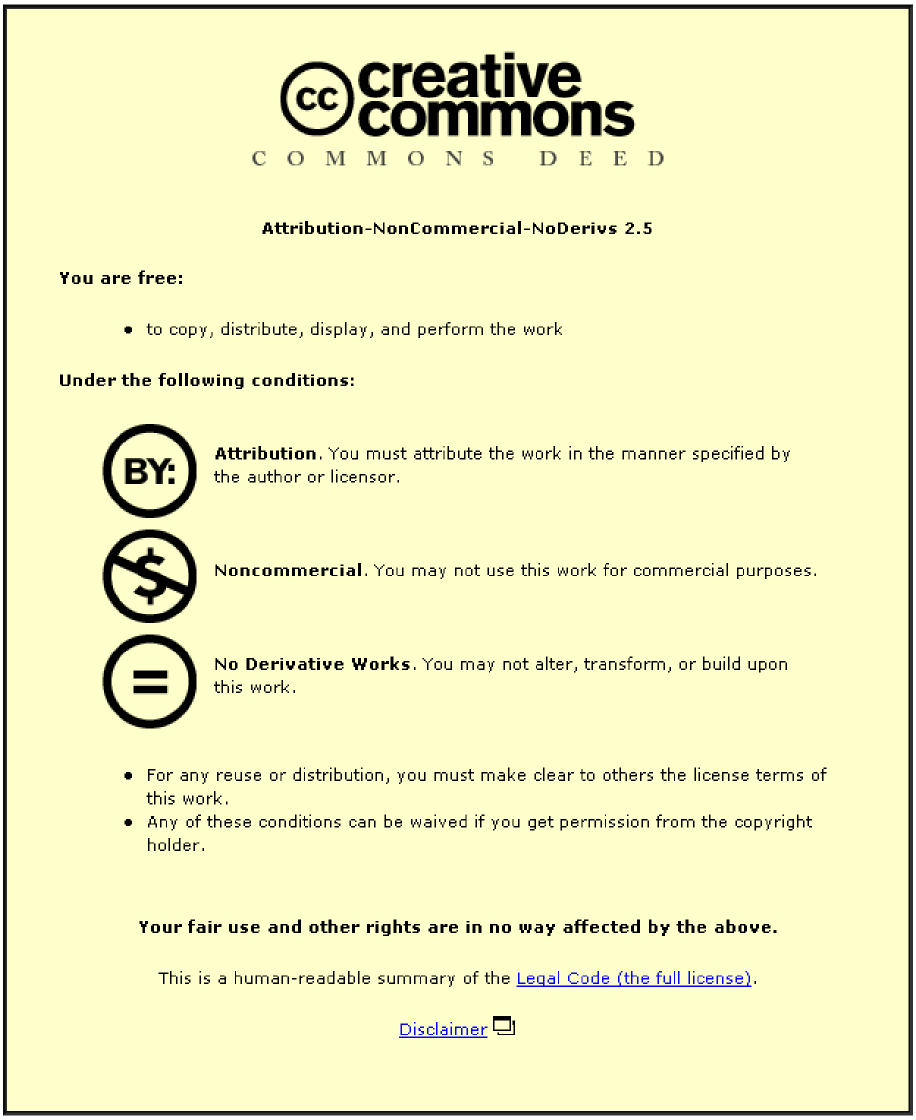

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SUITABILITY OF CURRENT SIDE IMPACT TEST DUMMIES IN FAR-SIDE IMPACTS

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ABSTRACT

This study set out to compare the suitability of five current side impact test dummies to simulate that of a 50th percentile Post Mortem Human Subject (PMHS) in a far-side impact crash configuration. A number of comparative crash tests were undertaken, involving a 50% PMHS and four current side impact crash test dummies (BioSID, a BioSID with a lumbar spine modification, EuroSID, and WorldSID) using the ECE95 test procedure at 65km/h. Crash test data were collected from full-scale crash tests conducted using a Holden Commodore fitted with a 50% Post Mortem Human Subject (PMHS) and a BioSID and WorldSID test dummy in the driver seat. Additional crash test data were obtained using a similar full-scale validated sled test setup. The results demonstrate that the current WorldSID prototype and a BioSID dummy with a modified lumbar spine unit can provide reasonable simulations of occupant kinematics and injuries to help advance vehicle countermeasures. Further work is required to test the robustness and generality of these findings for improved far-side impact protection.

Key Words: Sled Tests, Biofidelity, Side Impacts, Dummies, Injury Criteria

INTRODUCTION

Side impact collisions are a particularly severe and harmful type of crash for vehicle occupants. Depending on the severity of the crash, side impacts can be involved in up to 35% of road trauma and particularly noteworthy in fatal crashes (Fildes 2002). While near-side impacts are commonly associated with side impact trauma, far-side crashes are not, yet still lead to a substantial number of injuries (Otte, Suren, Appel & Nehmzow 1984; Mackay, Hill, Parkin & Munns 1991; Fildes, Lane, Lenard & Vulcan, 1994; Frampton, Brown, Thomas & Fay 1998; Augenstein, Perdeck, Martin et al 2000) and Harm (Gabler, Fildes & Fitzharris, 2000; Gibson, Fildes, Deery H., et al, 2001; Digges & Dalmotas 2001). Recent attention in side impact intervention and regulation has focussed on near-side occupants, which is appropriate given that these crashes account for 60% of side impact Harm (Fildes, Digges, Carr, Dyte & Vulcan 1995). However, far-side occupants have been somewhat disregarded in this research effort, even though these crashes amount for approximately 40% of side impact Harm (Fildes et al, 1995; Digges & Dalmotas 2001).

The in-depth study findings reported by Fildes et al. (1994) showed that the frequency and rate of head injury was greater in far-side than near-side impacts with fewer chest and abdominal injuries. The head injuries resulted from contact with the far-side door, the impacting vehicle or object or other occupants. Dalmotas (1983) reported earlier on injury mechanisms for occupants in real world crashes restrained in 3-point seat belts in side impacts in Canada. While he noted different mechanisms for near-side and far-side occupants, he maintained that occupants in both positions would benefit from improvements in side door integrity and interior padding.

