aires
Argentina
Paper Number 05-0066

ABSTRACT

"A more synergistic view or approach to motor vehicle safety design aspects is needed." (Robbins – SAE-Paper 970488).

The aim of this work is to indicate some feasible innovations that may lead to a better side impact protection, pointing out some aspects that can be developed thoroughly within the corresponding settings and using the appropriate resources. The mentioned innovations will be analyzed from a general and synergistic point of view, using basic engineering and physics principles, and considering the following:

- simulations will be performed using a simplified model consisting on a single-mass/inelastic-spring system.
- some physiological premises will be considered (such as "direct impacts should be avoided at any place of the organism"; "high accelerations can be sustained during short periods of time"; etc.).
- the bases of safety in road crashes will be established, namely "control the perfect operation and use of the safety devices"; "maintain the structural integrity of the occupants' vital volume"; "absorb the whole kinetic energy both of the vehicle and of the occupants"; etc. Subsequently, these bases will lead to determining the main functions that the compartment, external/internal structure and restraint devices should perform to enhance the safety they offer.
- the protection offered by current safety devices will be analyzed, segmented into three groups (pre-impact, impact and post-impact).

All of this will allow the discussion of some feasible innovations leading to better side impact protection. Finally, considering the inherent reluctance to introduce valuable safety innovations into current automobiles (e.g.: four-point seatbelts) a strategy to perform this in a successful manner will be discussed.

INTRODUCTION

"Near side crashes have higher serious injury and fatality risks as compared to all crashes". (Samaha/Elliot – NHTSA side impact research: motivation for upgraded test procedures – Paper 492 18th ESV Conference).

Every year more than a million people die and dozens of millions must bear some kind of permanent impairment as a consequence of road crashes (1). The vast majority (90%) of the victims belong to low-income or middle-income countries, where most of the fatal crashes involve pedestrians, cyclists or motorcyclists. Moreover, it can be argued that the most frequent road crash involving only automobilists is the one where two vehicles sustain a frontal head-on collision. Yet, side impacts are both a common and a dangerous phenomenon, involving for instance, 20% of fatal crashes and 30% of injury crashes in the United States (2). Some of the highlight characteristics of side impacts are the following (3):

- most side impacts involve vehicles travelling perpendicular to each other.
- the struck car generally is travelling slower than the car that strikes it.
- the struck car generally has a low Δv (velocity change).
- the time epoch for side collision is slightly greater than that of a frontal collision.

Before going on, it can be argued that a driver travelling on his automobile has an intrinsic tolerance to injury which is opposed to a variable "injury potential". On one hand, the injury tolerance is defined by:

- an inherent biological tolerance to accelerations and direct impacts.
- the protection provided by his vehicle.
- the protection provided by the road infrastructure.
- an emergency environment that will assist him in case of a road crash.

On the other hand, and as far as this paper is concerned, the "injury potential" depends on the mass and speed of the striking vehicle; that is to say, on the kinetic energy of the impact. As it is known, speed has greater influence than mass in the value of the kinetic energy of an object: while mass has a directly proportional influence on this physical dimension, speed has a directly quadratic influence. Moreover, when compared to frontal impacts, it can be argued that side impacts happen at lower speeds, therefore bearing lower levels of "injury potential".

EXAMPLE BOX 1

Estimated average travel speed in fatal crashes in the United States according to their manner of collision

An analysis using the data available at Fatality Analysis Report Systems (FARS) allows to estimate the average travelling speed of fatal crashes for the years 2002-2003 in the United States, according to their manner of collision. Two of the available categories were considered: on the one hand, "front-to-side, right angle (including broadside)" was used to estimate the average impact speed of perpendicular side impacts; on the other hand, "front-to-front (including head-on)" was taken to estimate the average speed of frontal impacts. The results of the analysis show that in the United States, in the considered years, the average impacts speeds for the mentioned impacts were:

- *61 km/h for perpendicular side crashes.*
- *79 km/h for frontal crashes.*

The frequencies for the travel speed for both types of crashes can be observed in the following figures:

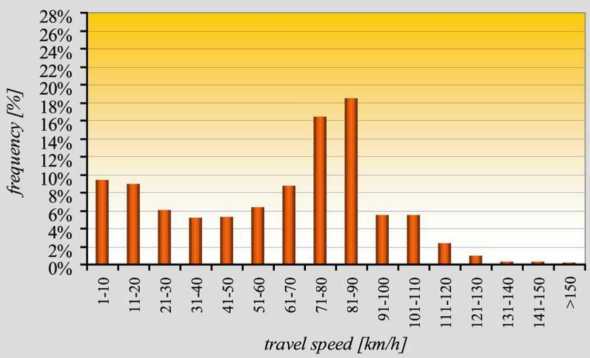


Figure 1. Frequency of registered fatal "front to side, right angle" crashes according to their travel speed in the United States for the years 2002-2003.

Source: reference 4

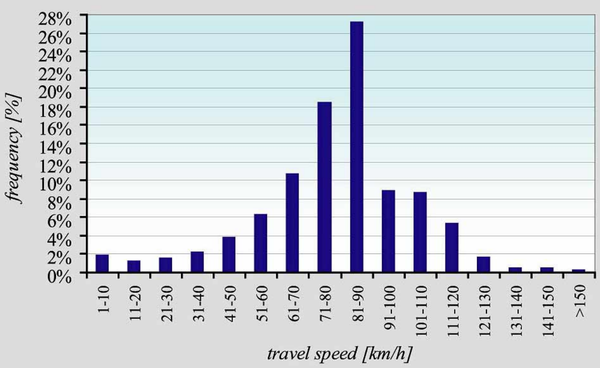


Figure 2. Frequency of registered fatal "front to front" crashes according to their travel speed in the United States for the years 2002-2003.

Source: reference 4

From both figures it can be deduced: firstly, regarding side impacts, most fatal crashes involve speeds that stretch out between 1 km/h and 90 km/h with a larger concentration in the range 70-90 km/h; secondly, in the case of frontal impacts, the majority of fatal crashes stretch out in a narrower range, between 60 km/h and 110 km/h, with a larger concentration, again, in the range 70-90 km/h.

It is worth mentioning that for side crashes there is a greater density of fatal crashes in the lower speed range, which gives a hint of an issue that is going to be discussed in the following pages: since equal speeds bear approximately the same level of "injury potential", when considering the available safety devices acting in frontal and side impacts, a higher proportion of fatal injuries at lower speeds may imply lower levels of protection as regards side crashes.

For a better understanding of the aspects of crash severity involved in a side impact, an example of an automobile sustaining a side impact against another vehicle will be analyzed and compared to frontal and rear crashes. The following figure sketches the general simplified scheme that is considered for the modeled automobile:

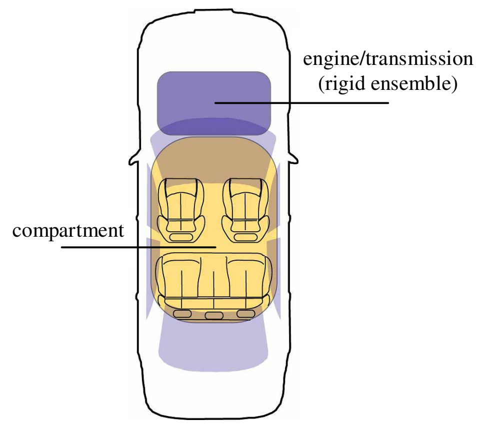
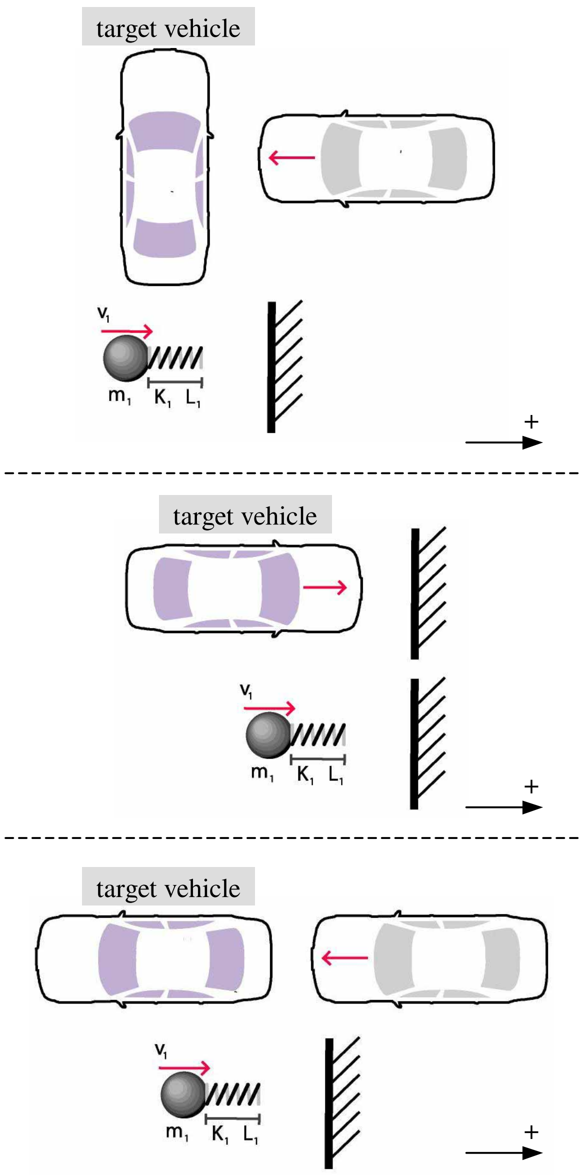


Figure 3. General simplified scheme used for the modeled vehicle.

The conditions that are going to be modeled are that of a medium-size car weighing 1.500 kg that in the case of the side impact, is struck perpendicularly on its side by another similar vehicle while stopped; in the frontal impact, it strikes a fixed object; and in the rear impact, it is struck from behind by another similar vehicle while stopped. In order to do so, a series of simplifications should be considered, namely: one dimension movements; reference of coordinates in the center of mass of the target vehicle; and the use of a system formed by a single mass and an inelastic spring which, according to what many experts agree, is the model for the description of the behavior of an automobile in a crash that suits properly the purpose of this work (5). The general models for the three types of road crashes that are going to be analyzed can be described as follows:



(m_1 = mass; K_1 = stiffness coefficient; L_1 = length of spring; v_1 = speed)

Figure 4. Models for a side perpendicular collision between two similar vehicles, a frontal collision against a fixed object, and a rear collision between two similar vehicles, respectively.

It must be remembered that although the physical phenomena that happen in a traffic crash are extremely complex to be accurately described, the considered mathematical models will allow to predict the general behavior of the automobile, with an appropriate precision for this paper, to assess the reasons why it is alleged that near side crashes have higher serious injury and fatality risks as compared to all crashes. In this regard, it can be argued that the side external structure of a vehicle has an inferior capacity of absorbing kinetic energy than the frontal or rear external structures, and passengers are much closer to the point of impact. Therefore, in a lateral collision the vehicle structures intrude into the compartment more readily, more often and more severely than they do in frontal and rear crashes of equivalent kinetic energy.

