SEVERE PARTIAL OVERLAP CRASHES – A METHODOLOGY REPRESENTATIVE OF CAR TO CAR REAL WORLD FRONTAL CRASH SITUATIONS

Lotta Jakobsson
Anders Kling
Magdalena Lindman
Linus Wågström
Anders Axelson
Thomas Broberg
Graeme McInally

Volvo Car Corporation
Sweden

Paper Number 13-0294

ABSTRACT

Frontal crashes can occur in numerous ways, including differences in degree of overlap, impact speed and angle of interaction. This poses special challenges with respect to structural design as well as occupant protection.

Traditionally, regulatory and consumer information crash testing procedures mostly focus on full frontal overlap and 40% overlap. In the real world, small overlap crashes where load paths of less than 30% of the vehicle's width and crashes with no front longitudinal members engagement are shown to represent an important share of frontal crashes resulting in occupant injuries. Thus it is essential to understand which impact configuration that would capture the important characteristics of small overlap crashes, yet being representative for a variety of car-to-car frontal impact scenarios, providing a complement to standardized frontal impact testing.

Based on real world crash data, important car-to-car frontal impact scenarios are identified and mechanisms studied. Full scale crash tests and finite element crash simulations are performed in order to evaluate different car to car configurations, forming the basis for studying structural load paths, focusing on structural design and occupant protection.

A crash test method, addressing 25% overlap against a fixed rigid barrier with a radius of 150 mm is found representative for a variety of car-to-car frontal impact scenarios, reflects mechanisms in real world crash situations and is a good complement to conventional frontal impact test methods. These findings support the findings by Planath et al. (1993), regarding Severe Partial Overlap Collision (SPOC), with 25% overlap against a fixed rigid barrier with velocities up to 64 km/h.

INTRODUCTION

In the late 1970s, the US-NCAP began frontal crash testing, comprising full overlap into a rigid barrier with a velocity of 56.3 km/h (Hackney and Kahane, 1995).

During the 1990s, partial overlap crashes were identified as a significant contribution to frontal crash injuries and fatalities using data from the UK (Hobbs, 1991), US (O'Neill et al., 1994), Germany (Scheunert et al., 1992) and Sweden (Planath et al., 1993, Kullgren and Ydenius, 1998). Although the methodologies varied, the findings identify the important share of serious frontal crashes involving partial loading of the cars' front end. This led to consumer information crash tests, by the car magazine Auto Motor und Sport in Germany, with 50% overlap into a rigid barrier (AMS, 1990). In 1996, a method comprising a deformable barrier with 40% overlap and impact speed of 64 km/h was used in the UK, simulating a car-to-car frontal collision between two similar cars with 50% overlap. This method was soon adopted within Europe by EuroNCAP. Today most vehicles are evaluated based on these full-frontal and moderate offset crash tests.

In a more recent real world study, Lindquist et al. (2004) found that small overlap crashes where load paths of less than 30% of the car's width is engaged, represented 48% of belted occupant fatalities in frontal crashes in Sweden. This stressed the need for further development of crash test procedures to better address small overlap crashes with no front longitudinal member engagement. Brumbelow and Zuby (2009) and Rudd et al. (2009), studied real world cases in US (NASS- CDS) with serious injuries for belted occupants of modern vehicles. Both suggested that future test programs promoting structural designs that address small overlap could reduce serious injuries in frontal crashes.

Sherwood et al, (2009) assessed the characteristics of small overlap frontal crashes and concluded that despite structural improvement prompted by offset crash tests, vehicle structures must improve if they are to prevent occupant compartment intrusion when a vehicle is loaded outboard of longitudinal structural members. Eichberger et al. (2007) investigated the crash statistics using GIDAS (German In-Depth Accident Study) and Austrian databases and concluded that, in small overlap situations, the longitudinal members are not involved and the wheel-to-wheel contact provides a load path into the occupant compartment which endangers the safety cage. Eichberger et al. (2007) proposed a car-to-car test method with 17% overlap collinear impact with a closing velocity of 112 km/h, to address the small overlap scenario. Also, studies by National Highway Traffic Safety Administration (NHTSA) (Bean et al., 2009) and The Insurance Institute of Highway Safety (IIHS, 2012) have initiated development of test methods in this area.

