

A SAFETY RATING FOR FAR-SIDE CRASHES

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ABSTRACT

A research team from Australia, Europe and the United States has conducted the research needed to provide a technology base for far-side crash protection. To date the findings are as follows: (1) in the USA and Australia there are large opportunities in far-side impact injury reduction, especially if safety features could mitigate injuries in both far-side planar impacts and rollovers, (2) a modified MADYMO human facet model was validated for use in evaluating far-side countermeasures, (3) either the THOR-NT or the WorldSID dummy would be satisfactory test devices for assessing far-side protection with minor modifications such as changing in the location of the chest instrumentation and (4) injury criteria and risk functions for use with WorldSID in far-side crashes have been documented. There is now a sufficient technology base so that far-side protection can be evaluated and rated by consumer information tests.

INTRODUCTION

An impediment to improved far-side protection has been the lack of a technical base to permit the evaluation of countermeasures. This deficiency has now been resolved by a collaborative international research project. The ARC Far-Side Impact Collaborative Research Project has been described by Fildes [2005]. It involved the assembly of a research team from industry, government and academia in Australia, Europe, and the United States. A list of the participating colleagues and organizations is included in the Acknowledgements Section.

The research involved the following projects:

- The definition of the far-side injury environment and the opportunities for injury reduction

- The development of representative test conditions and injury criteria for use with far-side test dummies
- The development and validation of computer human models for use in the evaluation of far-side countermeasures
- A matrix of sled tests of Post Mortem Human Subjects (PMHS) to determine occupant kinematics representative far-side crashes that produce injury and of the dummies available for the evaluation of far-side countermeasures.
- The assessment of the opportunities for injury reduction based on generic countermeasures

A technology base now exists to provide a far-side dummies, injury criteria, computer models, and test environments that can be used to evaluate countermeasures for far-side crash protection. This paper summarizes the research and documents its value to consumer information testing.

THE FAR-SIDE INJURY ENVIRONMENT

The National Highway Traffic Safety Administration (NHTSA) maintains the NASS/CDS database of vehicle crashes in the United States. The NASS/CDS is a stratified sample of light vehicles involved in highway crashes that were reported by the police and involved sufficient damage that one vehicle was towed from the crash scene.

In the NASS/CDS data query, far-side occupants in planar crashes were defined as drivers in vehicles with right side damage or right front passengers in vehicles with left side damage. Drivers in rollovers that were passenger side leading were classified as being in far-side rollovers. The converse was true for passengers.

Each NASS/CDS case contains a weighting factor that is used by the NHTSA to extrapolate the individual cases to the national numbers. The distributions to follow are based on the NASS/CDS weighted events.

Table 1 shows the annual distribution of MAIS 3 and greater injuries by belt use, crash direction and crash mode, using at least nine years of data for years prior to 2004 [Digges, 2006]. The data in Table 1 shows that about 43% of the MAIS 3+ injuries in side crashes and rollovers occur in far-side crashes. More than half of the MAIS 3+ injuries in rollover are in far-side rolls.

Table 1. Annual MAIS 3+ Injuries from NASS/CDS in Near-side and Far-side Crashes by Crash Type and Direction

Crash Type/ Belt Use	Planar	Roll
Far-side Belted	2,166	3,540
Far-side Unbelted	5,095	6,325
Far-side Total	7,261	9,865
Near-side Belted	7,360	3,532
Near-side Unbelted	6,714	5,551
Near-side Total	14,074	9,083
Near-side/Far-side Total	21,335	18,948
% Due to Far-side	34%	52%

An in-depth analysis of the crash environment for belted occupants in far-side crashes was presented in earlier papers [Gabler, SAE 2005 and ESV 2005]. The analysis indicated that for belted occupants with MAIS 3+ injuries, the 50% median crash severity was a lateral delta-V of 28 km/h and an extent of damage of 3.6 as measured by the CDC scale [SAE Standard J224, Collision Deformation Classification]. The most frequent damage area for seriously injured belted occupants was the front 2/3 of the vehicle (42%), followed by the rear 2/3 (21%). The most frequent principal direction of force (PDOF) was 60° (60%), followed by 90° (24%). The head and chest were the most frequently injured body regions, each at about 40% [Gabler 2008]. The injuring contacts that most frequently caused chest injury were the struck-side interior (23.6%), the belt or buckle (21.4%) and the seat back (20.9%) [Fildes, 2007]. A Harm analysis showed 30% of the Harm associated with side impact crashes occurred to the far side occupant and that this figure was reasonably consistent in both the US and Australia (Gabler, Firzharris, et al 2005).