A further analysis of this last statement can be done by completing the simplified models for each of the manners of collision that are being compared. To begin with, the lengths of the inelastic springs must be defined. The following figures will show the structures of the modeled vehicle that are destined to absorb the kinetic energy of road impacts, their estimate lengths, and their relative position in regards to the occupants compartment:

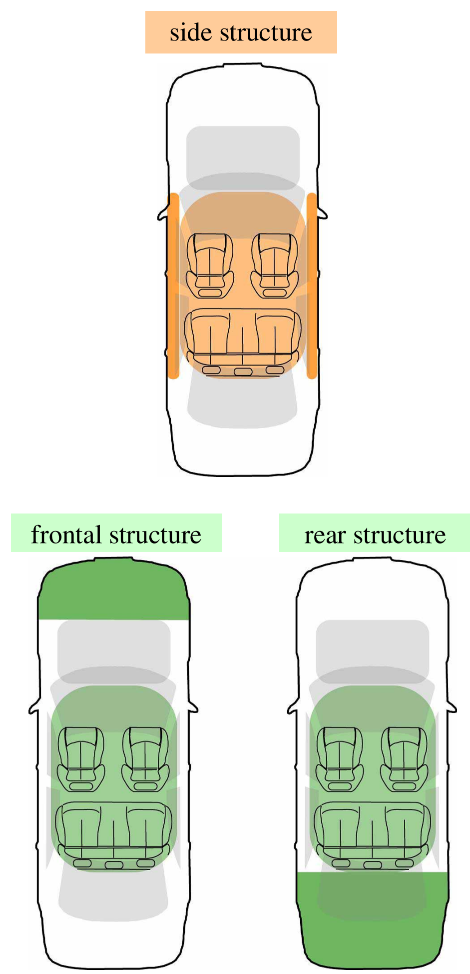


Figure 5. External structures of the modeled car which are destined to absorb the kinetic energy, their estimate length and their relative position to the occupants compartment.

This last figure allows a visual review of the mentioned issues regarding side safety, specially the one that states that passengers are much closer to the point of impact in the case of a side crash when compared to frontal or rear ones. Nevertheless, to complete the model so as to be able to evaluate the capacity of each external structure to absorb the original kinetic energy, the last characteristic of the inelastic springs must be considered: their stiffness coefficients. It is the intention of this paper to use approximate values, since there is a great difference between the various makes and models. Therefore, the numbers that are going to be used in the case of the frontal structure are based on the consulted bibliography (6, 7). As regards the rear and side structure, it is considered that they bear stiffness coefficients that are half the one of the frontal structure, since they lack in the frontal rails that provide an additional reinforcement to the structure. It is important to highlight that the estimated values should be considered only as a result of a series of theoretical and simplified assumptions, in order to perform some analysis that will help to understand better the issues discussed. Hence, taking into consideration both the recently named aspects and the length estimation derived from Figure 5, the values for the inelastic springs that are going to be used are the following:

Table 1.
Estimated characteristics of the inelastic springs of the lateral, frontal and rear structure of the modeled vehicle.

protection structure	spring length [m]	stiffness coefficient [N/m]
lateral	0,15	612.500
frontal	0,75	1.225.000
rear	1,10	612.500

Now that the models are complete, the amount of kinetic energy that each structure can absorb will be analyzed. Since the considered structures behave as mass-spring systems, the maximum kinetic energy that can be absorbed is going to be equal to the maximum potential energy that the springs can store:

$$E_p = \frac{1}{2} K.L^2$$

(E_p = potential energy; K = stiffness coefficient; L = length of spring)

Thus, using the values indicated in Table 1, the maximum kinetic energy that the modeled structures can absorb in an impact is:

- 345 kjoule for the frontal structure
- 371 kjoule for the rear structure
- 7 kjoule for the side structure

The following figure compares such results:

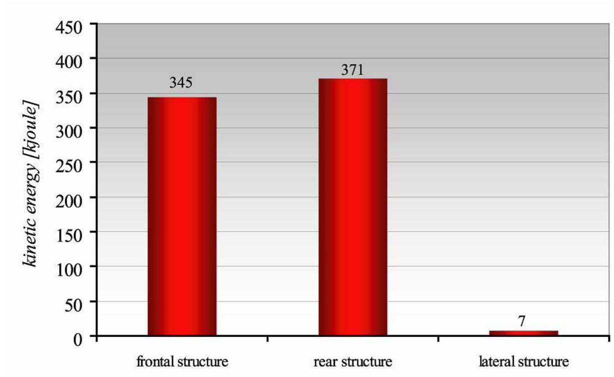


Figure 6. Maximum estimated capacity of absorption of the kinetic energy of an impact for the frontal, rear, and lateral structure of the modeled vehicle.

Once again it must be remembered that the shown values may not reflect the exact response of an actual automobile, and are only intended as rough, theoretical approximations to indicate the great differences in managing the kinetic energy of an impact for the various structures; a key issue that certainly defines whether a car occupant survives undamaged or not a road crash. When kinetic energy is not properly managed, extremely high acceleration phenomena can manifest, exposing automobilists to levels of accelerations that are beyond their biological tolerance. Even worse, when part of the original kinetic energy is not absorbed, it may lead to compartment intrusions and thus, to direct impacts to the motorists. Hence, deeming the aspects recently analyzed, it can be argued that the structural protection offered by modern vehicles as regards side impacts is far less efficient (given crashes of equivalent kinetic energy) than the one offered in frontal or rear impacts.

Moreover, it can be stated that these days automobiles are every time faster, heavier, and more powerful, most of them allowing stable driving at speeds that a few decades ago only sports cars permitted. Furthermore, circulation speeds are expected to be increased in most countries since:

- many drivers prefer to travel at very high speeds, exceeding by far the legal limits (apart from the fact that human beings have a serious fascination for speed, the dangers related to high speed circulation are not completely understood; in this context some people even argue that it is safer to circulate at high speeds because some advantages are enjoyed –e.g.: it takes less time to ar-

rive to destination, so drivers are less exposed to traffic dangers–)
- both the drivers and the system have proven to be unable to maintain the circulation speeds below legal limits.

As a result, automobiles structures are constrained to manage every time higher levels of kinetic energy, that is to say, to efficiently respond to situations that bear every time higher "injury potential".

To conclude, this paper does not propose a milestone technological innovation nor it states that the actions taken so far in the field of side impact safety have been incorrectly directed. Instead, it provides an additional general review to the feasible innovations (consisting mainly either in improvements or in the reengineering of existing devices) that can lead to a more efficient protection in the case of a side road crash. It is also its intention to encourage everyone who is or will be dedicating great amounts of efforts to diminish the burden of traffic crashes –and who believes that the best way to do so is by a general and synergistic approach– indicating some innovations that, developed thoroughly within the corresponding settings and using the appropriate resources, may provide the conditions where the human body is capable of undergoing a side road crash without serious or fatal injuries.

PHYSIOLOGICAL PREMISES

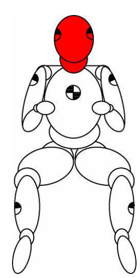
"Intrusion is either a major or contributing cause to most near side collision injuries" (Hyde – Crash injuries– how and why they happen).

The incredible and enormous biodiversity of the human beings is of such extent that the experts have not been able yet neither to understand completely how injuries happen nor to determine with precision the biological tolerance to direct impacts and acceleration phenomena. In the preface to the "Handbook of human tolerance" of the Japan Automobile Research Institute (1976) one of its authors pointed out that the current state of the field of biomechanics of trauma can be compared to the state of the celestial mechanics before Kepler: it is composed of a multitude of measurements and experimental data that lacks in unifying theories that would be able to predict the outcome of a new situation. In this way, the alleged tolerances of the human body are based almost exclusively on empiric results, or are elaborated from tests using dummies or other mechanical devices which do not represent accurately the response that a human body would show to the given situation. In the better of cases, they do represent it only for a certain percentage of the population (7). Therefore, what follows is only an overview to the topic, aimed at making a general approach to some relevant aspects for the upcoming discussions. As said before, kinetic energy management is vital. Residual kinetic energy may provoke violent acceleration phenomena or severe intrusions that can inflict direct impacts to the automobilists. Hence, considering that the mechanics of a road crash necessarily imply the combination of changes of speed and deformations, some basic assumptions must be made so as to define the lesser evil. So, the questions to answer are, among others:

- is it preferable to exert high levels of acceleration upon an automobilist without exposing him to direct impacts? Or is it the other way around?
- are side-to-side movements of the neck more dangerous than rear-forward ones?
- can a direct impact on one part of the body affect vital organs situated away from the point of impact?

These and other vital questions are not herein responded thoroughly, since the intention of this paper is to analyze some aspects of road crashes considering the available information as a general guide. Yet, some assumptions are made in order to deduce the bases about safety in side impacts. These assumptions must be confirmed by the corresponding experts using the appropriate resources. To begin with, the injury mechanisms are concisely described as follows (7).

Head, neck and spine injury mechanisms



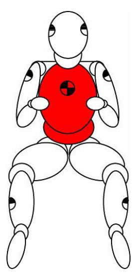
Injuries in these vital organs are devastating, and generally lead either to the automobilist's death or to various forms of permanent physical impairment.

Direct impacts in the head can severely affect the brain and most of the sensory organs located within it. It is both probable and frequent to observe brain harm without any cranium fracture, since the relative movement between the rugose base of the cranium and the brain can torn blood vessels and nerves entering and exiting the head, causing cognitive and behavior deficiencies as well as memory disorders. Regarding sensory organs, smell, taste, sight, sound and balance can be affected by direct and indirect impacts (even minor ones) to the cranial nerves or to the organs situated in the head.

Compression forces in the neck can provoke fractures in the first vertebrae of the vertebral column damaging the arteries that circulate through them. This damage seriously compromises the blood supply to the brain; besides, tears of the vertebral arteries are often fatal. Tension forces caused by hyperflexion or hyperextension (namely when whiplash, or severe flexion of the neck take place) generate cervical sprains with the potential to provoke fatal injuries, or functional disabilities which may arise years after the crash took place.

Finally, direct impacts can also damage the spinal cord severely; furthermore, this type of injury cannot be treated medically, as no therapy results in recovery. Crash injuries involving the spinal vertebrae are often violent events in which the flexed spinal column is additionally subjected to coupled forces of rotation and lateral bending. Damage to the lower section of the spinal cord may derive in paraplegia or serious urinal and sexual problems. Injuries above the lumbar region add breathing disorders to the mentioned consequences. Lastly, injuries in the higher section of the spinal cord frequently derive in quadriplegia, with a total loss of many essential body functions.

Abdomen and chest injury mechanisms

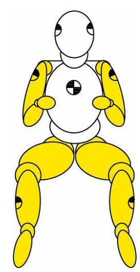


Injuries in these vital organs are also devastating.

