

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

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Paper number 05-0036

### 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  $10 \times 10^3$  N. As the door pushed the dummy against the console, this increased to about  $20 \times 10^3$  N. With no console and a laterally translating seat, peak pelvic load decreased to about  $4 \times 10^3$  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.

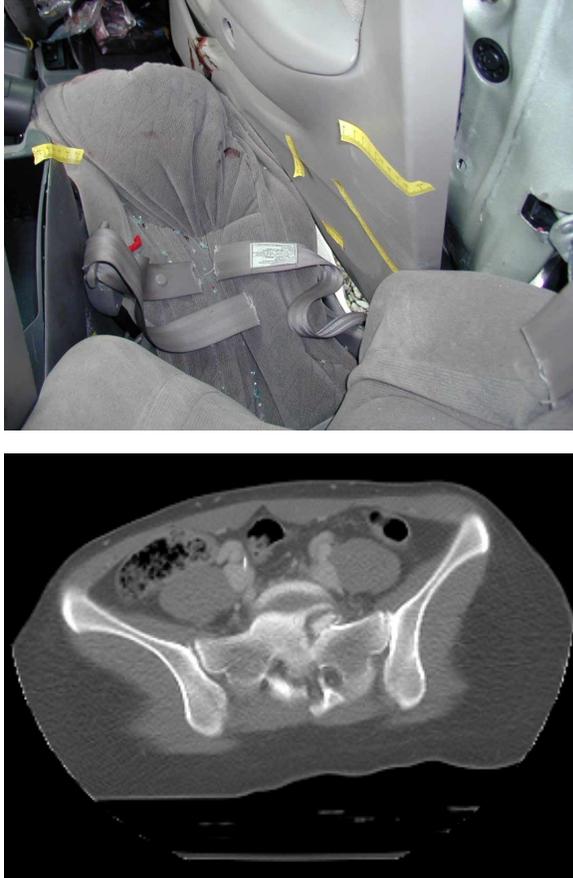
### INTRODUCTION

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, SIDII, 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.

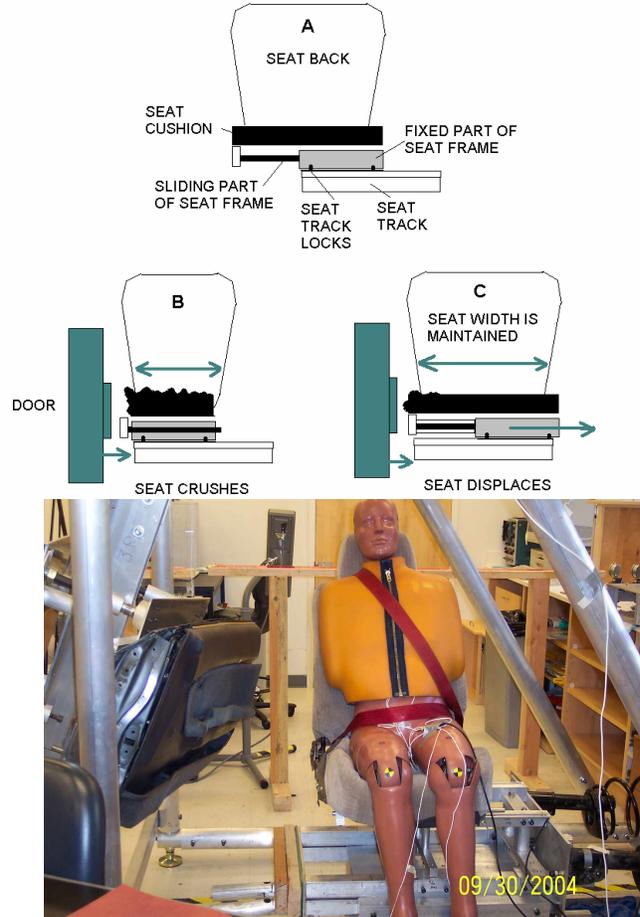
For this study we identified 62 occupants in 54 crashes in vehicles between model years 1998 and 2004. The study was limited to drivers or front seat passengers, and only nearside occupants in crashes with a PDOF (principal direction of force) between 8 and 10 o'clock or 2 and 4 o'clock (approximately 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](http://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 1/4") 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.