Kallieris and Schmidt (1990) conducted simulated far-side impacts using cadavers seated in the rear seat with inboard-anchored shoulder belts. They reported no head injuries for far-side occupants with these belt configurations compared with those of near-side occupants and lower angular head/neck velocities and accelerations. However, most of the PMHS showed AIS1 injuries to the neck, which in the light of recent whiplash research corresponds to a high probability of disabling injury outcome (i.e. hemorrhages in the inter-vertebral discs).

There has been extensive work completed on near-side impacts to define injury tolerance and biofedility requirements (Cavanaugh et al., 1990; Walilko, Malhotra, Zhu and King (1990); and Pintar et al., 1997). In the latest work, Pintar and his colleagues conducted 26 side impact sled tests with PMHS impacting a sidewall with a range of different surface conditions. They investigated a number of biomechanical responses and injury tolerances from these tests for occupants involved in near-side crashes. Because injury criteria and biofidelity requirements for near-side occupants are dependent on a direct impact to one whole side of the body, these results are not directly applicable to far-side crashes. Additional far-side impact tests are critical for understanding occupant kinematics, forces and accelerations for occupants involved in these kinds of real world crashes. Stolinski, Grzebieta and Fildes (1999) undertook a series of crash tests in Australia focussing on near- and far-side occupant outcomes. They showed by means of far side HIII and US-SID full-scale crashes, deploying belt pre-tensioners can significantly reduce lateral excursion of the far side occupant and reduce lap belt loads. However, there is reason to question whether current side impact test dummies, designed for near-side impacts can accurately reflect far-side kinematics and injuries.

From this review of the literature, it is clear that there is an urgent need to better understand the kinematics and injury tolerance of occupants in far-side impacts to highlight ways in which they can be better protected. However, there is a need first to evaluate the current generation of side impact test dummies for their suitability for use in developing far-side impact countermeasures. Dummy responses need to be compared with human-like behaviour which are generally more flexible than test dummies. Unfortunately, there has been little comparative test results published to date.

METHOD

This study set about to compare a number of current generation side impact test dummies against test results from a 50th percentile Post Mortem Human Subject (PMHS) in a far-side crash configuration to judge their suitability for use in developing far-side impact countermeasures and design solutions. Crash tests involved a combination of car and Mobile Deformable Barrier (MDB) crashes and simulated sled tests (sled test results were initially validated against full car crash tests which has been previously published in Bostrom, Judd, Fildes, et al. 2002). All tests adopted the ECE95 test procedure using a Holden Commodore vehicle and the European MDB but at a higher 65km/h test speed. Whereas there was no deformation of the non-struck side B-pillar, the acceleration in the y-direction (along the direction of impact) at the driver's side B-pillar and at the tunnel differed significantly. Figure 1 shows the difference in speed time-history for one of the MDB tests. The striking and struck vehicle moved together without separating from each other during the crash and the speed change until the dummy head swiped or hit the door was about 24 km/h. A number of other vehicle and sled measures were also recorded but not analysed here.

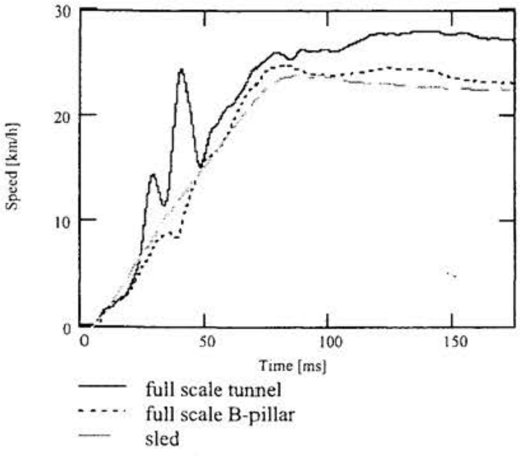

Figure 1 Time vs. speed history of car at the driver side B-pillar and longitudinal tunnel centre of the car in the BioSID MDB test. The corresponding BioSID sled test speed is also indicated.

The PMHS and dummies were instrumented to measure acceleration on the top of the head as well as at T1, T12 and Pelvis CG using triaxial accelerometers. Seat belt loads were measured from load cells placed on the lap and sash belts. Kinematics were determined from plots of target movements in 3 dimensions from high speed films placed in strategic positions around the car. Photo's 1 and 2 show the set up of the crashed vehicle test procedure used and the test buck set up.