Injuries in the abdomen are caused when suffering a direct impact, with the aggravating circumstance that as it is an incompressible hydraulic cavity, a blow in a sector of the abdomen can generate a serious damage in another place, away from the impact point. As regards the organs that can be affected by a direct impact in the abdomen, the peritoneal cavity gathers many vital organs and glands such as the liver, the spleen and the pancreas; except for the mouth and esophagus, the entire digestive tract is contained within the peritoneal cavity or is partially covered by peritoneal membranes; also, the abdominal aorta and vena cava are located on the posterior wall of this cavity. Most of these organs are soft and crumbly, and a great quantity of blood circulates through them (specially through the liver), so their damage often results in losing the organ or in catastrophic bleeding.

In the case of the chest, most of the organs residing within it –as the heart and the lungs–, or transiting it –as the esophagus, and, again, the aorta and the cava– are vital, so any damage to them has the potential to generate very serious or fatal injuries. It is worth mentioning that injuries to this body region may be fatal in the short-term, but they bear no consequences in the long-term (precisely the contrary to what happens with the extremities, as it will be discussed). Damage to the chest can provoke either respiratory or circulatory complications. As regards the first ones, direct impacts may injure the intrapleural membrane, affecting air movement into the lungs, and resulting in death if not treated immediately. Moreover, any injury that affects the capacity of the diaphragm to contract or that damages lung tissue may lower the quantity of oxygen in blood (as a result of deficient respiration) affecting other organs that are sensitive to oxygen insufficiency. Brain tissue is specially sensitive to this kind of insufficiency, so concurrent lung injuries directly and adversely affect brain injuries. As regards the circulatory complications caused by direct impacts, they are also extremely harmful. There are estimations that state that only 30% of the victims of injuries to the heart or main blood vessels survive long enough to be able to receive medical attention.

Lower and upper extremities injury mechanisms



Injuries in the extremities (arms and legs) may be seldom the cause of death in a road crash, but they are surely a major –if not the main– cause of permanent physical impairment. Injuries in these organs are generally a consequence of direct impacts, and while they do not involve particularly risky situations, it has to be taken into account that the movement of fractured bone fragments generates serious damages to the muscular tissues and massive internal hemorrhages that, unless treated expeditiously, can provoke severe injuries.

It is worth mentioning that the extremities are not restrained in any case, and that even in the event of crashes at moderate speeds they are liable to strike the interior surfaces of the vehicle. Moreover, the upper extremities can also strike the body of the other occupants of the car, exposing the latter to potential damage –specially in the head–.

Impact and acceleration resistance

First of all it can be highlighted that in a road crash there is commonly a combination of direct impact and acceleration phenomena. Most body organs are viscous and gelatinous, so direct impacts generate relative movements and consequent deceleration processes. On the other hand, restrain devices apply a certain amount of force in localized parts of the body, as in the case of the thin strip of the seatbelt fastening the chest. These restrain actions combine a deceleration process with a determined degree of pressure that, depending on the severity of the road crash, can lead to direct impacts. Hence, the question whether it is preferable to exert high levels of acceleration upon an automobilist without exposing him to direct impacts, hides a tricky issue, for the reasons recently explained. In this regard, it can be argued that direct impacts in most regions of the human body seriously compromise vital organs, and bear the potential to inflict very serious and fatal injuries. The parts of the human body that should be particularly protected from direct impacts are: the head; the neck and spinal cord; the chest; the abdomen.

On the other hand, empirical evidence demonstrates that human beings can be exposed to high levels of accelerations with a resistance that diminishes as the time of exposure to it increases, and that there are senses and directions more favorable than others. In other words, it is possible to survive without serious damage from extremely high levels of accelerations given that: firstly, the time of exposure remains below extremely short periods of time; secondly, the direction of the movement is transverse to the body, and in the sense of pushing the person backwards; and thirdly (and the least common of all), the process is not combined with direct impacts. The following figure shows the direction and senses that may damage seriously a human being that is being accelerated, and that coincide with frontal and lateral impact movements (7):

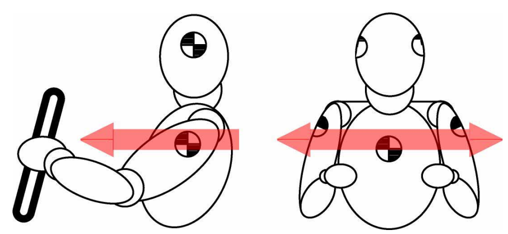


Figure 7. Most dangerous directions and senses for acceleration processes.

Furthermore, it can be stated that when it comes to acceleration resistance, a sudden acceleration of the head can lead to hyperflexion or hyperextension of the neck, and that the most harmful movements are the following (7):

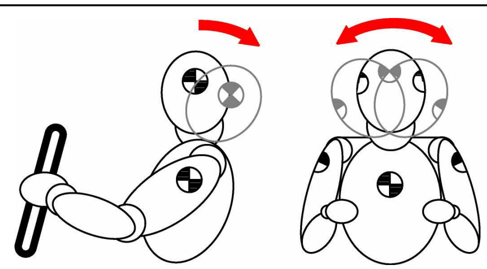


Figure 8. Most dangerous directions and senses for acceleration of the head processes.

To conclude, as far as this paper is concerned, the following figure summarizes the conclusions extracted from the concepts mentioned above (instantaneous changes of speed, which were not previously mentioned, are considered as phenomena that involve extremely high levels of acceleration over a period of time that tends to zero, are associated with elastic-type crashes, and are deemed to be more dangerous than normal deceleration processes):

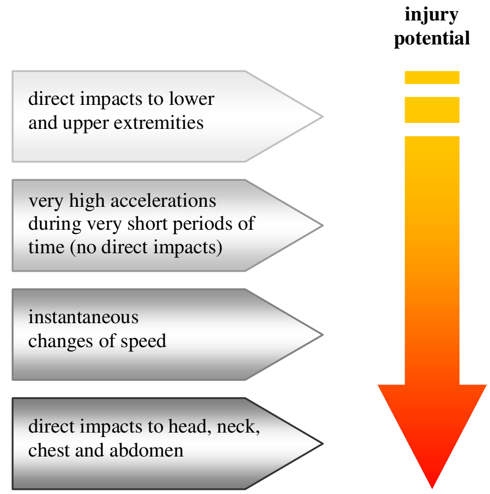


Figure 9. Alleged risk factors according to their injury potential when considering a road crash.

EXAMPLE BOX 2

***Case story of a crash involving harmful direct impacts without significant variation of speed** (8)*

In June 1993, a driver was struck by another car, thus losing control and hitting the guardrail. As this happened, the right side of the car rode up onto the guardrail, stayed on it some 12-24 meters, and then fell back to the ground, coming to rest in the emergency lane. During the incident, the rear occupant, a 31-year old female, flexed forward and to her right, and sustained head contact against the front seat. The Δv of the frontal impact was estimated at between 8 km/h and 16 km/h, and the vertical acceleration at between 10 g and 20 g. As a result of the impact, the female rear occupant sustained an L1 (lumbar vertebrae) fracture with anterior wedging, resulting in paraplegia.

BASES OF IMPACT SAFETY IN SIDE ROAD CRASHES

"In the new paradigm, the principle of social responsibility involves the vehicle manufacturer providing crash protection inside and outside the vehicle". (World Health Organization – World report on road traffic injury prevention).

Based on the previously analyzed aspects it can be concluded that there are high probabilities of surviving a road crash without serious damage as long as:

- no direct impacts are received in any part of the body.
- no high accelerations are undergone during relatively long periods of time.

Modern vehicles are provided with an array of safety devices that aim at assuring the above conditions. These devices can be segmented into three groups, according to their moment of acting within the sequence of the traffic impact event:

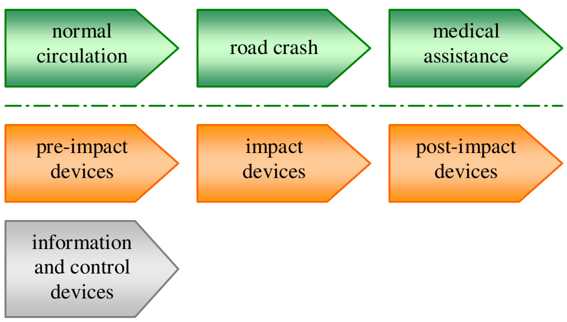


Figure 10. Segmentation of safety devices according to their moment of acting within the sequence of the traffic impact event.

The next important aspects to point out about the bases of impact safety in side road crashes are:

– firstly, it is well known that pedestrian protection is not a minor issue. Once again it has to be remembered that 90% of road fatalities take place in low-income or medium-income countries, the vast majority of the victims being pedestrians, cyclists or motorcyclists. However, it can be argued that the most frequent initial point of impact for these crashes is the frontal sector of the vehicle, an aspect of road safety that is not being discussed in this paper. Therefore, considering that few collisions against pedestrian involve the side section of the motor vehicle –e.g.: 4% of pedestrian deaths in the United States are due to crashes where the side of the vehicle is the initial point of impact (2)–, everything that is going to be stated in this paper refers to the protection of the occupants of a motor vehicle.
– secondly, the vast majority of road impacts involve automobiles and light-trucks (including SUVs) –e.g.: 94% of all types of crashes and 82% of fatal crashes in the United States involve either automobiles or light trucks (2)–. So, the bases herein discussed refer to the named types of vehicles. Yet, most of the aspects analyzed can be applied not only to such types of vehicles, but also to others as large trucks or buses, with the exception of motorcycles, since this type of motor vehicle lacks the minimum protection that is needed to overcome unharmed any kind of traffic crash, as it is often confirmed by the fatalities statistics.
– lastly, information devices (xenon cornering lamps, high-mounted stop lamps, tyre-pressure monitoring, etc.) and control devices (anti-lock braking systems, electronic stability management, etc.) are considered to perform their functions adequately; additionally, they are related to the prevention of a road crash. Consequently, the feasible innovations regarding these devices are not discussed here.

Deeming these aspects, what follows is a general review of the main functions that safety devices should perform before, during and after a traffic impact, in order to enhance the probabilities of surviving undamaged from a traffic impact as regards the occupants of either automobiles or light-trucks.

To begin with, it can be argued that in a traffic accident a little more than a second is the time that mediates between the instant of the first impact and the complete stop of the vehicle (depending on the initial speed, mass of the automobile and stiffness coefficient, among others). In several NCAP frontal-impact tests it can be observed that the driver's head impacts the airbag after around 1/10th of a second, indicating that the period of time available for safety countermeasures is infinitesimal. In this context, every action aiming at increasing the protection offered to automobilists which can be performed before the actual accident happens will bring great benefits. Therefore, the function proposed for the pre-impact devices are the following:

– control the perfect operation and use of the safety devices, and perform the necessary actions to assure both of them.
– pick up and process the necessary information so that the safety devices can act during the impact.
– establish the "injury potential" (mainly through the circulation speed) and adjust the configuration of the vehicle according to each circumstance.