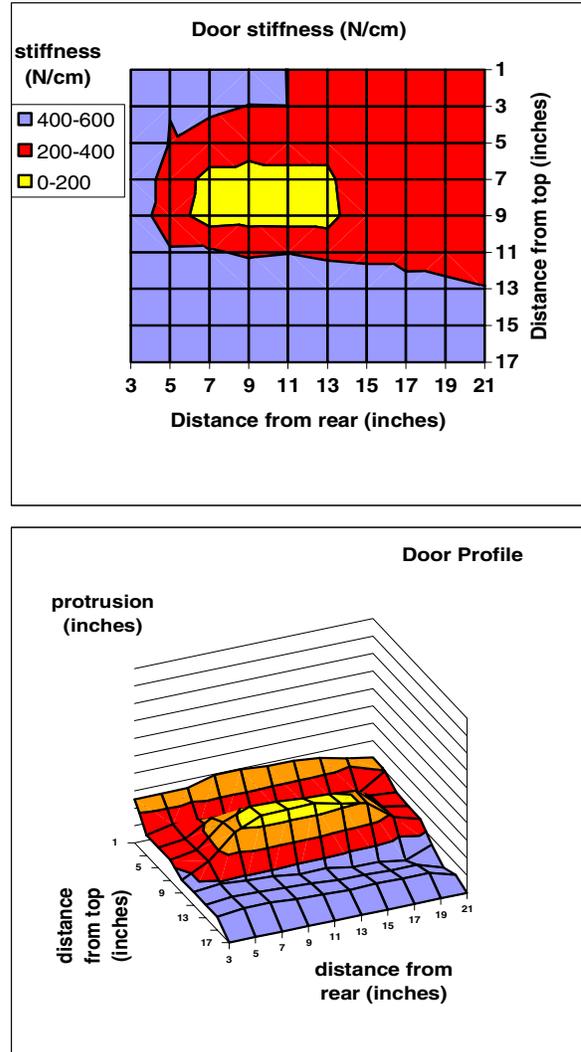
Data collection was performed at 10 KHz (National Instruments, Austin, TX). High speed video (Kodak Ectapro., San Diego, CA) running at 1000 frames/sec was used capture each impact. Data from the accelerometers was filtered using the FIR 100 filter. Maximum and minimum accelerations from each test were 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  $p < 0.05$ .

#### 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.

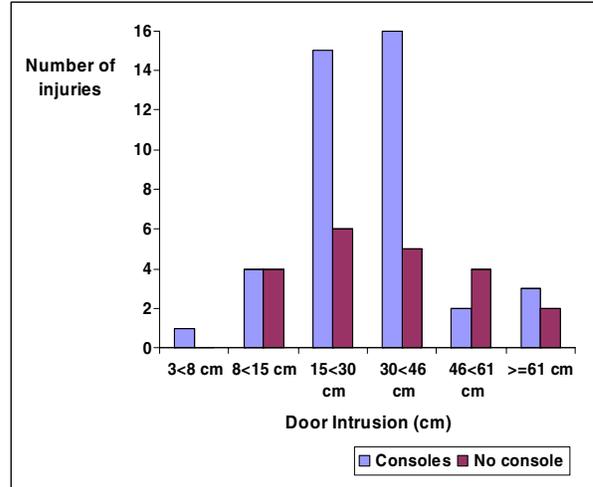
The door was represented in the model as a series of translational joints of prescribed stiffness based on the mechanical testing described above with a finite element mesh of shell elements as the door contact surface to the dummy. The door surface, being coarser, was selected as the master surface 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  $1 \times 10^2$  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  $1 \times 10^3$ , 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

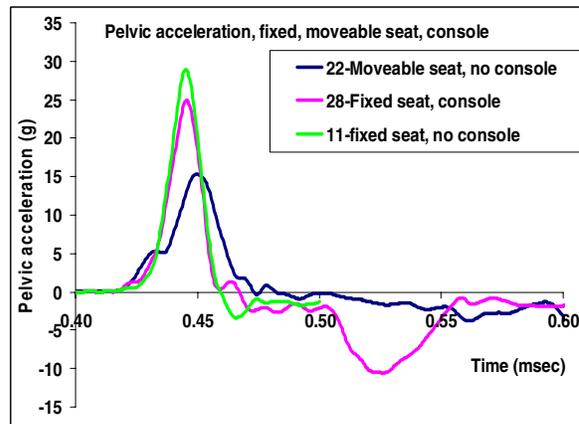
For side impacted vehicles with consoles from the CIREN database, 41 occupants suffered pelvic injuries. The mean age was 40 years (range 15-89 years), 33 (80%) were female, 29 (71%) were drivers, and 36 (88%) were belted. The mean delta V for collisions in this group was 36 kph. Those suffered pelvic 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.