MODELS AND DUMMYS FOR USE IN FAR-SIDE TESTS

The MADYMO human facet model was initially validated for the far-side crash condition by duplicating the far-side PMHS test reported by Fildes [2002]. The model validation was reported in a separate paper [Alonso, 2005]. The model was then used to evaluate occupant kinematics when subjected to a 28 km/h delta-V pulse that approximates the one produced by the IIHS barrier [Alonso, 2007]. The human facet model was also used to evaluate the consequence of variations in crash pulse and in generic countermeasures. The MADYMO human facet model was considered to be a good tool for assessing the influence of countermeasures on occupant kinematics in far-side crashes [Alonso 2007].

The accuracy of the seat belt to shoulder interaction for the MADYMO human facet model was evaluated by Douglas [ESV 2007 and AAAM 2007]. The shoulder complex of the model was modified to better duplicate the belt interaction. Validation of the model was based on low severity human volunteer tests and higher severity PMHS tests involving varying belt configurations and levels of pretension.

Initially, a range of current side impact test dummies (BioSID, BioSID_Mod, EuroSID1, and WorldSID) were compared with a single PMHS test to evaluate their potential to represent a human in a far side crash [Fildes 2002, Bostrom 2003]. Subsequently, the MADYMO computer models of the existing adult side and frontal dummies were compared with the human facet model [Alonso, 2007]. The dummy models evaluated included the following: Hybrid III, Biosid, Eurosid 1, Eurosid 2 and SID2S. It was evident from the evaluation that none of the standard dummies possessed the kinematics to duplicate the motion observed in either the initial PMHS test or the MADYMO human facet model. Consequently, these dummies were eliminated from further testing. The WorldSID and the THOR-NT were subsequently selected as the best candidates for a far-side dummy. Sled testing indicated that the BioSID with a modified spine and shoulder unit did provide reasonable human-like kinematics [Fildes 2002, Bolstrom 2003]. However, this modified dummy was not a serious contender given its pure research status.

THE BIOMECHANICAL TEST PROGRAM

Under the Far Side Impact Collaborative Research Program, a series of PMHS tests was conducted by the research staff at The Medical College of

Wisconsin [Pintar, 2006, 2007]. The purpose of the PMHS tests was to assess the kinematics that needed to be reproduced in a dummy. The development of injury criteria was not a requirement. A test program that involved 18 different test configurations was conducted. Each test condition was run first with a PMHS and then the WorldSID and THOR-NT dummies were subjected to the same test condition. The test variations included test impact angle (60 and 90 degrees), test speed (11 and 30 km/h), shoulder belt type (inboard and outboard anchorages), center support (chest and shoulder load paths), shoulder belt tension, and shoulder belt anchorage location (high, low, mid and forward). All configurations included a center console support for the pelvis.

Three of the MCW tests involved different configurations of conventional three-point belts tested at 90 degrees. These configurations varied the height of the D-ring. In the low-position the D-ring was aligned with the top of the shoulder. In the mid-position, the D-ring was 90mm above the shoulder and the high-position it was 150mm above the shoulder.

The complete data for these tests is contained in the Stapp paper [Pintar 2007]. The y-z head trajectory plots are shown in the figures to follow.

Both the WorldSID and the THOR-NT response in far side impacts compared favorably to the PMHS responses. The WorldSID performed somewhat better in the 90deg tests while the THOR-NT was better in the 60deg tests. However, both dummies closely mimicked the head trajectory of the PMHS subjects in the testing conditions to which they were subjected. The greatest limitation of the dummies was the location of the chest deflection instrumentation. Some relocation of the chest instrumentation would be required in order to accurately measure this parameter in far-side crashes. The test results have been reported by Pintar [Pintar 2007] who concludes, "The THOR and WorldSID dummies demonstrate adequate biofidelity to develop countermeasures in this (far-side) crash mode". [Pintar 2007].