The mentioned actions, all of which can be performed while the vehicle is circulating normally, will allow a better performance for the safety devices. As an example of the advantages of the first function, the assurance of the use of the seatbelt by every motorist can be named, since this action will not only protect the restricted occupant but also the other occupants, as an unbelted person may hit others in the vehicle, possibly damaging them in a serious way. This control should lead both to "informative" actions (as most modern vehicles perform) as well as direct actions such as the elimination of the possibility of circulation if any of the occupants of the vehicle does not have his seatbelt buckled up. In the second proposed function, the efficiency of the safety devices will be incremented, since elements such as the airbag, the pre-tensioner or the load-limiter will be able to adapt their response according to the occupant's weight, size, and impact speed and direction. These named physical phenomena and their values must be measured and stored during normal circulation, and be ready to be used as inputs in the event of a road crash. Lastly, the third function proposed allows changes in some of the settings of particular devices while speed increases. In this way, for instance, the pre-tensioner of the seatbelt can begin to exert a certain amount of pressure as the vehicle travels faster, anticipating the necessary actions in case of a road crash (which will be thus less violent) and also letting the driver know that he is stepping into a more dangerous level of "injury potential".

On the other hand, the functions that impact safety devices should perform are simply defined by the aspects briefly discussed in the last section (avoid both direct impacts and dangerous accelerations):

- maintain the structural integrity of the occupants' vital volume, assuring enough survival space to avoid any direct impacts.
- avoid the penetration of objects to the occupants' vital volume.
- absorb the whole kinetic energy both of the vehicle and of the occupants (to avoid elastic-type crashes or instantaneous changes of speed), maintaining the deceleration within safe levels.
- avoid any contact with the potentially dangerous surfaces of the interior of the vehicle.

Finally, it must be highlighted that after the road impact takes place, it is vitally important to provide medical assistance to the victims as soon as possible. There are some modern vehicles that are equipped with a combination of GPS and mobile communication devices, supported by a 24-hour emergency center that when an impact is detected is capable of assisting the occupants and alerting the emergency medical service, giving them the precise position of the vehicle. Yet, it is very important that while the emergency medical service gets to the road crash site the occupants be protected from fire, noxious gases or other impact-related dangerous phenomena. It is worth mentioning that fire occurrence is not frequent in a road crash, but when it does occur it represents a very dangerous phenomenon –fire occurrence crashes bear 0,1% of total road crashes in the United States whereas they represent 2,8% of fatal crashes (2)–. Finally, it is also particularly important to assure that the emergency medical service is able to assist the victims without losing precious time in extracting the occupants from the deformed vehicle (it can be stated that in many high-speed road crashes the external structure and the compartment deform in such a way that occupants can be extracted only with the use of specific cutting machines, a kind of action that can last even hours). Therefore, the following functions proposed for post-impact devices complete the bases for side impact safety:

- warn the nearest medical care services.
- protect the occupants in case of a fire taking place, from noxious gases or other impact-related dangerous phenomena.
- allow the quick extraction of the victims to be assisted.

To conclude, it is important to point out that the bases of side safety recently stated can be extended to frontal and rear impact, given their general approach to the mechanisms of injury, human tolerance aspects, and the ways to overcome the potential dangers involved in a side road crash.

ANALYSIS OF THE PROTECTION OFFERED BY CURRENT SIDE SAFETY DEVICES

In the last section the bases of side impact safety have been established and segmented into the ones pre-impact, impact, and post-impact devices should perform. In this section, the stated functions will be assigned to the vehicle functional groups, so as to facilitate the identification of the feasible innovation as regards each component. The groups considered are: automation devices; compartment and interior structure; external structure; restrain devices.

Thus, the analysis of the protection offered by current safety devices will be compared to the functions they should perform, grouped in the indicated way.

Automation devices analysis

This includes all of the electronically based equipment, including sensors, communication devices, and the corresponding software and hardware. The bases of side impact safety that apply for this group include the following:

Table 2.
Summary of main functions of the side safety devices grouped in the automation devices.

traffic impact sequence	function
normal circulation	– control the perfect operation and use of the safety devices, and perform the necessary actions to assure both of them. – pick up and process the necessary information so that the safety devices can act during the impact.
road crash	– (none)
medical assistance	– warn the nearest medical care services.

As regards this functional group, the next improvement opportunities can be highlighted:

- most modern vehicles indicate when seatbelts are not buckled up, but no direct action is performed if the vehicle is moving with a non-restrained passenger. Given the danger associated with this situation, and from a strictly safety point of view, circulation should be permitted only if every occupant is correctly buckled up.
- modern technology allows to measure the position of the head, shoulders, and other parts of the body, and their relative location regarding relevant elements, such as the headrest, to assure that the safest position is set. Modern technology also allows to modify the interior of the vehicle (namely the seats and seatbelt anchorages heights) if the conditions are not the fittest.
- most safety devices (such as the pre-tensioner, the load limiter or the airbags) act according to default parameters, disregarding the vital real information that would greatly foster their efficiency.
- the majority of modern vehicles lack the already developed technology that automatically warns the nearest emergency medical service, and provides the exact location of the vehicle.

Compartment and interior structure analysis

This segment groups all of the components immediately surrounding the occupants, such as the passenger cell, side door beams, A and B pillars, etc. Therefore, the bases regarding them are:

Table 3.
Summary of main functions of the side safety devices grouped in the compartment and interior structure.

traffic impact sequence	function
normal circulation	– adjust the configuration of the compartment and interior structure according to the defined "injury potential".
road crash	– maintain the structural integrity of the occupants' vital volume, assuring enough survival space to avoid any direct impacts. – avoid the penetration of objects to the occupants' vital volume. – avoid any contact with the potentially dangerous surfaces of the interior of the vehicle.
medical assistance	– protect the occupants in case of a fire taking place, from noxious gases or other impact-related dangerous phenomena. – allow the quick extraction of the victims to be assisted.

The next improvement concerning the compartment and interior structure can be pointed out:

- no modification of the circulation condition takes place as speed increments. An example of this can be considered: as the vehicle gains speed all the seats should adjust themselves to the most favorable position regarding impact safety.
- impact tests and empirical evidence show that the passenger cell suffers relevant deformation, even at arguably low-speed crashes, leading to direct impacts to the occupants. On top of that, the compartment is frequently unable to prevent the penetration of external objects through the door panels or, specially, through the fragile side windows.
- the A and B pillars offer hard and thus potentially harming surfaces, as the roof does (it is worth mentioning that use of glass roofs lacking shock absorbing materials is more and more common every time). In real-world side crashes all of the named interior elements can be hit by the occupants as a result of a combination of rotation movements following the impact.
- there is no safety device prepared to prevent a fire from extending into the occupants' survival space. What is worse, most of the interior surfaces are capable of easily catching fire while at the same time they offer relevant resistance to extinguishing actions.
- compartment deformation generally affects seriously the possibility of extracting rapidly the passengers in a negative way, reducing their probability of survival.

External structure analysis

This analysis is directed towards the crushable zones of the vehicle that receive the direct impact of the road crash, and which safety bases are stated as:

Table 4.
Summary of main functions of the side safety devices grouped in the external structure.

traffic impact sequence	function
normal circulation	– adjust the configuration of the exterior structure according to the defined "injury potential".
road crash	– absorb the whole kinetic energy of the vehicle, maintaining the deceleration within safe levels.
medical assistance	– allow the quick extraction of the victims to be assisted.

In this case the improvement opportunities are the following:

- no modification of the circulation condition takes place as “injury potential” is altered. An example of this may be the modification of the stiffness coefficient with the real mass of the vehicle. It must be remembered that the NHTSA states that frontal crash test results can only be compared to other vehicles whose weight is plus or minus 115 kg. Thus, it can be argued that in a side crash against a fixed object a vehicle transporting only the driver behaves in a different way than when transporting five passengers and baggage.
- as analyzed in the introduction, the side external structure is capable of absorbing an extremely low amount of kinetic energy, allowing the remnant energy to deform the passengers’ compartment dangerously. Additionally, it can be argued that at high-speed impacts, and after a great amount of compartment intrusion takes place, the increased rigidity of the cockpit will probably generate an elastic-type collision, leading to extremely high and dangerous acceleration phenomena.
- for the same reasons stated above, significant structure and compartment deformation make the extraction of the injured occupants utterly difficult.

EXAMPLE BOX 3

Two examples of relevant compartment intrusion in side crashes leading to direct impacts to occupants

The following photograph shows the extent of lateral compartment intrusion sustained by a small car when it is hit on its side. It is worth pointing out that the striking vehicle bears only minor deformation of the frontal structure:

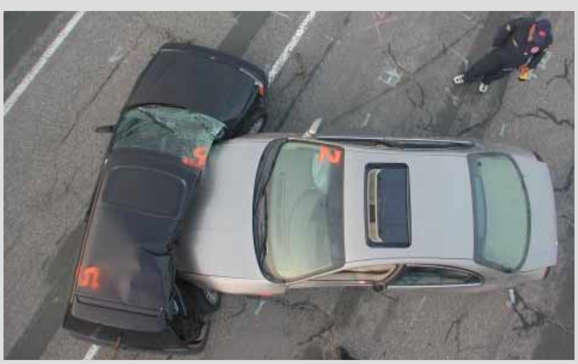


Figure 11. Compartment intrusion in a car-to-car side impact.

Source: reference 9

Similarly, the next picture of a pole test conducted by the European New Car Assessment Program shows a considerable amount of lateral intrusion in an impact at 50 km/h, with the pole entering the compartment and occupying most of the driver’s original position, throwing him towards the other occupant who will be moving in the opposite sense:

Figure 12. Compartment intrusion in a pole side impact test for a 5-star rated automobile (Renault Velsatis).

Source: reference 10

Restrain devices analysis

The group of restrain devices includes the seatbelts and the airbags (considered as SRS – Supplementary Restraint System– devices) and are related to the following safety bases:

**Table 5.
Summary of main functions of the side safety devices grouped in the restrain devices.**

traffic impact sequence	function
normal circulation	– adjust the configuration of the restrain devices according to the defined “injury potential”.
road crash	– absorb the whole kinetic energy of the occupants, maintaining the deceleration within safe levels. – avoid any contact with the potentially dangerous surfaces of the interior of the vehicle.
medical assistance	– allow the quick extraction of the victims to be assisted.

Considering these devices, the relevant improvement opportunities are:

- no modification of the circulation condition takes place as the vehicle gains speed. An example of this was already mentioned (an in-

crease of the pressure of the pre-tensioner as speed increments should lead to less violent actions in case the crash happens).
- three-point seatbelts are designed to act efficiently in full-lap frontal impacts. Yet, in side crashes, the far-side occupant is launched towards the near-side occupant, since the three-point seatbelt is unable to prevent this movement. On the other hand, compartment intrusion may cause the near-side occupant to be pushed towards the far-side occupant (who is moving in the opposite direction).
- there is no restrain for the relative movement between the head and the body (a kind of action that can be extremely harmful as explained before). On top of that, the head which is highly susceptible to direct impacts may hit dangerous interior surfaces such as A or B pillars. An available safety device that suits this purpose is the H.A.N.S. (Head and Neck Support System) device used in motor racing, but which permanent use will surely be considered a major nuisance.
- there is no restrain for the extremities. As mentioned before, unrestrained arms have the capacity of striking and damaging seriously the other occupants of the vehicle.
- every action performed by the restrain devices will be more efficient if their response could vary according to the real parameters previously measured and processed, a kind of characteristic that most restrain devices are not provided with.
- once the crash is over, a device that permits the disengagement of all restraint devices (even form the outside of the vehicle) would be of great help to quickly extract the occupants, considering that some of them could be unconscious and unable to liberate their seatbelts.