IIHS published in 2012 results from eleven vehicles tested in a car-to-barrier method using 25% overlap of the vehicle front with an initial velocity of 64 km/h (IIHS, 2012). NHTSA stated its intent to further analyze small overlap as well as oblique frontal crashes in its Vehicle Safety Rulemaking & Research Priority Plan 2009-2011 (NHTSA, 2009). This was followed by studies on evaluating the small overlap impact procedure's ability to replicate real world injury potential, complemented with tests comparing 7 different vehicles (Saunders et al., 2011 and 2012). It was found that the tests demonstrated head contact locations that are common in the field, torso loading of the restraint system and steering wheel, as well as a distribution of injury assessment values that are representative of the field injury risk

Small overlap frontal crashes, which are not currently addressed by federal standards or consumer information testing, account for a significant percentage of serious frontal crashes (Brumbelow and Zuby, 2009, Lindquist et al, 2004). Sherwood et al. (2010) studied the configurations and speeds of these real world crashes to understand and develop a potential crash test to evaluate vehicle crashworthiness in these types of crashes. By comparing the estimated closing relative velocity (delta-V) using field reconstructions techniques to the delta-V calculated on vehicle accelerometer data for crash testing, they found that an impact speed in the range of approximately 64 km/h would represent a significant portion of such real crashes causing severe and fatal injuries.

Occupant compartment intrusion was the primary injury mechanism and was found to have a strong correlation with overall injury severity (Sherwood et al. 2009). Of the occupants with an AIS2+ head injury, 80% of the head injuries came from contact with structures on the outboard side of the vehicle (e.g. A-pillar, striking vehicle, trees), indicating an influence of lateral occupant movement (Sherwood et al. 2012). Performing numerous full-scale car crash tests in a variety of small overlap crash configurations, Sherwood et al. (2012) emphasizes the significant lateral movement during the early phases of the crash, causing the driver dummy to move forward and outboard.

Severe partial overlap crashes where engaged load paths represent less than 30% of the vehicle's width and crashes with no engagement of front longitudinal members are shown to represent an important share of frontal crashes resulting in occupant injuries. Thus, it is essential to understand which impact configuration that would capture the important characteristics of small overlap crashes.

The objective of the study is to evaluate a car-to-barrier crash test set-up in its capability to represent a variety of car-to-car frontal impact scenarios and capture important real world characteristics of severe partial overlap crashes.

METHODS

Based on real world crash data, important car-to-car frontal impact scenarios are identified and mechanisms studied. Finite Element (FE) crash simulations of different car-to-car configurations helps to identify the crash configurations of high structural loading. Full scale crash tests are performed to replicate the real world mechanisms of severe partial overlap crashes. A study lay-out is shown in Figure 1. The different parts are described in detail further down.

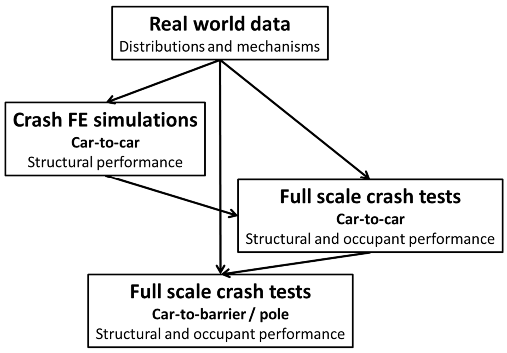


Figure 1. Study lay-out.