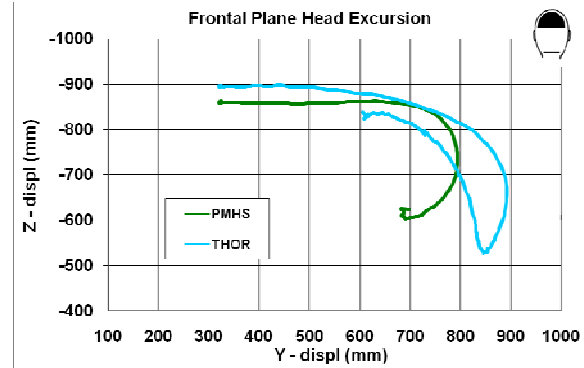


Figure 1. PMHS and THOR Far Side Sled Test (HS139) with Mid-Back Belt geometry @ 30km/h

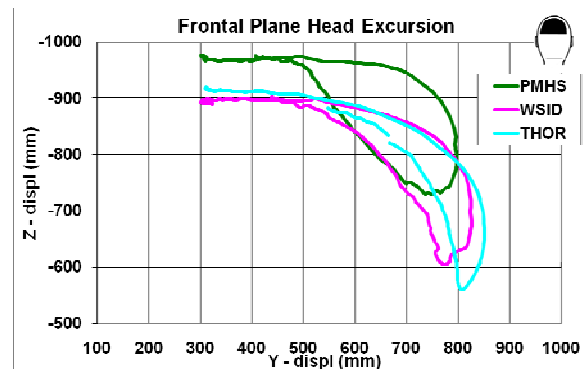


Figure 2. PMHS, WorldSID and THOR Far Side Sled Test (HS104) with Mid-Back Belt geometry and pretension @ 30km/h

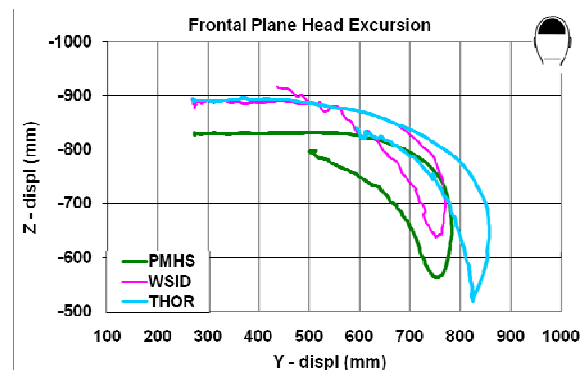


Figure 3. PMHS, WorldSID and THOR Far Side Sled Test (HS139) with Mid-Forward Belt geometry and pretension @ 30km/h

INJURY CRITERIA FOR FAR-SIDE DUMMY

The WorldSID Working Group has proposed injury criteria for use when the dummy is subjected to near-side impacts. Many of the injury measures are also applicable to far-side impacts. The WorldSID criteria applicable to far-side impacts have been summarized and criteria needed for the evaluation of

far-side countermeasures has been added in a Task Report prepared for the project [Gibson and Morgan 2008]. The Task Report contains the available injury risk functions for the head and face, neck, spine, shoulder, thorax, abdomen, pelvis, lower extremities and upper extremities. It contains proposed injury risk curves for head, neck (skeletal), spine, chest, abdomen, pelvis, lower extremities and upper extremities.

One of the injury measures currently missing from most dummy measurements is the criteria for injury to the soft tissues of the neck. Of particular concern is the injury to the carotid artery from direct or induced loading by the shoulder belt or by other countermeasures. This issue has been attacked by teams from Medical College of Wisconsin, and Wake Forrest-Virginia Tech. The results have been reported in a series of papers [Stemper, IRCOB 2005, J. Bio., 2005, Bio. Sci. Inst., 2005, IRCOB 2006, J. Trauma, 2007, Annals Bio.Eng., 2007, J. Bio, 2007, and Gayzik, AAAM, 2006 and Bio. Sci. Inst., 2006].