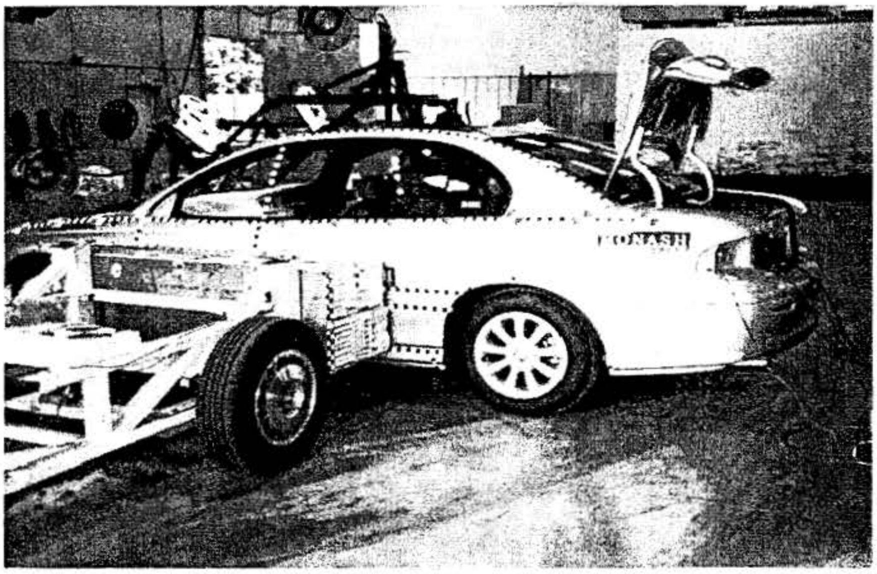

Photo 1 Set up of the side impact test procedure used in the Commodore test

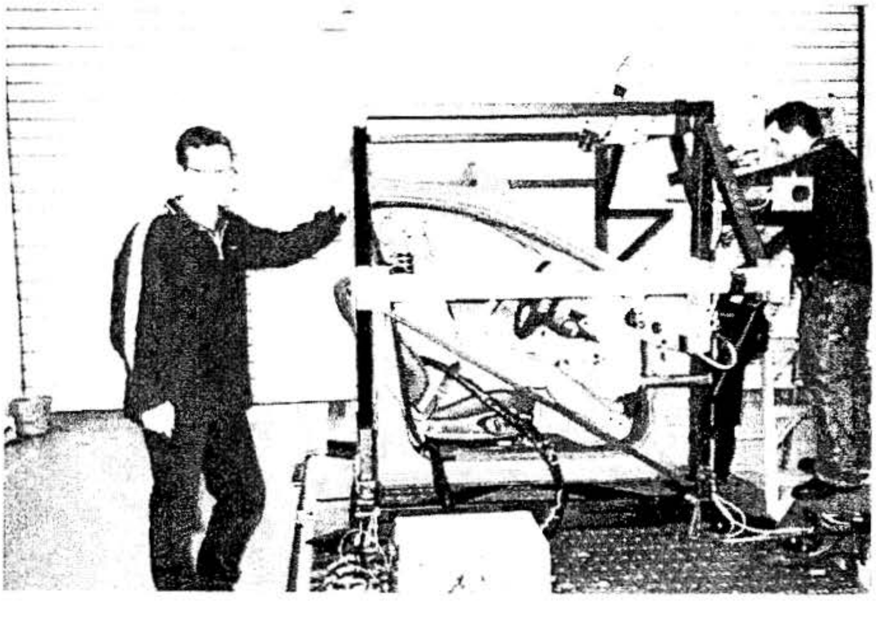

Photo 2 Pre-deformed test buck used in the sled test series

The modification to the BioSID lower spine was a trapezoid device built by Autoliv Research, which provided the dummy with increased lateral shear capability (Kruse 2001). This device is shown in Photo 3 below.

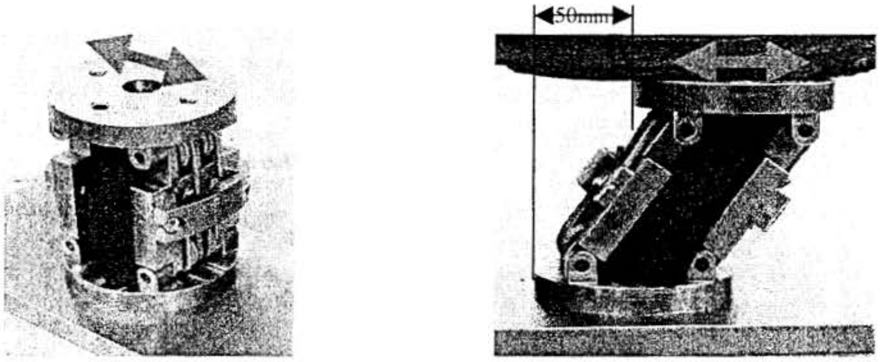

Photo 3 Modified lower spine device developed for the BioSID test dummy

Six crash tests were conducted with the human surrogate (cadaver or dummy) seated in the drivers seat with the 3-point seat belt fastened. The vehicle was impacted on the passenger side (opposite where the surrogate was seated). The test buck was constructed using the deformed vehicle from an earlier crash test (i.e., it's damage was pre-deformed – see Bostrom et al, 2002, for further details). Table 1 shows the combinations of crash tests and surrogates in the test program.

Table 1 Details of the six human surrogate tests conducted in the far-side test program

Test No.	Human Surrogate	Test Set up
1	50th percentile human cadaver	Full car-MDB crash test
2/3*	BioSID test dummy	Full car-MDB test (plus sled test)
4	BioSID with modified lower spine unit	Sled test (with predeformed buck)
5	EuroSID-1 test dummy	Sled test (with predeformed buck)
6	WorldSID prototype (2001)	Full car-MDB crash test

* Tests 2 and 3 were conducted to evaluate the test dummy plus the sled test procedure (see Bostrom, Judd, Fildes, Morris, Sparke and Smith, 2002).

RESULTS

The analysis of the test results of the dummy and PMHS in the far-side crash configuration tested here was confined to the kinematic movement of each of the dummies, the accelerometer loads experienced at each measurement position and the seat belt loads. These are discussed below.

PMHS crash test

The performance of each of the test dummies was to be judged against the findings of the 50th percentile PMHS test results. The specimen was a 68-year male 165cm tall and 78kg mass. Its seated height was 88.9cm with a knee height of 47.6cm. Key aspects of these findings relevant for the dummy evaluations are summarised in Table 2 and Figure 2 below.

Table 2 Observations of the PMHS crash performance

Event	Evidence
The head did hit the far side door	Photo and head acceleration
The spine was straightened	T1 and head vertical accelerations, belt force
The spine was laterally sheared	Pelvis, T12, T1 and head accelerations

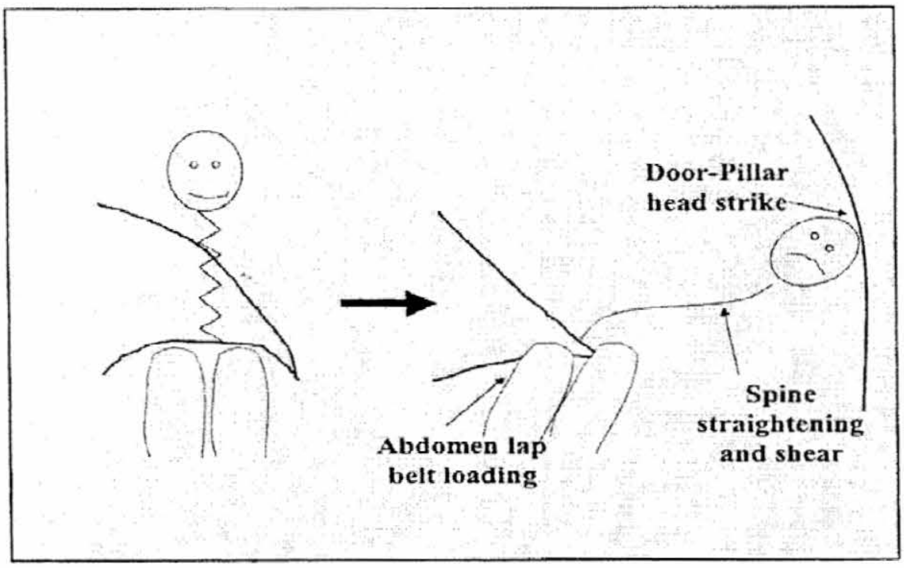

Figure 2 Schematic view of the spine straightening, spine shear and head strike of the PMHS in the 65km/h far-side crash test

