F2008-08-131

THE TECHNOLOGY BASE FOR FAR-SIDE OCCUPANT PROTECTION

[1]Digges, Kennerly*, [2]Fildes, Brian
[1]George Washington University, USA, [2]Monash University, Australia

KEY WORDS – Crashworthiness; Far-side Crashes; Side Impact Dummies; Side Impact Simulation; Side Impact Data

ABSTRACT - A technical team from Australia, Europe and the United States has been assembled to plan and conduct 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 for far-side injury reduction, especially if safety features could mitigate injuries in both far-side planar impacts and far-side rollovers, (2) the IIHS test barrier offers considerable promise as a suitable test device to induce the damage that is representative of far-side crashes that produce injury, but the test speed should be higher for far-side crashes than for near-side crashes, (3) a modified MADYMO human facet model was validated for use in evaluating far-side countermeasures, (4) either the THOR-NT or the WorldSID dummy would be a satisfactory test device for assessing far-side protection, but would require minor modifications such as changing in the location of the chest instrumentation and (5) injury criteria and risk functions for use with WorldSID in far-side crashes have been documented.

INTRODUCTION

Recent changes in US Federal Motor Vehicle Safety standards have introduced additional testing requirements intended to further improve near-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. However, occupants in far-side crashes may benefit vicariously as well. 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 largely resolved by a research project involving participation from government, academia and industry. The participating colleagues and organizations are listed in the Acknowledgements section.

The results of this research provide designers an opportunity to consider far-side safety improvements in conjunction with their design changes to comply with the new US side impact standard.

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.

The assessment of the occupant kinematics representative of the far-side crashes that produce injury and of the dummies available for the evaluation of far-side countermeasures. Occupant kinematics have been assessed by a comprehensive biomechanical test program of post mortem human subjects (PMHS).
The assessment of the opportunities for injury reduction based on generic countermeasures.

The overall 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. The research is nearing completion. A technology base now exists to provide far-side dummies, injury criteria, computer models, and representative test environments that can be used to evaluate countermeasures for far-side crash protection. This paper describes the results of the research to date.

THE RESEARCH RESULTS

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 right front 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 average annual distribution of MAIS 3 and greater injuries by belt use, crash direction and crash mode, using at least nine years of NASS/CDS data for years prior to 2004 [Digges, 2006].

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	Total
Far-side Belted	2,166	3,540	5,706
Far-side Unbelted	5,095	6,325	11,420
Far-side Total	7,261	9,865	17,126
Near-side Belted	7,360	3,532	10,892
Near-side Unbelted	6,714	5,551	12,265
Near-side Total	14,074	9,083	23,157
Near-side+Far-side Total	21,335	18,948	40,283
% Due to Far-side	34%	52%	43%

The data in Table 1 shows that about 43% of the MAIS 3+ injured in side crashes and rollovers occur in far-side events. More than half of the MAIS 3+ injured in rollover crashes are in far-side rolls. The number of MAIS 3+ injured that occur annually in planar and rollover far-side events is 17,126. This compares with 14,074 MAIS 3+ in near-side planar crashes.

An earlier study of belted occupants in NASS/CDS far-side crashes found different injury patterns for the driver and right front passenger [Augenstein 2000]. For drivers the two most frequent contacts that produced AIS 3+ injuries were the far-side interior and the seatbelt. For the right front passengers, the two most frequent injuring contacts were the seat and the other occupant.

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 principal direction of force was 90^o and the delta-V was approximately 15 kph. 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^o and the delta-V was 40 kph. 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.

An in depth analysis of the crash environment for belted occupants in far-side crashes was conducted under this project and 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 kph 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^o (60%), followed by 90^o (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].