KINEMATICS OF AVAILABLE DUMMIES

A review of the crash test films available at the NHTSA/FHWA Crash Film Library found only one documented test of a far-side crash. In this crash the crash direction was 90 degrees and the delta-V was approximately 15 km/h. The dummy slid out of the shoulder belt. Six far-side crashes were subsequently conducted and documented [Digges, 2001]. In this series of tests, angle of impact was 60 degrees and the delta-V was 40 km/h. The tests evaluated variations in shoulder belt tension and latch plate design. In all configurations, the Hybrid III dummy slid out of the shoulder belt. These tests suggested that additional countermeasures would be necessary to limit the excursion of the upper body.

Fildes [2002] reported on efforts to develop a dummy for use in far-side impacts. He found that existing dummies lacked the flexibility in the spine to duplicate the kinematics of a baseline PHMS test. In a later paper, Fildes reported better results based on limited testing of a BioSID dummy in which the spine had been replaced with a coil spring [Fildes 2003]. He recommended continuing research to develop a dummy and injury criteria so that countermeasures could be specified and evaluated.

CRASH TESTS WITH FAR-SIDE DUMMIES

Several vehicle crash tests have been reported in the literature that included both near and far-side dummies

[Newland 2008]. The Newland study reported the result of 3 Moving Deformable Barrier (MDB)-to-car tests and 3 pole side impact tests. Four of the tests used the WorldSID as the far-side dummy. The other two tests used the bioSID. The MDB speeds in the tests were at 50 and 65 km/h. The impacts with the pole were at 32 km/h.

In all the tests, there was interaction between the two dummies. However, in all cases this later interaction had no influence on the injury measures from the near-side contact. The authors concluded that: "the presence of the adjacent dummy occupant seated on the non-struck side was observed to have no influence on the injury to the struck side dummy occupant resulting from intruding side structure".

In all six of the tests, the far-side dummy slid out of the shoulder belt. In two of the tests that involved a side impact with a pole, there was a head-to-head impact that produced a HIC in excess of 2000 on both dummies.

The authors recommended a minor change in the WorldSID to reduce the tendency of the belt to penetrate the cavity between the shoulder and thorax. This penetration occurs as the dummy begins to slip out of the shoulder belt.

MADYMO MODELING OF BELT GEOMETRY

To further evaluate the influence of belt geometry on the ability of the belt to retain the far-side occupant in a crash, the MADYMO Human Facet Model from TNO was used. This model had been validated against a single PMHS test and the results were published [Alonso 2007]. Further improvements in the model shoulder to belt interaction were accomplished, based on human volunteer testing at low severity far-side impacts and PMHS testing in more severe impacts [Douglas 2007]. As part of the present study, the model was validated against the three PMHS tests reported in an earlier section [Echemendia 2009]. The model was then applied to determine the effect of shoulder belt geometry and pretensioning on the response of a far-side dummy in tests typical of the NCAP and IIHS tests. The results show that the belt geometry that performed well in the PMHS tests continued to perform well in the consumer rating tests. The belt configurations that permitted the highest head excursion in the PHMS tests also permitted the highest head excursion in the consumer rating tests.

When using the Human Facet Model, the interaction between the seat belt and the shoulder area was known to be critical for accurate simulation. The

Human Facet Model was modified to better represent this shoulder area by adding rigid ellipsoids as previously reported by Douglas [2007]. A sphere with a radius of 0.053 m represented the shoulder and a sphere with a 0.045 m radius represented part of the upper arm near the shoulder. A Multi-body surface to Finite Element surface kinematic contact was used to describe the interaction between the safety belt and the ellipsoids representing the shoulder area.

The simulations of the PMHS tests showed that a seatbelt and the D-ring at a mid-height and back position resulted in the lowest head excursion. The PMHS test with the same belt position showed the same result. Simulations done with the D-ring at a mid-height and forward position and at a low-height and back position resulted in higher head excursions. In both of these cases, the belt slipped from the shoulder. The PMHS test with the D-ring at a mid-height and forward position also showed the belt slipping from the shoulder. An increased head excursion resulted.

These MADYMO results were generally similar when the 11km/h, 21km/h (IIHS) 24km/h (NCAP), 30km/h and 40km/h pulses were applied in the lateral direction. In simulations with the same lateral acceleration pulse but different belt geometry, results showed that the head excursion in the lateral direction ranged between 185 mm to 245 mm greater for the worst configuration when compared to the best belt configuration. The 11 km/h test was the source of the lower range and the 30 km/h test was the source of the higher range.