Figure 2 shows the movement of the PMHS during the crash sequence where first it moved laterally in a vertical movement, then rotated laterally out of the sash belt with the spine straightening and the head striking the B-pillar and top of the door panel in the temporal region. A number of outlines from the PMHS crash sequence are also shown in Appendix 1.

Kinematics

For a test dummy to be useful in a far-side test for evaluating countermeasures, it was decided that it should be able to accurately represent torso movement in shear and elongation, measure neck shear and loading and head impact with the far-side door to that of the PMHS. The kinematics of movement of each of the test dummies and the PMHS were plotted and the degree by which each dummy replicated the movement of the PMHS was judged from these plots. Table 3 shows the results for the kinematic traces, judged in terms of their abilities to closely replicate that of the PMHS plot.

Table 3 Kinematic representativeness of each test dummy to the PMHS trace.

Dummy	Torso Shear	Spine Straightening	Head Impact
BioSID	Poor	Poor	Poor
BioSID – mod	Good	Poor	Poor
EuroSID	Good	Poor	Poor
WorldSID	Good	N/a	N/a

These results show that none of the test dummies performed particularly well against the PMHS. The original BioSID performed worst than all other dummies mainly because of its rigid torso and inability to replicate spine straightening and torso shear. The modified BioSID and EuroSID performed marginally better for torso shear but still performed badly on all other measures. While all the test dummies experienced a head strike apart from WorldSID, they were quite different to that of the PMHS as indicated in Figure 1 above and were judged to be a poor replication.

WorldSID provided good replication of torso shear to that of the PMHS but it was not possible to judge torso shear and spine straightening from the test as the passenger seat interfered with the movement of the dummy. The belt became caught in the gap between the torso and pelvic units of the dummy, thereby initiating the inertia reel lock and constraining it from completing a full movement across the car. This requires further attention and follow-up research before the dummy could be judged suitable for a comprehensive far-side testing program.

Accelerometer Traces

Data obtained from the crash tests was filtered using CFC1000 according to SAEJ211 for both the pelvis and the head. Accelerometer traces were plotted for PMHS and the dummy results in lateral "y" direction (towards the impacted door) and for Head and T1 in the downward vertical "z" direction and these are shown in the Figures 3 to 12. Unfortunately, the WorldSID head acceleration signals were not accurate and therefore could not be analysed. Also, the WorldSID failed to reach the door because of a problem with the dummy and the sash part of the belt causing it to impact on the passenger seat during its movement. The WorldSID, the EuroSID and the BioSID with the modified spine all had a good match to the PMHS pelvis acceleration. Clearly, the spine modification to the BioSID enhanced the biofidelity in terms of pelvis acceleration (Figure 5).