Section conclusion

To conclude, all of the improvement opportunities mentioned above should improve the protection offered by current side safety devices, yet they must be further analyzed thoroughly within the corresponding settings and using the appropriate resources. But if it is assumed that these improvements are possible to be introduced in modern vehicle from the technical, industrial and financial points of view, they may lead to the following feasible innovations.

FEASIBLE INNOVATIONS FOR SIDE ROAD CRASHES

The automobile revolution started more than a hundred years ago. Until these days, it has redesigned itself hundreds of times, and it has redesigned along its phenomenal development the way in which the world looks, and the lives of the people that live there. Regarding this paper, hundreds of thousand technicians, engineers and experts struggled over those years to develop literally millions of devices that assure the generation of the necessary power, the efficient movement and control, the adequate resistance to transport both the occupants and their loads, and the suitable reliability and a contained operation cost, among many other necessities. So it can be argued that most of the feasible technical solutions involving automobiles have been already introduced or discarded.

Yet, periodically, some ideas (probably discarded in less favorable conditions) arise and consolidate as valid new options. As a recent example, in the 2005 Detroit Auto Show Honda surprised everyone by introducing the new Ridgeline pick-up bearing a lockable, weather-tight space under the rear cargo floor, a simple device no other pick-up showed in their 80-years history. Therefore, the innovations that will be next introduced are intended to act as a starting point for a thorough analysis of their feasibility, considering that they have been studied in a general and synergistic way, considering that they consist mainly on improvements of already existent devices or on the reengineering of them, and considering that they have been conceived under the precept that rather than making a successful automobile safe it is highly preferable to transform a safe vehicle into a successful one.

Innovations in the compartment and interior structure

As for the innovations in the compartment of the automobile, the following are proposed:
- the elimination of the possibility of sliding down the side windows, while the car is moving.
- a rigid cockpit capable of maintaining its shape in high-speed impacts (using materials and a body framework with more mechanical stiffness, including a more resistant shape as the ellipsoid one).
- an increase in the resistance to impacts of the side windows while keeping approximately the actual mass (e.g.: glass laminated with polycarbonate).
- the establishment of a protection barrier against a fire produced at the exterior of the compartment that could endanger the occupants.
- the provision of a breathable atmosphere inside the compartment until the moment of the rescue of the victims of the crash.
- the provision of different options for the occupants' extraction, not only including the doors but also all the glass surfaces that should slip inside the rigid compartment, with a mechanism

able to be activated either from the interior or the exterior of the vehicle.

Innovations in the external structure

The feasible innovations in the external structure are:

- the increase of the length of the side sectors of the car, leading to higher levels of kinetic energy that can be absorbed .

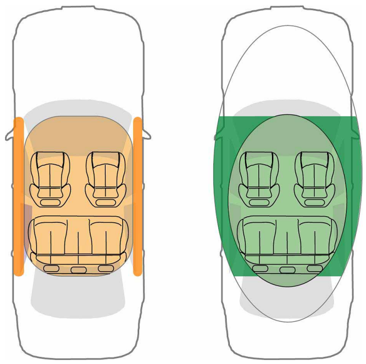


Figure 13. Comparison between current length of external structure (left) and a structure with increased length (right). The latter is also combined with an ellipsoid compartment .

- the establishment of areas with different stiffness coefficients according to the length of the structure, the mass of the vehicle, and the maximum probable impact speed.
- the multiplication of the areas with different stiffness coefficients as to improve the continuity of the structure.
- a homogeneous behavior of the collapsible area (and therefore the lack of mechanical elements or external objects such as baggage).
- the variation of the stiffness coefficient according to the variation of the mass of the vehicle.

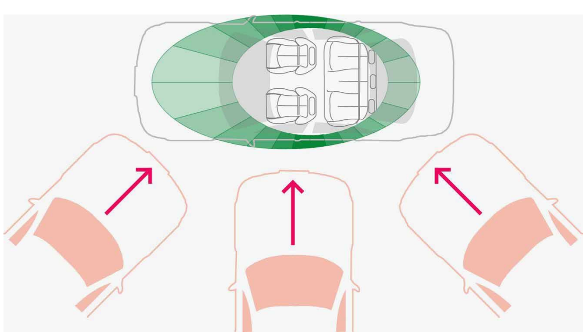


Figure 14. An external structure bearing multiple areas of different stiffness coefficients, and a homogeneous behavior of the collapsible area will absorb kinetic energy more efficiently.

Innovations in the restrain devices

As regards the innovations in the restrain devices the improvements consist of:

- the adaptation of the interior of the automobile in order to offer the occupant the safest position.
- the progressive increase of the seat belt tension along with greater speeds.
- the provision of four-point seat belts for all the occupants.
- the improvement of the pre-tensioner and of the load limiter so that they can act according to the parameters measured previously or during the accident.
- the provision of an inflatable device similar to the H.A.N.S. adjoined to the seatbelt that acts only in the case of an accident.

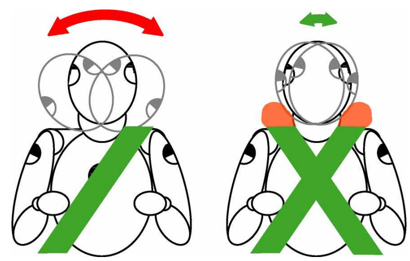


Figure 15. Current safety devices do not prevent dangerous lateral movements of the head (left) which could be minimized by the combination of a four-point seatbelt and an inflatable device similar to the H.A.N.S that acts only in the case of an accident (right).

- the provision of a restraint device for the extremities (arms and legs).
- the development of central and external disengagement mechanisms for the restraint devices that should be operative immediately after the road crash.

Innovations in the interior structure

The following innovations in the interior structure of the automobile are proposed:

- the provision of electromagnetic mechanisms which should be completely collapsible and able to move away from the occupants in the crash (as an example, the possibility of forwarding the steering-wheel will eliminate the possibility of the head impacting it, and make the driver airbag unnecessary).
- a larger space between the occupants and the potentially dangerous objects.

Figure 16. The Hy-wire concept car by General Motors proposes an interior structure that bears a large space between the occupants and the potentially dangerous objects by using electromagnetic mechanisms.

Source: reference 11

- the provision of lateral airbags in the windows (with a somehow different function from the current one, since they should cover the whole surface in the minimum possible time to avoid direct impacts).
- an important increase of the capacity to offer soft surfaces where there are potential points of contact (including the roof).
- the elimination of all combustible materials of the interior of the vehicle.

Integral design

Finally, when thinking about an integral design the way to satisfy the driver's basic necessities can be analyzed as a whole, among which impact safety and protection of the environment should occupy a preponderant place, adding the following ones to the previous innovations:

- the measurement of all the parameters for the correct performance of the safety devices; the elimination of the possibility of circulation if any safety device does not work properly, it is misused or not used at all (e.g.: any of the occupants of the vehicle does not have his seatbelt buckled up); and the warning to the nearest medical care services indicating the exact location of the crashed vehicle.
- the generation of power and its transmission by means of four electric engines, one in each wheel (reducing the volume destined to the engine and transmission and allowing larger spaces destined to the absorption of kinetic energy while maintaining the current overall dimensions).
- the placing of the energy source under the cockpit (this generates both a lower center of mass and no increase in length or width).
- the increment of the wheels' diameter (this provides the vehicle with a smaller tendency to overturn and it allows to increase the height of the center of mass without affecting the stability).
- speed management through a mandatory intelligent speed adaptation system, which integrates GPS arrays, road and speed limits digital databases, and in-vehicle currently available hardware and software (namely on-board computer, speed limiter, and cruise control) that will help to reduce circulation speeds to comply with the legal limits, or even better, to remain within safe limits.

Section conclusion

To conclude, it has to be pointed out that the intention of this paper is to present the feasible innovations, without being thoroughly described, as a compendium of integrated ideas that should be analyzed from a technological, industrial, and economical point of view in order to determine whether they can be introduced in modern vehicles or not. As mentioned before, this work has been done with the idea that rather than making a successful automobile safe it is highly preferable to transform a safe vehicle into a successful one, and bearing in mind that safer cars will produce lower quantities of road victims, and will probably bring higher profits to the carmaker that is able to successfully sell the feasible innovations.

SELLING SAFETY INNOVATIONS

"The world's first automobile to be built with the safety of the occupants as the sole design objective was unveiled in New York by Liberty Mutual Insurance Company and Cornell Aeronautical Laboratory Inc. who designed and built the car in a joint undertaking". (The safest car in the world – Safety maintenance and Best's insurance news – 1959).

Selling safety innovations has always been a very sensitive issue. Even nowadays, when there is greater awareness of the benefits of having and using as many safety devices as possible, some people refuse to use their seatbelts, which have proven to be one of the most useful safety devices ever introduced in automobiles. Furthermore, many among the "rebels" show neither oblivion nor lack of awareness in their behavior; instead, they show resentfulness. They feel that using seatbelts is an annoying imposition conceived to make their lives miserable, stealing them away the pleasure of driving their automobiles freely, a sensation strongly associated with the ideas of freedom, individuality and prosperity. So they simply and rationally refuse to buckle up. This gives a hint about the reason why 4-point seatbelts (which have demonstrated to offer a more efficient protection than 3-point seatbelts, but which are less comfortable) are not offered even as an optional in current automobiles. Another example that shows how unpopular road safety is can be found in every Motor Show around the world where all kinds of new technical solutions burble in dozens of concept cars whereas the last concept vehicle designed with the safety of the occupants as the sole design objective is the Volvo SCC that dates far back to 2001.

To conclude this very concise discussion about the selling of the safety innovations, it can be stated that it is a very difficult target to achieve (even considering the mentioned present greater awareness and the great economic and social benefits that safer cars would imply), and that automobile history demonstrates that safety innovations have not had a great success, unless they have been introduced in the high-volume automobiles, particularly those more prestigious, so that the innovations are perceived as an added value not as a pernicious imposition, dragging in this way the consumer to desire the most sophisticated devices available.

CONCLUSIONS

"The uncertainty of human behavior in a complex traffic environment means that it is unrealistic to expect that all crashes can be prevented". (World Health Organization – World report on road traffic injury prevention).

Side impacts kill. So do frontal impacts, rear impacts, rollovers and other manners of traffic collision which as a whole generate more than a million deaths every year. Yet, road crashes and their consequences result from an extremely complex combination of aspects involving government, industry and individual users, thus any effective response will necessarily require a large mobilization of effort by all those concerned at the international, national, and local levels. The wider and more synergistic approach to the global challenge of reducing traffic casualties, the more effective the results and the faster the benefits. Similarly, great advantages should be found when a safe automobile design is thought as a whole and every aspect is deemed in a general and synergistic way. On the other hand, when only partial improvements are added, better safety than current one would also be achieved, although this would happen over a longer period of time, and would probably be less efficient.