Finite element vehicle models were used to compare the damage patterns induced in a 2004 Taurus when impacted in the side by a GMC 1500 pickup truck at a crash severity of 28 kph lateral delta-V [Mohan, 2005, Digges, 2005]. The 60^o impact produced an extent of damage CDC 4. The 90^o impact produced a CDC extent of damage of 3.6. The FEM Taurus model was impacted by both NHTSA and the IIHS barrier at a lateral delta-V equivalent to 28 kph. The IIHS barrier produced a CDC 3.6 damage pattern that closely duplicated the pattern of the pickup truck at 90^o but produced the maximum damage at the same location as the pickup test at 60^o. Since the IIHS barrier and IIHS side impact test condition are generally accepted as de facto standards, the IIHS barrier test was established as the baseline for assessing the performance of available dummies based on MADYMO computer modeling. However, the test speed was increased to produce a lateral delta-V of 28 kph.

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 kph 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, BioSIDMod, 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, EuroSID1, EuroSID2 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. Fildes reported improved kinematic response based on limited testing of a BioSIDMod dummy in which the spine had been replaced with a coil spring [Fildes 2006]. However, this modified dummy was not a serious contender, given its pure research status. The WorldSID and the THOR-NT were subsequently selected as the best candidates for a far-side dummy.

Under the Far-side Impact Collaborative Research Project, dummy and PMHS tests were conducted by the research staff at The Medical College of Wisconsin [Pintar, 2006, 2007]. The purpose of the PMHS tests was to determine 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 sled test angle (60^o and 90^o), test speed (11 and 30 kph), shoulder belt type (inboard and outboard anchorages), center body support (chest and shoulder load paths), shoulder belt tension and shoulder belt anchorage location (high, low, mid and forward).

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 90^o tests while the THOR-NT was better in the 60^o 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 who concludes, "The THOR and WorldSID dummies demonstrate adequate biofidelity to develop countermeasures in this (far-side) crash mode.." [Pintar 2007].

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 has been summarized and criteria needed for the evaluation of far-side countermeasures has been added in a Task Report prepared for the far-side 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 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 is being attacked by teams from Medical College of Wisconsin and Wake Forrest-Virginia Tech. The neck injury criteria are still under development. However, progress has been reported in a series of papers [Stemper, IRCOBI 2005, J. Bio., 2005, Bio. Sci. Inst., 2005, IRCOBI 2006, J. Trauma, 2007, Annals Bio.Eng., 2007, J. Bio, 2007, and Gayzik, AAAM, 2006 and Bio. Sci. Inst., 2006].

CONCLUSIONS

The far-side crash environment that produces 50% of the MAIS 3+ injured for belted adult occupants in planar crashes is as follows: (1) Lateral Delta-V = 28 kph and (2) CDC Extent of Damage = 3.6. This crash environment was reproduced by a simulated crash of a full size Chevrolet pickup into a Ford Taurus using finite element models. The damage pattern was found to be generally similar to that produced by the IIHS barrier. However, it was necessary to impact the vehicle far-side at a higher delta-V than specified in the IIHS test for near-side safety ratings.

The MADYMO human facet model was shown to accurately duplicate the human kinematics when applied to an available test of a PMHS in a far-side impact. Further improvements in the model shoulder to belt interaction have been accomplished, based on human volunteer testing in low severity far-side impacts and PMHS testing in more severe impacts. The modified MADYMO human facet model offers a basis for evaluating human kinematics when exposed to far-side impacts. Consequently, the model should be useful for evaluating design variables in far-side safety systems. The MADYMO models of the Hybrid III, Biosid, Eurosid 1, Eurosid 2 and SID2S were found to produce kinematics that did not duplicate the human response. Research to apply computer models to assess countermeasures is underway and will be reported when completed.

The WorldSID and the THOR-NT both demonstrated a high degree of biofidelity in 18 tests that were representative of a 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. 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. Additional criteria for soft tissue neck injury are under final development.

Improved safety features in far-side crashes offer a large opportunity for reducing motor vehicle casualties. The research cited in this paper provides the technical basis for evaluating and developing far-side countermeasures.