The largest difference in head excursion occurred in the 30 km/h tests and the Y-Z plots are shown in Figure 4.

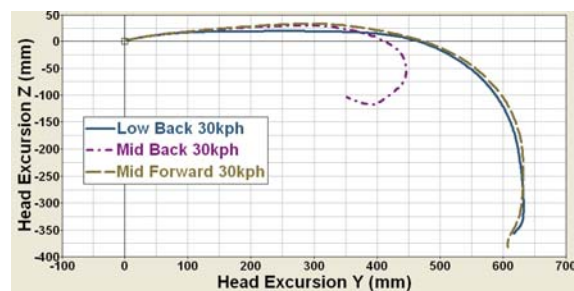


Figure 4. Human Facet Model Y-Z head excursion with three D-ring positions (tests @ 30km/h)

MODELING OF BELT PRETENSIONING

The same tests configurations were also simulated using a belt pretensioner. The belt pretensioner

allowed 72 mm of belt retraction and it was activated 10 ms after time zero. The belt pretensioner did not prevent the belt from slipping from the shoulder in the mid-height and forward position and in the low-height and back position tests. It did reduce the head excursion in the lateral direction from 10 to 75 mm. The belt did not slip in the test with the D-ring at mid-height and back position similar to the test without pretensioning. It also reduced the head excursion by 61 to 74 mm. The largest difference in head excursion occurred in the 30 km/h tests and the Y-Z plots are shown in Figure 5.

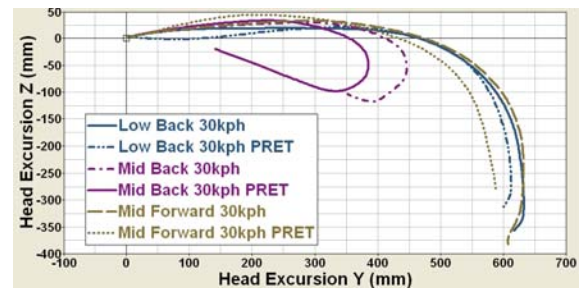


Figure 5. Human Facet Model Y-Z head excursion with three D-ring positions and with the use/no use of pretensioner (tests @ 30km/h)

These results show that while pretensioning helps reduce head excursion up to 75 mm, the appropriate location of the D-ring has a better benefit. According to these results the belt geometry is important to prevent the belt from slipping and to reduce head excursion.

A SAFETY RATING SCHEME

The THOR and WorldSID have both demonstrated good biofidelity in reproducing human kinematics in far-side crashes. The initial consumer information tests should utilize these validated capabilities and base the rating on head excursion. Ultimately, either dummy could be used to measure injury to all relevant body regions.

This strategy is similar to that employed in the initial standard FMVSS 213, "Child Restraint Systems". The pass-fail criterion for the original 213 standard was based on head excursion.

The MADYMO modeling has shown that reduction of head excursion can be achieved by appropriate belt geometry and pretensioning. A key to reducing the head excursion is the retention of contact with the shoulder. If the occupant's shoulder slips out of the belt the upper body is free to move laterally at increased velocity. The resulting impacts of upper body regions with intruding structure are likely to be

increased in severity. In addition, undesirable loading of the abdominal region by the belt system may result. Retaining the occupant in the belt system should be beneficial in both far-side planar crashes and rollovers.

It is anticipated that the greatest benefit in controlling head lateral excursion will be a reduction of the severity of head contacts with intruding structures. This benefit provides another reason for using head excursion as the rating metric.

The NCAP test condition at a severity of about 25 km/h provides a reasonable crash environment for rating far-side protection. Figure 6 shows the distribution of occupants with MAIS 3+ head injuries. The figure shows a very sharp increase in frequency of head injuries in the range of 25 to 30 km/h lateral delta-V.