This paper proposed a general and synergistic approach, analyzing firstly and briefly the mechanisms of injury and biological resistance, after what it was concluded that direct impacts should be avoided at most parts of the body, specially at the head, neck and spinal cord, chest, and abdomen; and it was also concluded that high levels of acceleration can be safely undergone, provided that they are exerted over extremely short periods of time, that they coincide with favorable directions and senses, and that they are not combined with direct impacts phenomena. Secondly, the bases of side safety were established, aiming at avoiding direct impacts and harmful accelerations, but also at setting the fittest conditions before the crash, and at allowing fast and efficient medical attention after it. Thirdly, the improvement opportunities of current safety devices were studied, and this lead to a series of feasible innovations, aiming at enhancing the protection that an automobile offers to their occupants in case of a side crash, and that should be further analyzed within the corresponding settings and using the appropriate resources. Yet, most of the aspects discussed can be easily translated to other types of road crashes. Lastly, some comments about the ways in which the feasible safety innovations should be marketed were argued, considering that selling this type of devices has always been a very difficult and sensitive issue.

To conclude, everything herein stated is intended to provide several starting points for future developments, based either on improvements of available safety devices or on their reengineering; to highlight those starting points as the conclusion of a general and synergistic analysis; to encourage the people working to protect automobile passengers sustaining a side impact every time in a more efficient way; to help assuring that side impacts stop killing.

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SIDE IMPACTS AND IMPROVED OCCUPANT PROTECTION

Chris Coxon

Department of Transport & Urban Planning, South Australia

Michael Paine

Vehicle Design & Research

Jack Haley

NRMA Motoring and Services,

Australia

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ABSTRACT

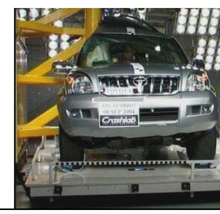
New Car Assessment Programs (NCAP) in Australia, Europe, Japan and the USA are giving increasing attention to the protection of vehicle occupants in side impact crashes. We review the range of crash tests that are available or are under development for assessing side impact protection, together with the types of vehicle that exists in each market. Real world crashes in the region are reviewed to determine the suitability or influence of existing occupant protection features in reducing injury. The potential benefits of the Australian NCAP consumer crash test program are presented to publicly demonstrate improved side impact protection in reducing injury.

The results of recent pole crash tests conducted by the ANCAP are described in terms of a new strategy for improving side occupant protection.

INTRODUCTION

Real world data shows that many occupant injuries could be avoided with improved side impact protection measures. Recent NCAP test results show that, in most modern vehicles, occupants are protected reasonably well when struck from the side by a small car. However when the striking vehicle has a higher frontal structure, such as many SUVs (four-wheel-drives) there is higher risk of serious head and chest injuries to occupants in the struck vehicle unless head-protecting side airbags are fitted. The Insurance Institute for Highway Safety (IIHS) in the USA has developed a side impact barrier that replicates these higher striking vehicles and test results are now available to assess vehicles for occupant injury in these side crashes. In this paper we compare recent IIHS results with the results of ANCAP/Euro NCAP pole test and mobile barrier side impact tests..

Sources of data

Euro NCAP / ANCAP MDB Side Impact Test at 50km/h (from 1997) JNCAP at 55km/h (from 2000)	
Euro NCAP / ANCAP 90^o Pole Test at 29km/h (from 1999)	
IIHS MDB (SUV) Side Impact Test at 50km/h (from 2003)	
NHTSA Crabbed MDB Side Impact Test at 62 km/h (from 1997)	
NHTSA / IHRA Oblique Pole Test at 30km/h (no consumer data)	

The International Harmonisation Research Activity (IHRA) program proposes two new side impact tests - one with a small female dummy in a side test and the other an oblique pole test using a 50 percentile male dummy. In addition IHRA proposes interior head-form impact tests. More details should be available at the 19th ESV.

NHTSA is developing the oblique pole test. The intention is to better replicate real world pole-type crashes but only experimental test results were available the time of preparation of this paper.

VEHICLE MIX AND REAL WORLD CRASHES

The mix of vehicle types varies considerably between global markets. Each NCAP organisation has tended to tailor its test programs to suit the local mix and best represent real world crashes.

Europe	mostly small cars	mass =< 1400kg
USA/Canada	large vehicles	mass => 2200kg
Japan	mostly small cars	mass =< 1300kg
Australia	larger vehicles	mass => 1600kg

The Australian vehicle mix

Changes in Australian market over last 5 years are characterised by consumer demand falling slightly for larger passenger vehicles and growing for SUVs and light trucks (Figure 1).

This is not expected to change significantly in coming years, unless there is a large increase in fuel costs.

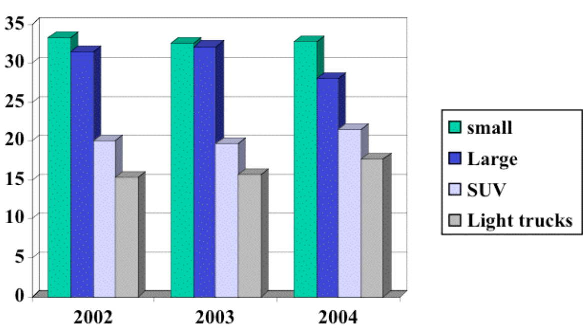


Figure 1. Change in Australian Vehicle Market 2002-4

(% of New Light Vehicle Registrations)

A Monash University Accident Research Centre study on the Australian vehicle market in mid 2004 suggests that SUVs will continue to gain market share to the detriment of small car safety due to incompatibility of ride height, structural mismatch and mass - factors favouring the heavier high-seat SUVs (Newstead and others 2004).

Australian real world crash types

Collisions between vehicles travelling in opposite directions are the most common fatality crashes in Australia. Next are single vehicle crashes where the vehicle leaves the road followed by intersection crashes and then pedestrian impacts. When a vehicle leaves the road the most commonly struck object is a tree or a pole. These are more likely to be fatal in a side impact. Road safety strategies in Australia should therefore give emphasis to reducing the risk of loss of control (so that vehicles stay on the roadway) and providing better occupant protection in intrusive side impact crashes.

Safety features that may reduce serious side impact crashes

There is scope for NCAP organisations to promote the following safety features, which are often optional or unavailable on some models. Avoiding a crash or reducing the energy of impact by using better technology can reduce occupant injuries.

Primary crash avoidance

- Electronic Stability Control
- Antilock brakes
- Tyre pressure warning system
- Good rollover star rating from NHTSA test
- Daytime running lights

Secondary crash protection

- Frontal airbags
- Side airbags
- Side head or curtain airbags
- Structural integrity of occupant space
- Pre-tensioner seatbelts
- Load limiting seatbelts
- Active head restraints
- Pedals that release during severe intrusion
- Automatic crash notification
- Doors that do not open in the crash

NCAP crash tests are designed to assess the performance of the complete vehicle rather than individual components. However some features stand out as providing exceptional protection. An example is head-protecting side airbags. Pole crash tests conducted by ANCAP (detailed below) show that these devices usually turn a likely fatality, due to severe head injury, into an easily survivable crash.

COMPARISON OF IIHS AND EURO NCAP POLE TEST RESULTS

The following table contains a comparison of published data on IIHS SUV barrier crash tests and Euro NCAP pole tests. It is provided subject to the cautions that:

- Vehicle specifications may vary between countries
- Smaller dummies (5% female) are used in the IIHS test
- IIHS reports HIC15 whereas Euro NCAP/ANCAP report HIC 36

Table 1 Comparison of Head Protection in IIHS and Euro NCAP/ANCAP Crash Tests

High Seat Vehicles (H-Point 700mm or above ground)

Vehicle Model	Head Protecting Side Airbag	IIHS SUV Barrier Result	Euro/ANCAP Pole Test Result
Ford Escape/Mazda Tribute	Side airbag with head bag	Good	Poor*
Ford Escape	None	Marginal	Poor
Honda CR-V	Curtain	Good	No head airbag option in Australia
Honda CR-V	None	Good	Poor
Toyota RAV4	Curtain	Good	Good
Toyota RAV4	None	Good	Poor
Landrover Freelander	None	Good	Not tested
Hyundai Santa Fe	Side airbag with head bag	Good	No head airbag option in Australia
Suzuki Grand Vitara	None	Poor	Not tested

* Head bag failed to deploy correctly in ANCAP test

Low Seat Vehicles (H-Point less than 700mm above ground)

Vehicle Model valid 2004/5	Head Protecting Side Airbag	IIHS SUV Barrier Result	Euro/ANCAP Pole Test Result
Honda Accord	Curtain	Good	Good#
Honda Accord	None	Poor	-
Jaguar X-Type	Curtain	Good	Good
Mercedes C-Class	Curtain	Good	Good@
Saab 9-3	Curtain	Good	Good
Subaru Legacy/Outback	Curtain	Good	Good
Toyota Camry	Curtain	Good	No head airbag option in Australia
Toyota Camry	None	Poor	Not tested
Volvo S40	Curtain	Good	Good
Saab 9-5	Side airbag with head bag	Good	Good
Subaru Forester	Side airbag with head bag	Good	Good

Honda Accord Euro tested by Euro NCAP is a different model to the US one

@ Euro NCAP applied a modifier to the C-Class pole test result due to incorrect deployment of the curtain.

Discussion of Table 1 results

Subject to the small sample sizes, these results suggest that the IIHS SUV barrier test and the Euro NCAP pole test produce similar outcomes for cars. In this class of vehicles, the IIHS test does tend to show a substantial difference between vehicles with and without head protecting side airbags . This suggests that the IIHS test will encourage head-protecting side airbags in cars and other low seat vehicles.

Several SUVs have obtained good/acceptable head injury results in the IIHS test, despite lacking head-protecting side airbags (Ford Escape, Honda CR-V, and Toyota RAV4). The Ford Escape with head-protection obtained good results in the IIHS test but the equivalent Mazda Tribute obtained a poor result in the ANCAP pole test because the side head airbag did not deploy correctly. The Escape, RAV4 and CR-V without side head protection airbags obtained poor head results in pole tests by ANCAP

This suggests that the IIHS test would not necessarily encourage head-protecting side airbags on these compact SUVs or other high-seat vehicles.

Large SUVs such as the Toyota Landcruiser Prado and the Nissan Patrol could also be expected do well without head protection in the IIHS test since the higher seats and heavier mass would benefit the occupants in this particular test.

In the case of high-seat vehicles ANCAP intends to be cautious about accepting the IIHS result as alternative evidence of head protection in side impacts. ANCAP pole test results for these large 4WD vehicles without head-protecting side airbags are expected to be poor.

Comparison of Pole and MDB Side Impact Scores

ANCAP reviewed available test data on Euro NCAP side impact and pole tests and scored pole test using the same scoring system as that outlined in the Euro NCAP Assessment Protocol for side impact tests. This included scoring the chest, abdomen and pelvis (note that usually only the head injury data is assessed for the pole test). Figure 2 shows the results of this comparison. This illustrates that most vehicles have no difficulty with the MDB side impact test and many score the full 16 points. It is apparent that the pole test is much more demanding.