ACKNOWLEDGEMENTS

Research participants, managers and resource personnel involved in the Far-side Collaborative Research Project include the following: Monash University- B. Fildes (Chair), C. Douglas, M. Fitzharris, A. Linder and T. Gibson; George Washington University – K. Digges (co-chair), B. Alonso, P. Mohan, and R. Morgan; Medical College of Wisconsin - F. Pintar, N. Yoganandan, K. Brazel, G. Stinson, M. Steinman and T. Generelli; Va. Tech/Wake Forest - S. Duma, C. Gabler, S. Gayzik, and J. Stitzel; University of Miami School of Medicine - J. Augenstein; Wayne State University – K. Yang; Autoliv - O. Bostrom, O. and Örtenwall; GM Holden - L. Sparke (retired) and S. Smith; General Motors – R. Lange; Ford – S. Rouhana; DoT Australia - C. Newland.

The funding for the far-side project was provided in part by the Australian National Research Counsel to Monash University in Australia, with funding contributions from Autoliv, Ford, and GM Holden and cost sharing from the other participants. Additional funding for this research has been provided by private parties, who have selected Dr. Kennerly Digges [and the FHWA/NHTSA National Crash Analysis Center at the George Washington University] to be an independent solicitor of and funder for research in motor vehicle safety, and to be one of the peer reviewers for the research projects and reports. Neither of the private parties have determined the allocation of funds or influenced the content of the research.

REFERENCES

Alonso, B., “Validation of the MADYMO Human Facet Model for Far-Side Crash Simulation”, Report to the National Crash Analysis Center, GW University, May 2005.

Alonso, B., Digges, K., and Morgan, R., “Far-side Vehicle Simulations with MADYMO”, SAE 2007-01-0378, April 2007.

Augenstein, J., Perdeck, E., Martin, P., Bowen, J., Stratton, J., Horton, M., Singer, M., Digges, K., and Steps, J., “Injuries to Restrained Occupants in Far-Side Crashes”, pp. 57-66, 44th *Annual Proceedings of the Association for the Advancement of Automotive Medicine,* October 2000.

Bostrom, O., Fildes, B., Morris, A., Sparke, L., Smith, S., and Judd, R., “A Cost Effective Far Side Crash Simulation”, ICRASH Vol 8, No. 3 pp. 307-313, 2003.

Digges, K., and Dalmotas, D., “Injuries to Restrained Occupants in Far-Side Crashes”, Paper Number 351, *ESV Conference*, June 2001.

Digges, K., Gabler, H., Mohan, P., and Alonso, B., “Characteristics of the Injury Environment in Far-Side Crashes”, 49th *Proceedings of the Association for the Advancement of Automotive Medicine*”, pp. 185-214, September 2005.

Digges, K., Gabler, H., "Opportunities for Reducing Casualties in Far-side Crashes", SAE 2006-01-0450, April 2006.

Douglas, C., Fildes, B., Gibson, T., Bostrom, O., and Pintar, F., "Modeling the Seat Belt to Shoulder-Complex Interaction in Far Side Crashes", Paper 07-0296, *20th ESV Conference,* June 2007.

Douglas, C., Fildes, B., Gibson, T., Bostrom, O., and Pintar, F., "Factors Influencing Occupant to Seat Belt Interaction in Far Side Crashes", *51th Proceedings of the Association for the Advancement of Automotive Medicine",* pp. 319-342, October 2007.

Fildes, B., Sparke, L., Bostrom, O., Pintar, F., Yoganandan, N., and Morris, A., "Suitability of Current Side Impact Test Dummies in Far-side Impacts", Proceedings of the 2002 IRCOBI Conference, pp. 43-56, September 2002.

Fildes B., Bostrom O., Haland Y., and Sparke L., "Countermeasures to Address Far-Side Crashes: First Results", Paper No. 447, *18th ESV Conference*, May 2003.

Fildes, B., Linder, A., Douglas, C., Digges, K., Morgan, R., Pintar, F., Yoganandan, Y., Gabler, H., Duma, S., Stitzel, J., Bostrum, O., Sparke, L., Smith, S., and Newland, C., "Occupant Protection in Far-side Crashes", Paper 05-0299, *19th ESV Conference*, June 2005.

Fildes, B., Bostrom O., Sparke L., Pintar F., and Yoganadan, N., "The Influence of a Flexible Lumbar Spine in Far-side Impact Testing", *International Journal of Crashworthiness*, Vol 11, No 3, pp. 273-280, 2006.