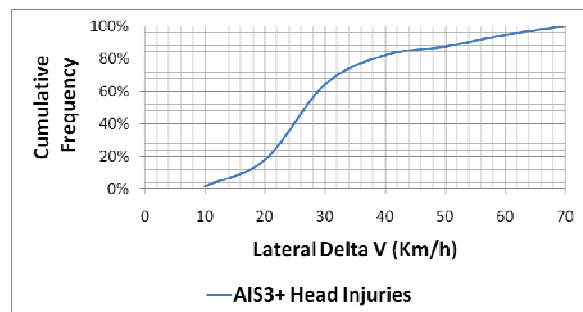


Figure 6. Distribution of occupants with AIS 3+ head injuries vs. lateral delta-V based on NASS/CDS 1993-2007

One consequence of limiting the lateral head excursion is an increase in the amount of intrusion that can be tolerated before a head strike occurs. This relationship is illustrated in Figure 7 [Echemendia 2009]. The figure is based on the maximum head excursion predicted by the MADYMO modeling of 30 km/h far-side crashes. The figure shows the clearance or interference between the head and the side structure as a function of the CDC extent of damage to the side of the vehicle. The head to side structure clearance for the best and worst belt configurations are plotted.

Figure 7 provides one possible basis for the far-side safety rating. The objective of the rating is to encourage designs to prevent a head impact with the intruding far-side structure. The more intrusion that can be tolerated before a head impact occurs, the higher the star rating should be. For the Taurus model, the belt systems that prevented the belt from slipping off the shoulder would tolerate an extent of damage CDC 4 before head contact occurred. If the dummy slipped out of the belt, the head strike would occur when damage reached a CDC of 3. Vehicles with less lateral occupant space might have different ratings for the

same restraint configuration. If the restraint system prevents a head impact for an extent of damage CDC 5, the rating is 5 star. Lower star ratings would be assigned to correspond to the lower extent of damage permitted.

A moving deformable barrier side impact test at 65 km/h with WorldSID dummies in both the near-side and far-side front seat locations indicated that interaction between the dummies occurred at about 90 ms [Newland 2008]. In this test, the belt restraint system allowed the dummy to slip out of the belt. The interaction between the dummies was late enough so that it did not influence the interaction of the near-side dummy with the near-side countermeasures. The interaction was also late enough to permit the far-side dummy to slip out of the shoulder belt. However, the full range of head excursion was interrupted by the interaction of the two dummies. This impediment may require a modification to the star rating for belt systems that do not retain the far-side dummy. Additional crash testing should permit suitable refinements in the basic rating concept. Ultimately, head and chest injury measures could be used as is done in the NCAP ratings.

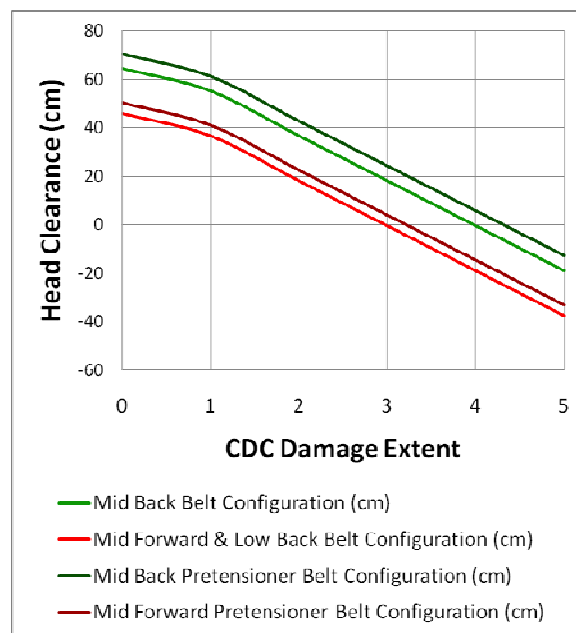


Figure 7. Clearance between the head and the intruding side structure in 30km/h MADYMO simulations for best and worst belt configuration on a Mid-Sized Vehicle (Ford Taurus)

DISCUSSION

Recent changes in US Federal Motor Vehicle Safety standards have introduced additional testing requirements intended to further improve side impact

protection. These standards include tests with both 50% male and 5% female dummies in near side crashes with both a pole and a movable deformable barrier. The principal benefits from these tests are in near-side crash protection. There is no regulatory requirement for far-side protection based on dummy crash test performance.