Figure 3 shows the scores for individual body regions for the pole tests (each body region can score up to 4 points). It is evident that with most vehicles there is a high risk of serious chest injury during the pole test, even for vehicles with thorax side airbags. It is understood that there may be a concern with the biofidelity of the EuroSID II dummy under the extreme intrusion that occurs in the pole test. Due to this uncertainty ANCAP does not propose to use this method of scoring pole test results at this stage. However, the test results do suggest that chest injury should be monitored in real-world pole type side

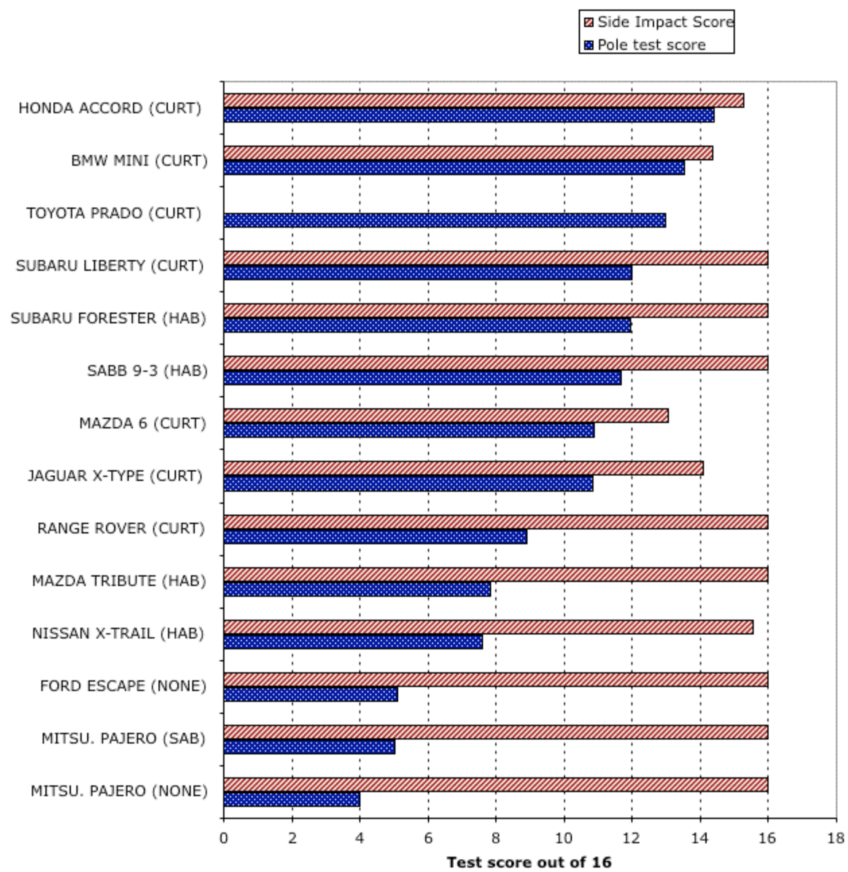


Figure 2. Comparison of Scores for Pole Test and MDB Side Impact Test

Notes: The pole test injury measurements for head, chest, abdomen and pubic symphysis have been scored in the same way as the side impact test. This is not an official ANCAP score.

CURT=curtain, HAB=Head-protecting side airbag, SAB=thorax side airbag.

impact crashes to determine if greater emphasis should be placed on protecting occupants from serious chest injuries.

A high risk of serious abdomen injury has also been observed in some pole tests. A contributing factor may be the crushing of the driver's seat between the intruding door and an unyielding centre console (figure 4). These consoles may also be a source of far-side occupant injuries in side impacts.

Other issues that should be taken into consideration when assessing pole tests are:

- Nature and degree of intrusion into occupant survival space (undertaken by IIHS for the MDB SUV test)
- Fuel leaks (reported by IIHS)
- Extrication of driver dummy (reported by IIHS)
- Head protection provided for rear seat occupants (assessed by IIHS - not directly assessable in pole test)
- Potential for occupant protection in rollover crashes with the curtain remaining inflated long enough to be effective during the rollover.

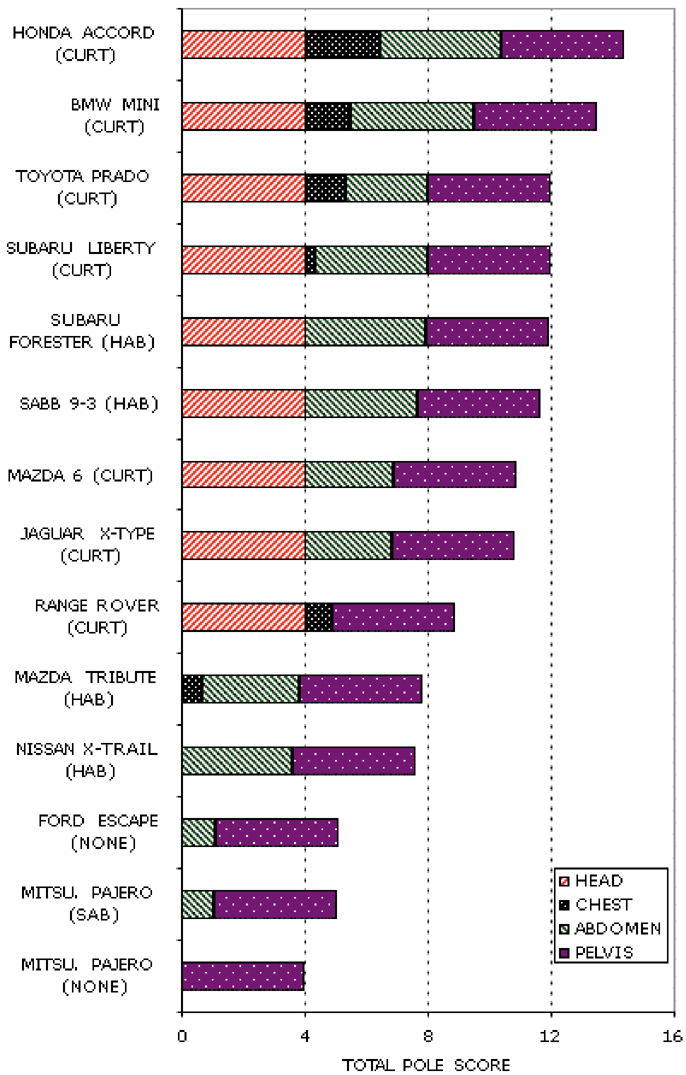


Figure 3. Body Region Scores for Pole Test

Notes: The pole test injury measurements for head, chest, abdomen and pubic symphysis have been scored in the same way as the side impact test. Each body region scores 4 points for a "good" (low) injury measurement. Zero score means a "poor" injury measurement. This is not an official ANCAP score.

CURT=curtain, HAB=Head-protecting side airbag, SAB=thorax side airbag.

RESULTS

ANCAP has completed a pole test program on a range of SUVs with and without head protecting side airbags. The results clearly showed the benefits of such equipment when operating properly. The vehicles without such protection produced HIC measurements with an extremely high risk of fatal head injuries. The vehicle with head protecting airbags achieved a low HIC with low head injury risk. One vehicle was fitted with a head protecting side airbag, but it did not deploy properly, resulting in a high risk of fatality.

ANCAP published the results of the pole tests to show that head protecting side airbags provided good protection against collisions with narrow objects such as poles and trees. Side airbags, while providing protection against impacts by conventional vehicles, do not protect the head against higher intruding objects, such as SUVs and pole-type structures.

ANCAP recommends that front, side and head protecting airbags and ESC should be made available by vehicle manufacturers as standard equipment, or at least as a “safety package”, not linked to luxury items such as sunroofs and leather seats. This packaging is common in Australia and increases the cost of the airbag protection, sometimes substantially, which can price it beyond the reach of some vehicle purchasers.

ANCAP also advocated the incorporation of Electronic Stability Control (ESC) into all SUVs, as research by IIHS has shown that such systems drastically reduce the number of run-off-road crashes, thereby reducing the number of pole and tree side impacts (Farmer 2004).

Even with side airbags, chest deflection levels are generally high in most pole crashes with a high risk of injury likely.

CONCLUSIONS

Head protecting side airbags provide clear head injury mitigation benefits in collisions with stiff vertical road-side objects such as trees and poles, and provide protection against impacts by vehicles with high fronts, such as SUVs.

Consumers need to be better educated about the value of head protecting side airbags. This will further encourage vehicle manufacturers to make them available as optional equipment or, even better, install them in all vehicles as standard equipment.

Figure 4. Plan View of Crushed Seat After Pole Test

Figure 5. Peak of Intrusion during Pole Test

Some types of NCAP crash tests are able to assess the head protection provided in vehicles during severe side impacts. The results of these tests need to be strongly promoted amongst new vehicle buyers.

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EFFECTIVENESS OF THORAX & PELVIS SIDE AIRBAG FOR IMPROVED SIDE-IMPACT PROTECTION

Stephanie Schneider
Minoru Niwa
Toyoda Gosei North America Corporation
United States
Toru Koyama
Toshinori Tanase
Yuji Sato
Masanari Sakamoto
Michihisa Asaoka
TOYODA GOSEI CO., LTD.
Japan
Paper Number 05-0273

ABSTRACT

In recent years, side-impact crashes in the US between SUVs (Sports Utility Vehicle) or LTVs (Light Trucks & Vans) and passenger cars are increasing, resulting in a high number of serious or fatal injuries. It has become an important task to reduce body injury levels, not only to the head, but to the thorax and pelvis as well. One way to protect the occupant's thorax and pelvis in side-impact crash is T&P SAB (Thorax & Pelvis Side Airbag).

This research paper will show a reduction of injury levels as a result of T&P SAB, using IIHS (Insurance Institute for Highway Safety) SUV side-impact crash conditions in MADYMO simulation and sled test results. Furthermore, analyses of the pelvis area were conducted using THUMS Simulation. It was confirmed that T&P SAB has the potential to protect the occupant's thorax and pelvis during side-impact crash, as well as reduce the level of injury.

THUMS (Total Human Model for Safety)
FEM Human model, created by Toyota Central R&D Labs

INTRODUCTION

Within the last 2 decades in the US, the number of side-impact crashes involving SUV/LTVs to passenger cars has increased remarkably. According to FARS (Fatal Analysis Reporting System) data, comparing the fatality rate by side crash type, between 1980-81 to 2000-01 the fatality rate of SUV/LTV vs car increased from 29% to 57%. The fatalities reported for passenger car vs passenger car decreased from 71% to 43%(Table 1). According to NASS (National Automotive Sampling System) Crashworthiness Data, the body parts inflicted with the highest injury levels (higher than AIS3) during side crash were thorax 61% and pelvis 35%, these ratios being higher than head injury level 31% (Table 2).