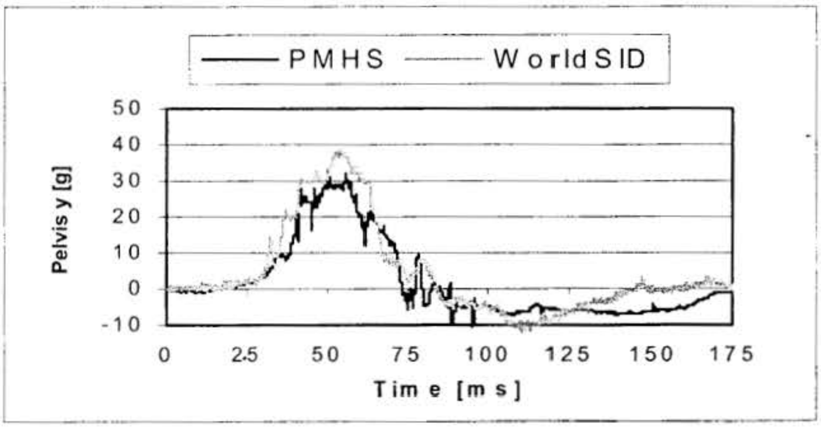

Figure 3 – Pelvic lateral g-forces for the PMHS and WorldSID

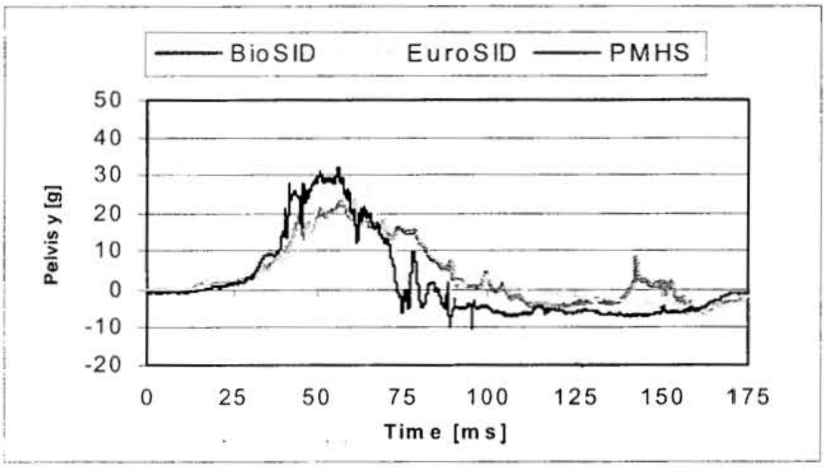

Figure 4 – Pelvic lateral g-forces for the PMHS and BioSID and EuroSID dummies

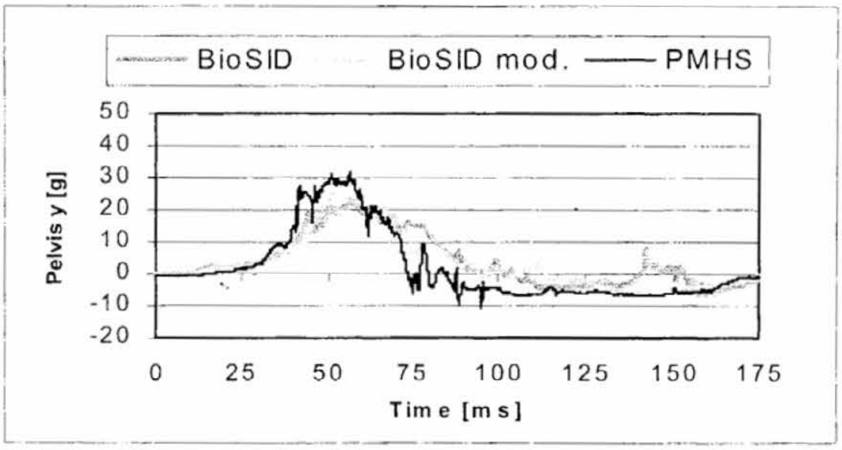

Figure 5 – Pelvic lateral g-forces for the PHMS and BioSID dummy with and without spine modification

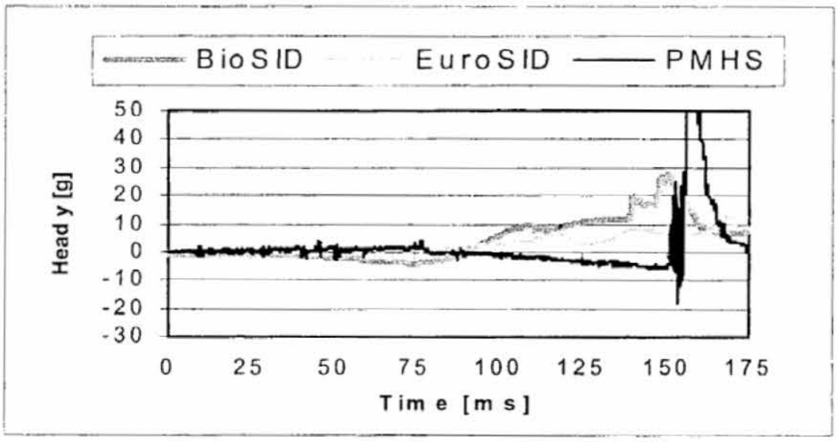

Figure 6 – Head lateral accelerations for PMHS and BioSID and EuroSID dummies

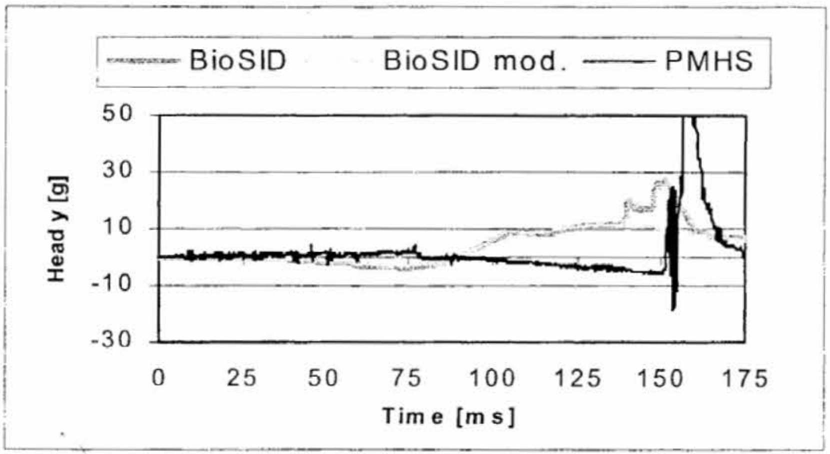

Figure 7 Head lateral acceleration of BioSID with and without spine modification

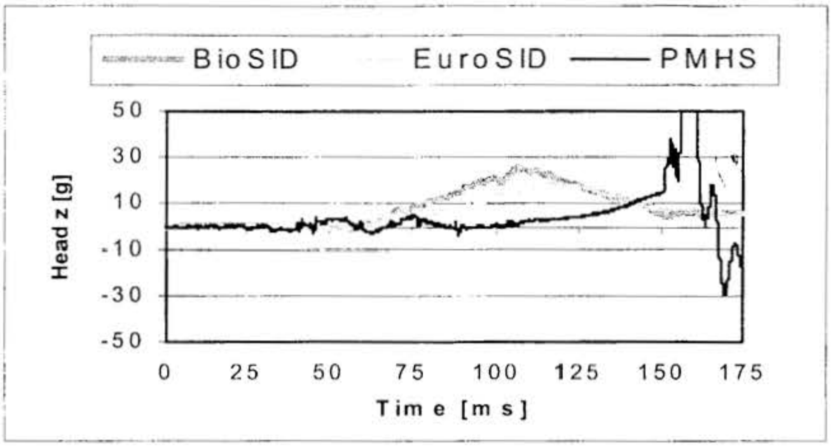

Figure 8 – Head vertical accelerations of PMHS and BioSID and EuroSID dummies

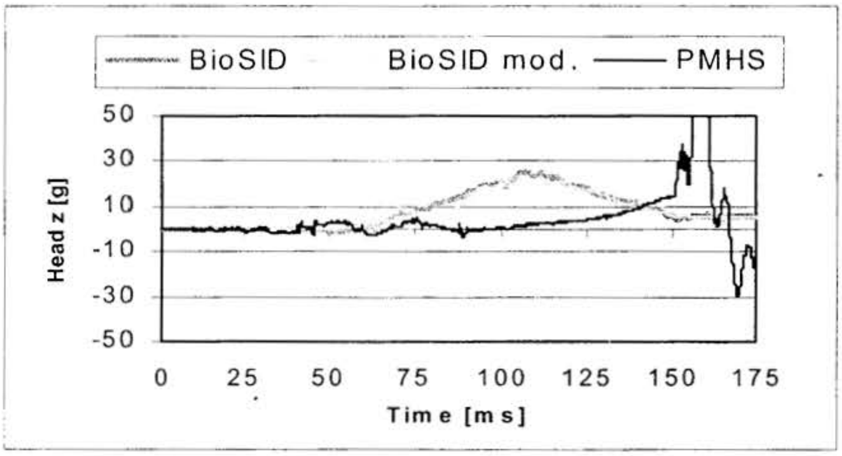

Figure 9 - Head vertical accelerations of BioSID with and without spine modification