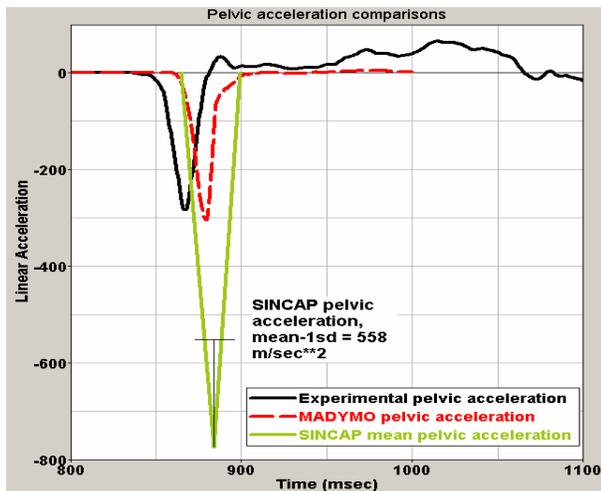
**Figure 5.** Sample pelvic acceleration-time histories from the experimental testing, with a laterally moveable seat and no console, a fixed seat with no console, and a fixed seat with a console.

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.

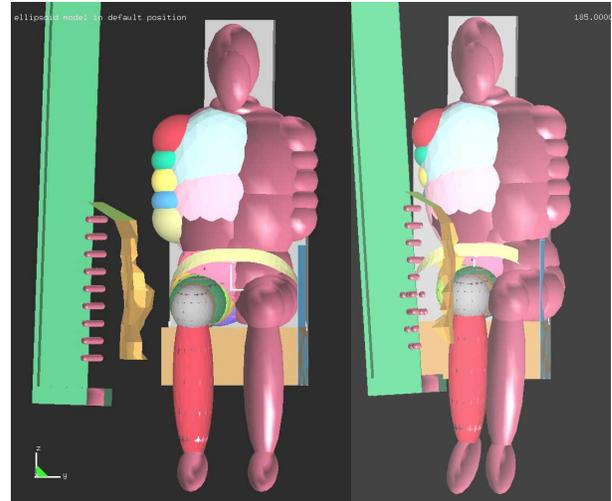
### MADYMO results

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).

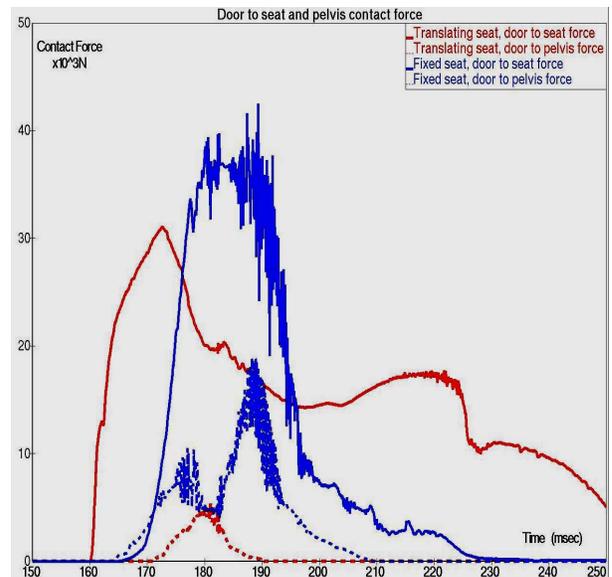


**Figure 6** A comparison of pelvic acceleration from the experimental pendulum results and the MADYMO model of the experiment, both in relation to mean values from SINCAP testing.

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  $10 \times 10^3$  N. When the pelvis contacted the console, the second force on the pelvis peaked at about  $20 \times 10^3$  N. In contrast, with the stiffer translating seat and no console, the initial pelvic contact force was much lower, about  $4 \times 10^3$  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 compatibility 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**

This work represents the opinions of the authors and not necessarily that of the National Highway Traffic Safety Administration. Support was provided by a grant from the National Center for Injury Prevention and Control, Centers for Disease Control and Prevention, Atlanta, GA, and by the CIREN program, National Highway Traffic Safety Administration.

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