Table 1.
Percent of driver death in 1-3-year-old passenger vehicle struck on the driver side by another passenger vehicle, by type of striking vehicle

STRIKING VEHICLE	STRUCK VEHICLE	CALENDAR YEARS 1980-81	1990-91	2000-01
Car	Car	71%	61%	43%
SUV or pickup	Car	29%	39%	57%
Car	All passenger vehicles	70%	60%	43%
SUV or pickup	All passenger vehicles	30%	40%	57%

Source: Fatality Analysis Reporting System, National Highway Traffic Safety Administration

Source : NHTSA STATUS REPORT (Vol.38, No.7 June 28,2003)

Table 2.
Distribution of serious and fatal injuries, by body region, to drivers of passenger vehicles struck on the driver side, calendar years 1997-2001

BODY REGION	MALE	FEMALE	TOTAL
Head, face, or neck	29%	34%	31%
Thorax	66%	51%	61%
Abdomen	14%	13%	13%
Upper extremities	15%	18%	16%
Pelvis & lower extremities	33%	38%	35%
Spine	5%	2%	4%

Notes: Serious injuries are AIS (Abbreviated Injury Scale) 3 or greater. Drivers frequently suffer AIS 3+ injuries to multiple body regions.
Source: National Automotive Sampling System/Crashworthiness Data System, National Highway Traffic Safety Administration

Source : NHTSA STATUS REPORT (Vol.38, No.7 June 28,2003)

CIREN (Crash Injury Research & Engineering Network) reported, during a public meeting that it is important to reduce injury level of thorax and pelvis because those parts are at highest risk of getting injured by the door panel in a side-impact crash.

One way to protect the occupant's thorax and pelvis during a side-impact crash is utilization of T&P SAB. Adding a Curtain Airbag to protect the head during a crash (in combination with T&P SAB) can further reduce full side body injury levels. In this research, it is perceived that injury levels decrease as an effect of using T&P SAB in the condition of IIHS SUV side-impact testing by using MADYMO Simulation and Sled Testing. A more detailed analysis of the pelvis area was conducted using THUMS Simulation.

Evaluation Method

This research consists of MADYMO Simulation and Sled Testing, with the behavior of the door derived from the result of IIHS SUV side-impact testing.

MADYMO Simulation

MADYMO Simulation was used to measure the relationship between injury level of thorax and pelvis of occupant and design of T&P SAB (configuration, dimensions, etc.). Shown in Figure 1, T&P cushion was divided into 3 parts. 3 levels of bag size and inner pressure were set for each of the 3 parts. Rib Deflection and Iliac Force were evaluated (the average of the 5 ribs was reported) using a Morris Quadratic Design DOE that consisted of 78 simulations (Table 3). The result can be seen in Figures 2, 3 and 4.0

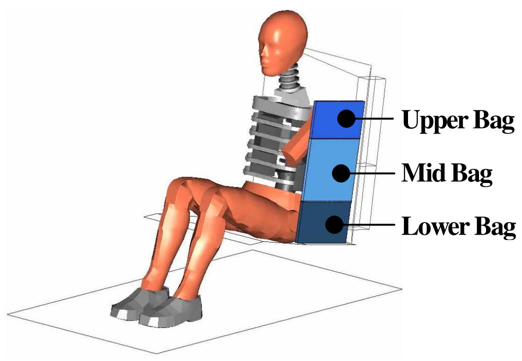

Figure 1. MADYMO Simulation model

Table 3.
Simulation matrix

Case	Upper Airbag Length	Upper Airbag Thickness	Upper Airbag Pressure	Mid Airbag Length	Mid Airbag Thickness	Mid Airbag Pressure	Lower Airbag Length	Lower Airbag Thickness	Lower Airbag Pressure
1	A1	B3	C1	D3	E3	F3	G1	H1	I1
2	A1	B1	C3	D3	E3	F3	G3	H1	I1
3	A3	B1	C1	D3	E1	F3	G3	H3	I1
4	A1	B3	C1	D3	E3	F1	G3	H3	I3
5	A1	B1	C3	D3	E1	F3	G1	H3	I3
6	A1	B1	C1	D3	E1	F1	G3	H1	I3
7	A3	B1	C1	D3	E3	F1	G1	H3	I1
8	A3	B3	C1	D3	E1	F3	G1	H1	I3
9	A3	B3	C3	D3	E1	F1	G3	H1	I1
10	A1	B3	C3	D3	E1	F1	G1	H3	I1
11	A3	B1	C3	D3	E3	F1	G1	H1	I3
12	A3	B3	C3	D3	E3	F3	G3	H3	I3
13	A3	B2	C2	D3	E1	F1	G2	H3	I3
14	A2	B2	C3	D3	E2	F1	G2	H2	I3
15	A3	B1	C3	D3	E1	F2	G2	H2	I2
16	A3	B2	C2	D3	E2	F1	G3	H2	I2
17	A3	B2	C3	D3	E2	F2	G2	H3	I2
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23	A2	B1	C2	D3	E1	F1	G2	H2	I2
24	A2	B3	C2	D3	E2	F1	G1	H2	I3
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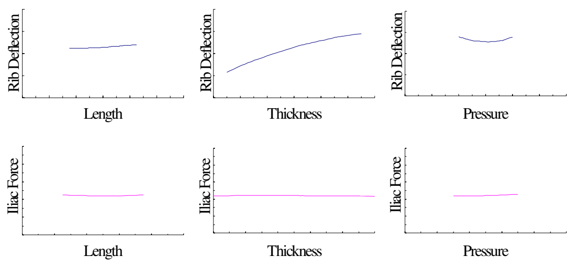


Figure 2. Effect of Upper Bag

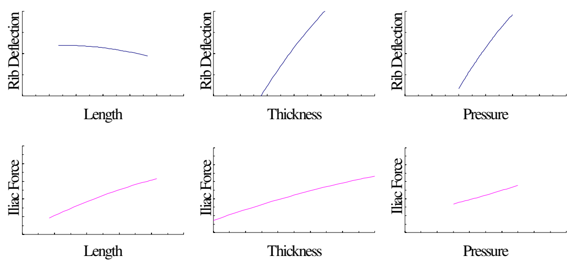


Figure 3. Effect of Mid Bag

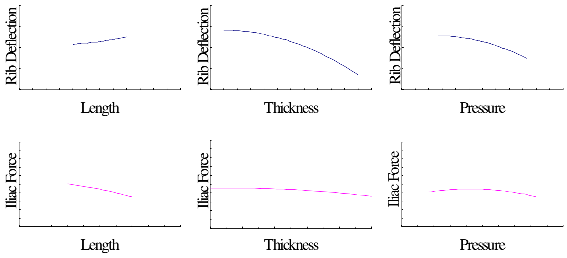


Figure 4.　Effect of Lower Bag

The simulation showed that the best condition was large size and high inner pressure for Lower Bag.　The injury level of thorax and pelvis for this design was lower than without SAB injury level (Figure 5).

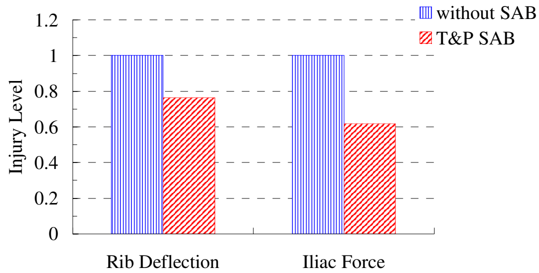


Figure 5. Simulation result of the best T&P design vs condition without SAB

With this result, it was confirmed that the T&P SAB is an effective way to protect occupants' thorax and pelvis in a side-impact crash.

Sled Test

Sled testing was conducted with and without T&P SAB.　The T&P SAB sample for this test was made on the basis of best solution obtained from the MADYMO Simulation.　Sled testing results were similar to simulation results, showing reduced thorax and pelvis injuries (Figure 6).

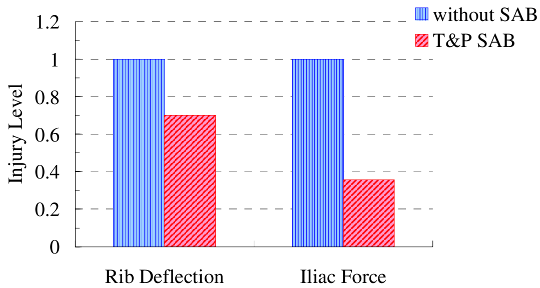


Figure 6. Sled Test Results

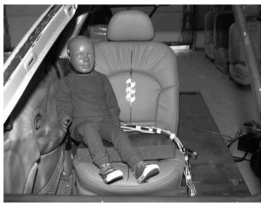
Out-of-Position Test

Out-of-Position (OOP) Testing was next conducted using the best design sample from simulation.　Four test conditions using child dummy, recommended by TWG, were selected for OOP testing (Figure 7).

TWG (The Side Airbag Out-of-Position injury Technical Working Group)
A joint project of Alliance, AIAM, AORC, and IIHS

Lying on seat
(Hybrid III　3yo)

Rearward facing
(Hybrid III　3yo)



Forward facing on booster seat
(Hybrid III　3yo)

Forward facing on booster seat
(Hybrid III　6yo)

Source : Recommended Procedures for Evaluating Occupant Injury Risk from Deploying Side Airbags
(First Revision - July 2003)

Figure 7. Out-of-Position Test Condition

All results gained by Out-of-Position testing showed injury levels less than IARV (Injury Assessment Reference Values).

From this, T&P SAB design was optimized based on OOP performance and restraint performance.

THUMS Simulation

The Human model, such as THUMS, is a very useful tool to analyze the effect of car crashes on human body parts. THUMS simulation was used to predict the effectiveness of airbags in the field, and contributed to the development of a higher performance SAB system.

Figure 8. THUMS human model

Figure 9. THUMS Simulation model

The effect of the T&P SAB was analyzed in more detail for the occupant pelvis using THUMS simulation. As a result, it was confirmed that T&P SAB can reduce the concentrated level of forces to the pelvis. The stress distribution is shown in Figure 10.

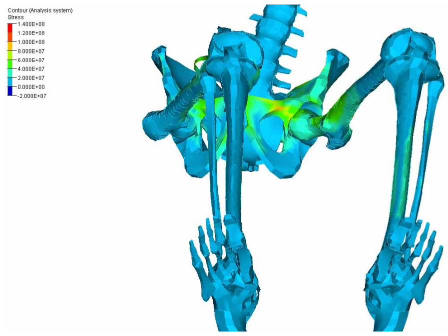


Figure 10. THUMS Simulation Results
(Stress distribution of the pelvis)

From the THUMS results, it was shown that T&P SAB can protect a wide area of the pelvis. It is one very effective way to reduce injury to the pelvis.

CONCLUSIONS

In this research, by utilizing simulation and sled testing, using IIHS SUV side-impact crash test conditions, it was confirmed that T&P SAB has the potential to protect both thorax and pelvis areas of occupant, and also reduce injury levels.

THUMS Simulation is a useful tool as it enables a more detailed analysis of the effect which is inflicted on a human body during a car accident. It can predict injury levels in the field, as well as define a clear mechanism of injuries, and help develop safer systems. We will continue to use THUMS simulation for future investigations.

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