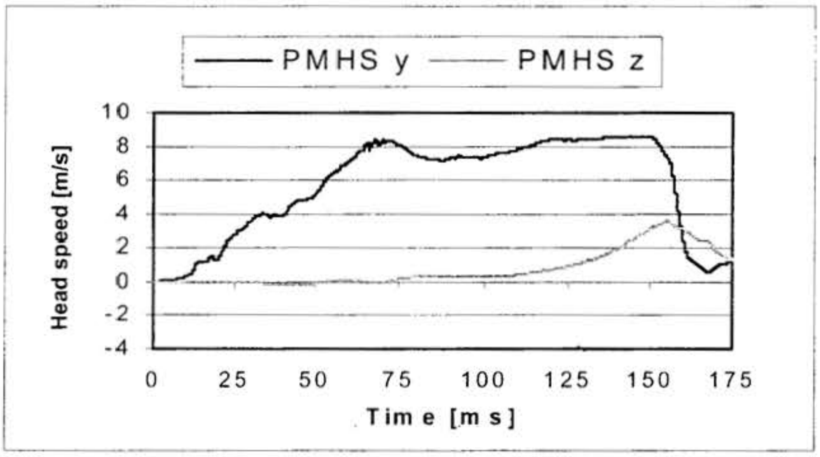

Figure 10 - PMHS lateral and vertical head speed relative to the intruding door/B-pillar

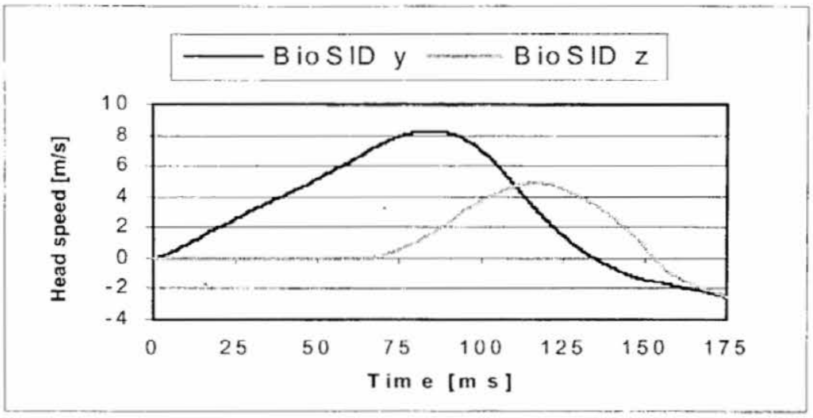

Figure 11 – BioSID lateral and vertical head speed relative to the intruding door/B-pillar

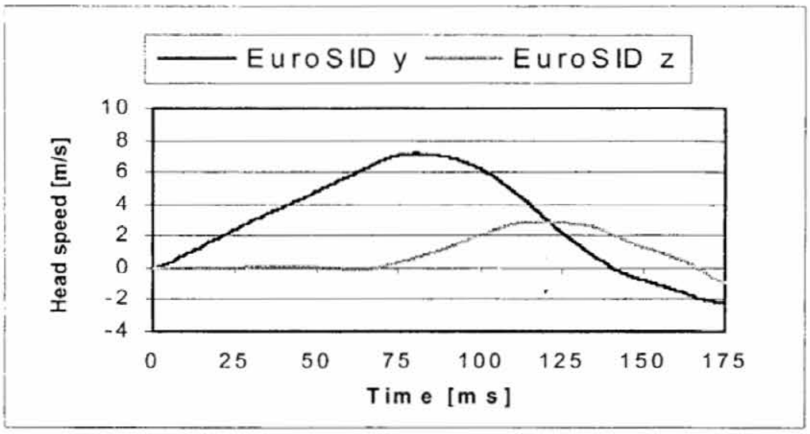

Figure 12 -EuroSID lateral and vertical head speed relative to the intruding door/B-pillar

While there was hardly any head acceleration of the PMHS before the head contact with the intruded door, the lateral and vertical accelerations of the EuroSID and the BioSID head (with and without modification) were substantially different. If the intrusion had been slightly less, there would not have been a head strike for either the EuroSID or BioSID. While the PMHS head had a true collision with the door and b-pillar, the EuroSID and the BioSID heads only marginally glanced or swiped the intruding door. The head of the modified BioSID did not contact with the door as is seen in Figure 7.

In Figure 10-12 the head speed relative the intruded door in a global co-ordinate system (the ground) is presented. As seen in Figure 10, the PMHS head speed in lateral direction towards the door was around 8 m/s relative to the intruded door after the sled is decelerated (@ about 70 msec). Thereafter, the head speed is constant until the collision. After about 70msec, the head starts to gain a vertical speed towards the ground and increases to about 3msec at the time of the collision. The resultant head collision speed was therefore about 9msec. Figure 11 and 12 confirm the inaccuracy of the existing side impact dummies to replicate the injurious event of head collision. Due to the substantial head lateral and vertical accelerations before the head swipe, the relative head-to-intruded door is reduced from 8msec to only a few at the conclusion of the deceleration period (Figure 11 and 12).

Lap Belt Loads

The final set of results analysed in this paper related to the belt loads experienced in the lap section of the seat belt fitted to the surrogates. In all cases, the surrogates slipped out of the sash section of the 3-point belt quite easily so these readings were not analysed. Figure 13 shows the results obtained for the lap belt comparisons for the far-side crash configuration tested here.