At present, no agency conducts consumer information tests to evaluate far-side protection. As a result, there is little market incentive to incorporate technology that has been available for far-side protection. Earlier papers reported improved far-side protection in tests of new countermeasures including center air bags and four point belts [Bostrom 2005 and 2008]. Tests and modeling of conventional 3-point belts show that even current countermeasures can provide enhanced far-side protection at crash severities employed in near-side NCAP and IIHS tests.

An impediment to improved far-side protection has been the lack of a technical base to permit the evaluation of countermeasures. This deficiency has now been resolved by the research conducted by the Far Side Impact Collaborative Research Project and summarized in this paper.

The Project showed that the WorldSID and the THOR-NT both demonstrated a high degree of biofidelity in 18 tests that were representative of a large range of far-side crashes. Either dummy appears to be a satisfactory measuring device with regard to its kinematic response. However, changes in the location of the chest instrumentation would be required to obtain accurate readings of the maximum chest deflection. A shield for the shoulder joint is recommended for the WorldSID to prevent inaccurate kinematics after dummy slips out of the belt. The available injury risk functions to be used with the WorldSID have been collected from the literature and summarized in a report developed under the Project.

The MADYMO human facet model was shown to accurately duplicate the human kinematics when applied PMHS tests that simulate a far-side impacts. The modified MADYMO human facet model offers a basis for evaluating human kinematics when exposed to far-side impacts. Consequently, the model is useful for evaluating design variables in far-side safety systems.

The THOR and WorldSID have both demonstrated good biofidelity in reproducing human kinematics in far-side crashes. The initial consumer information tests

should utilize these validated capabilities and base the rating on head excursion. Ultimately, the ratings could be based on HIC and other injury measurements that are possible on these advanced dummies.

The MADYMO models of the Hybrid III, Biosid, Eurosid 1, Eurosid 2 and SID2S were found to produce much less head excursion than observed in the PMHS tests that were used for model validation [Alonso 2007].

The MADYMO human facet model demonstrated that belt geometry and pretensioning can influence the performance of conventional three point belt systems as measured by a far-side dummy in a side NCAP or IIHS test.

Tests conducted in Australia have shown that the presence of a far-side dummy does not interfere with the side protection measurements made by the near-side dummy. However, there was interaction between the near-side and far-side dummies during the rebound of the near-side dummy. The interaction occurred well after the far-side dummy slipped out of the shoulder belt. Consequently, the ability of the belt system to restrain the far-side dummy could be determined by the test.

While most of this discussion has focused on consumer tests carried out in the US, it is also relevant for consumer tests in other parts of the world (eg; ANAP in Australia, EuroNCAP in Europe and JNCAP in Japan).

With the lack of any regulation in sight for ensuring improved far-side occupant protection, the inclusion of a WorldSID or THOR side impact test dummy on the non-struck side in current side impact tests is one option to address this shortfall.

CONCLUSIONS

All technical impediments to the crash test and evaluation of far-side countermeasures have now been removed by the research conducted under the Far Side Impact Collaborative Research Project.

There continue to be a large number of injuries that occur in far-side planar crashes and rollovers. A number of countermeasures have been demonstrated that could mitigate the injury producing environment of far-side crashes. There is at present no marketing incentive for introducing far-side countermeasures. The absence of regulatory and consumer information tests of far-side safety is now the major impediment to improved safety.

Either the WorldSID or the THOR-NT accurately mimic the kinematics of a human in far-side crashes of the severity used in SNCAP and IIHS tests.

Crash tests and modeling have shown that the retention of the far-side occupant could be improved by attention to the design of the existing 3-point belts. Consumer information tests to encourage these improvements would be a reasonable step to improve passenger safety in far-side crashes. One possibility for addressing this deficiency could be the inclusion of a WorldSID or THOR-NT test dummy in the far-side seating position when conducting a side impact consumer information test.

Crash tests have shown that the presence of a far-side dummy has no influence on the near-side dummy's measurement of injuries from the near-side contact.

Incorporation of a far-side dummy in SNCAP EuroNCAP, ANCAP, JNCAP and IIHS consumer information tests is a low cost and practical step to encourage safety improvements in far-side crashes.

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