Fildes, B., Fitzharris, M., Gabler, H., Digges, K., and Smith, S., "Chest and Abdominal Injuries in Far-side Crashes", Paper 07-0384, *20th ESV Conference,* June 2007.

Gabler, H., Digges, K., Fildes, B., and Sparke, L., "Side Impact Injury Risk for Belted Far-side Passenger Vehicle Occupants", SAE 2005-01-0287, April 2005.

Gabler, H., Fitzharris, M., Scully, J., Fildes, B., Digges, K., and Sparke, L., "Far-side Impact Risk for Belted Occupants in Australia and the United States", Paper 05-0420, *19th ESV Conference*, June 2005.

Gabler, H., Fitzharris, M., Scully, J., Fildes, B., Digges, K., and Sparke, L., "Task 1 – Injury and Harm Analysis", ARC Far-side Collaborative Research Program, MUARC Report (2008).

Gayzik, S., Bostrom, O., Örtenwall, P., Duma, S., and Stitzel, J., "An Experimental and Computational Study of Blunt Artery Injury", *50th Proceedings of the Association for the Advancement of Automotive Medicine"*, pp. 13-34, October 2006.

Gayzik, S., Tan, J., Duma, S., and Stitzel, J., "Mesh Development for a Finite Element Model of the Carotid Artery", *Biomedical Sciences Instrumentation*; 42:p19-24, 2006.

Gibson, T., Morgan, R., Kemper, A., and Duma, S., "Task 5 - Test Procedures and Injury Criteria", ARC Far-side Collaborative Research Program, MUARC Report (2007).

Mohan, P., "Crush Comparison in Side Impacts", Report to George Washington University, National Crash Analysis Center, June 20, 2005.

Pintar, F., Yoganandan, Y., Stemper, B., Bostrum, O., Rouhana, S., Smith, S., Sparke, L., Fildes, B., and Digges, K., "Worldsid Assessment of Far Side Impact Countermeasures", *50th Proceedings of the Association for the Advancement of Automotive Medicine"*, pp. 199-220, October 2006.

Pintar, F., Yoganandan , N., Stemper, B., Bostrom , O., Rouhana , S., Digges, K., and Fildes, B., "Far Side Impact Response and Dummy Biofidelity", *Proceedings of the 2007 Stapp Car Crash Conference,* October, 2007.

Stemper, B., Yoganandan, N., Pintar, F., "Methodology to Study Intimal Failure Mechanics in Human Internal Carotid Arteries", *Journal of Biomechanics,* 38(12):2491-2496, 2005.

Stemper, B., Stineman, M., Yoganandan, N., and Pintar, F., "Subcatastrophic Failure Characteristics of the Porcine Descending Aorta", *Biomedical Science Instrumentation,* 41:110-115, 2005.

Stemper, B., Stineman, M., Yoganandan, N., Pintar, F., Sinson, G., Gennarelli, T., "Mechanical Characterization of Intimal Layer Failure in the Human Carotid Artery", *Proceedings of the 2005 IRCOBI Conference,* pp. 269-277, September 2005.

Stemper, B., Stineman, M., Yoganandan, N., Gennarelli, T., and Pintar, F. "Effect of Common Experimental Storage Techniques on Arterial Biomechanics", *Proceedings of the 2006 IRCOBI Conference,* pp.417-420, September 2006.

Stemper, B., Yoganandan, N., Sinson, G., Gennarelli, A., Stineman, M., and Pintar, F., "Biomechanical Characterization of Internal Layer Subfailure in Blunt Arterial Injury", *Annals of Biomedical Engineering*, Vol.35, No.2, p. 285-291, February 2007.

Stemper, B., Yoganandan, N., Pintar, F., and Brasel, K., "Multiple Subfailure Characterize Blunt Aortic Injury", J*ournal of Trauma,* Volume 62 Number 5, p.1171-1174, May 2007.

Stemper, B., Yoganandan, N., and Pintar, F., "Mechanics of Subcatastrophic and Ultimate Arterial Failure as a Function of Loading Rate", *Journal of Biomechanics,* 40(2007) 1860-1812, 2007.