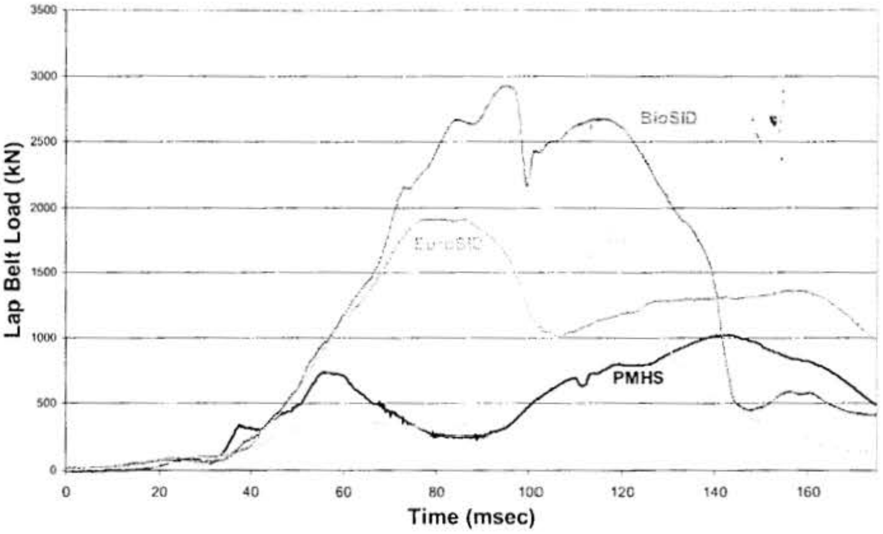

Figure 13 – Lap belt loads measured for the dummies tested in far-side crash tests

These results show a similar pattern up to about 60msec after which the load on the PMHS was considerably less than all the dummies, except perhaps for WorldSID. These higher can be explained generally by their greater rigidity compared with the PMHS. It should be noted that WorldSID loads were somewhat abnormal due to the belt lodging in the abdominal cavity.

DISCUSSION

There were a number of interesting new findings, implications for countermeasure development and needs for additional research that came from this research program and these are discussed below.

Far-side Occupant Performance

Real-world crash studies have illustrated the types of injuries that occupants sustain in a far-side crash. Of particular concern is the high rate of head injuries to occupants seated on the opposite side of the car from contact with the near-side door and side structure. This test program set out to try and understand the mechanism of far-side injuries and the ability of existing legislative and research test dummies to replicate these injuries.

A 50th percentile restrained PMHS (human cadaver) seated in the driver's position in a full-size large Australian sedan was tested in a perpendicular ECE95 type crash test to the passenger side at 65km/h. The results demonstrated that the PMHS moved laterally out of the sash section of the restraint towards the impacting MDB and its head struck the intruded door and B-pillar. Instrumentation revealed that the PMHS experienced a HIC of around 600, a 70mm extension of its spine, and torso and neck shear and bending. This test served to confirm human-like kinematics and injury mechanisms for this one crash condition and act as a baseline test condition for evaluating a series of equivalent dummy tests using a number of current side impact test dummies.

Dummy Evaluation

The ultimate aim of this research is to develop a range of in-vehicle countermeasures to offer improved protection to occupants in far-side crashes. However, one question that needed to be evaluated first was the suitability of an existing side impact test dummy to replicate accurately the occupant performance in this crash configuration. Existing side impact dummies have all been designed for near-side crash testing. A range of dummies were made available for this program including BioSID, BioSID (modified spine), EuroSID(1), and WorldSID[1] and were tested in either a full car and MDB crash or an equivalent (validated) sled test using a pre-deformed buck of a similar vehicle. Dummies were adjusted for use in this crash configuration and were restrained with a normal 3-point inertia reel seat belt and no airbags.

The results showed that none of the dummies tested gave equivalent kinematics or accelerometer performance to the baseline PMHS surrogate. Head accelerometer plots in the sideways travel direction were poor beyond 50msec for all dummies. Torso and pelvic measures were closer to those of the PMHS but again were generally slightly out of phase beyond 50-60msec. Vertical accelerations for the head and upper torso were poor compared with the PMHS. Likewise, the kinematics of the dummies were generally poor compared with the PMHS. Head kinematics was perhaps reasonable for the modified BioSID and EuroSID but all showed poor torso shear, neck shear and elongation and head impact movements.

The speed of the EuroSID and BioSID head swipe on the B-pillar/door was only a few km/h. Obviously, a human as 'stiff' as a these dummies would not be injured in a crash condition similar to the one used in this paper. The human ability of lateral flexibility as well as spine straightening and elongation most likely shifts the *moderate swipe* into a *severe impact*. According to a simple mathematical analysis there were two opposing effects influencing a potential head impact speed. First, the rotation due to the pelvis-tunnel impact initiating head impact speeds of magnitudes of the vehicle Δv. Second, the torque from the lap belt hindered this rotation. Both effects are a function of the lateral flexibility of the occupant. For a crash as assessed in this paper using the existing side impact dummies, the two effects out-balanced each other with a resulting low head speed. With a human, which is undoubtedly more flexible, the two effects are in this paper shown to be minor.

It is worth noting two important characteristics with these results. First, the WorldSID dummy was included in this test series because it seemed to offer a more humanlike spine than the others. Unfortunately, during its test, the torso and abdomen separated significantly because of this added flexibility and the lap section of the restraint became entangled in the space and the inertia-reel locked, thereby unnaturally constraining its sideways movement. This could be overcome relatively simple and would be worthwhile retesting in far-side crash configurations based on these preliminary results. It seemed to offer improved performance for this crash configuration over other existing test dummies and its spine unit gave improved spinal kinematics and accelerations. However, there were areas where further research was warranted, in particular, when the problem with the separation between torso and abdomen is addressed for this crash configuration. Moreover, as this test dummy is still going through its final evaluation testing, it is unlikely to be available for immediate testing.

Second, the trapezoid modified spinal unit was an improvement over the standard BioSID especially in torso shear as it allowed the dummy to adopt a more humanlike initial movement at the start of the test. However, its design failed to provide any added capability of spinal elongation and hence there was little improvement in either kinematics or accelerations beyond that. It would be worth exploring alternative designs of this lower spinal unit that allow these added movements as this could be a reasonable immediate option for far-side testing.

These findings suggest that none of the dummies would be suitable for developing whole vehicle countermeasures for far-side occupant protection at this stage. However, it is worth noting that both the modified BioSID and EuroSID did provide reasonable kinematics and accelerations during the first 50-60msecs. As this timeframe generally covered the initial phase of the surrogate's movement in the crash, they could be reasonable test dummies to use for developing countermeasures aimed at offering improved occupant retention in the seat.

To our knowledge, this study was the first attempt to examine crash testing for far-side occupant protection with an appropriate far-side dummy. The main focus of this paper was on evaluating the suitability of existing side impact test dummies for use in far-side countermeasure development. While

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[1] The authors are grateful to the International Harmonisation Research Activity committee for allowing us access to the 2001 prototype of WorldSID for inclusion in this evaluation.

there were some pointers to a suitable dummy for use in a testing program, it should be noted that the test program was limited to only a single crash configuration (perpendicular crash of a European MDB into the side of a single large Australian passenger car). Hence, the robustness and applicability of these findings for a range of different crash and vehicle types and impact speeds needs further experimental evaluation.

Further Research Needs

A number of future research needs have been identified during this research program and these are summarised below for information.

- Further work is required to develop an improved replacement spinal unit for the BioSID test dummy that offers improved torso shear and elongation movement in all impact directions.
- Further testing is required of the WorldSID test dummy in far-side crash configurations when it's design is finally settled and when a solution to the torso/abdominal separation is found.
- A more comprehensive testing program of PMHS and dummy kinematics, accelerations and other relevant measures for a range of different crash speeds, impact angles and two-occupant combinations is required to confirm the robustness and generality of these findings.
- Once the issue of dummy suitability is resolved, the identification of a range of suitable countermeasures and design strategies need to be identified to provide improved protection for far-side occupants in side impact crashes.

Acknowledgements

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Kinematic Sequence of PMHS Lateral Movement

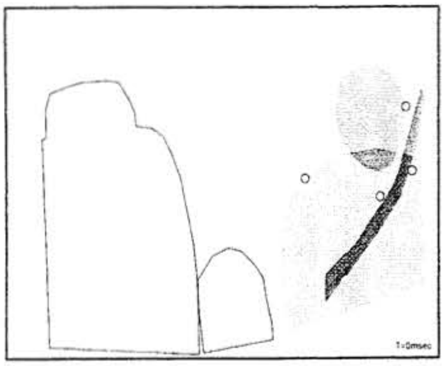

Photo 1 - Commencement

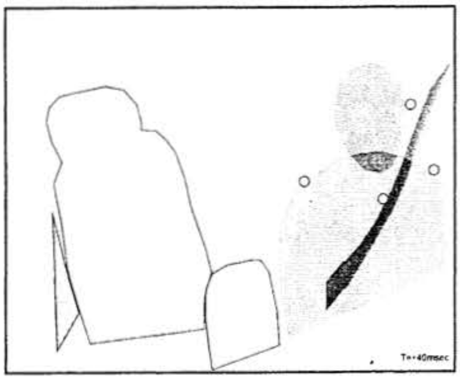

Photo 2

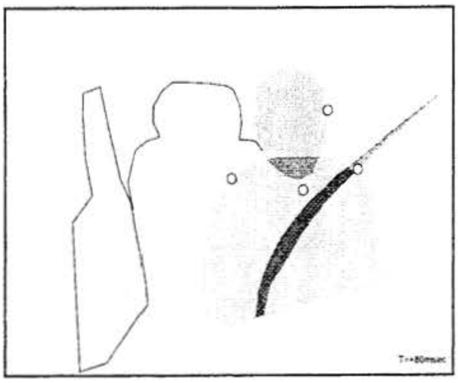

Photo 3

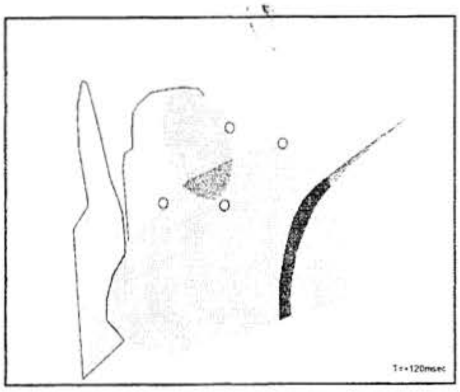

Photo 4

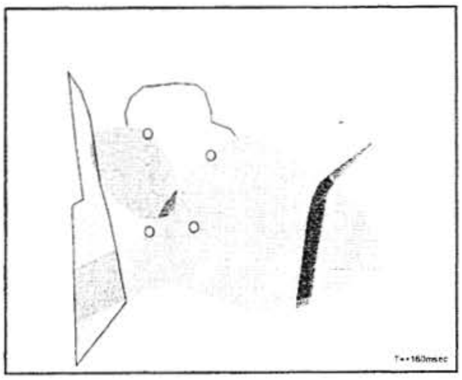

Photo 5

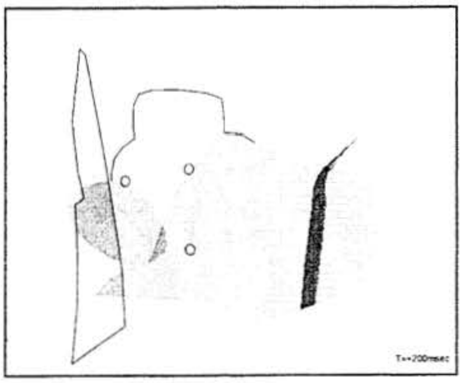

Photo 6 – final sequence

This kinematic sequence of the PMHS was derived from digital images of the on-board camera in the vehicle during the far-side crash test. It shows the lateral movement of the specimen from the moment of impact to when its head struck the opposite door panel. Note that the sequence is taken from the front of a left-hand drive vehicle configuration where the PMHS contacts the struck-side door.