Real world data

The real world crash data is a subset of Volvo Cars Accident Data base, which contains Volvo passenger vehicles in Sweden where the repair cost due to a crash exceeds a specified level. The limit of repair cost criterion is currently 4,500 euro. Inspectors from Volvia (If P&C Insurance), the company with which all new

Volvo passenger cars are insured, identify the crashes. Photos and technical details of the vehicles are sent to Volvo Cars' Accident Research Team. A detailed questionnaire is sent to the owner of the vehicle to gather information about the crash, the car and the occupants. With the approval of the occupants, medical records are requested (when applicable) and coded by a physician within Volvo Cars' Accident Research Team. Injuries are coded according to the Abbreviated Injury Scale (AIS) (AAAM, 1985). To date, the database contains a total of 42,619 Volvo cars with 70,771 occupants, involved in crashes from 1976 to 2009. More information about the database is found in Isaksson-Hellman and Norin (2005).

In a selection of Volvo cars from the700-series to newer models, a total of 4,770 frontal impact cases are used to study the deformation pattern distributions and the injured body part distribution. The SAE Collision Deformation Classification (CDC) codes were used to select the dataset (SAE, 1980). Belted drivers involved in a single frontal impact (direction of impact 11-1 o'clock) were selected including crashes with deployed as well as un-deployed airbags. Multiple impact crashes and crashes with rollover events were excluded. The cars selected had vertical damage to, at a minimum, the front and up to the hood. The general damage type for the crash was either 'wide', 'narrow', 'corner' or 'sideswipe'.

Also, one real world case of severe partial overlap crash is presented in more detail to illustrate typical mechanisms.

Tests

Results from hundreds of crash simulations and several full scale crash tests are used for detailed analyses of structural performance and integrity. The full scale tests are also used for study the occupant kinematics.

Crash simulations, Computer simulations of the full vehicle response in car-to-car situations were performed.

A methodology to evaluate a large set of crash configurations was developed, using state-of-the-art FE models. This methodology aimed at expanding the capability of crash simulation beyond what is practically possible by physical crash testing. A detailed description of the methodology is published in Wågström et al. (2012). The study was based on structural evaluation criteria such as passenger compartment intrusion and vehicle deceleration. Special focus was directed to identifying "worst case" scenarios and developing means to visualize structural robustness and the imbalance that arises from oblique loading even when colliding vehicles are identical.

To cover a wide range of car-to-car crash scenarios, the lateral offset was chosen from 0 to 1,800 mm and oblique angle from 0 to 45° as illustrated in Figure 2. The combination of lateral offset and oblique angle was set up by rotating the bullet vehicle around a rotation center on the target vehicle followed by applying a lateral offset (Wågström et al., 2012). Initial velocities were chosen from 30 km/h up to 70 km/h for each vehicle, i.e. a maximum closing velocity of 140 km/h. In total, 378 full-scale car-to-car simulations in the 42 initial positions illustrated in Figure 2 were performed and compared in terms of structural response with the aim to identify a worst case structural loading in car-to-car situations.

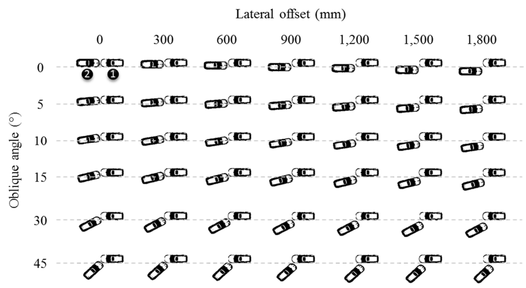


Figure 2 . Overview of simulated car-to-car crash scenarios.

Full scale crash tests, In total, seven different test set-ups, were performed and evaluated based on structural and occupant performance. Two of these are described more in detail in this study; one car-to-car test in an angle of 12 degrees and overlap arranged so that the longitudinal members strike each other without engagement, and one car-to-barrier test with a barrier radius of 150 mm and an overlap of 25% (Figure 3). The cars in the car-to-car crash were run at 35 mph each and the car in the car-to-barrier test at 40 mph.

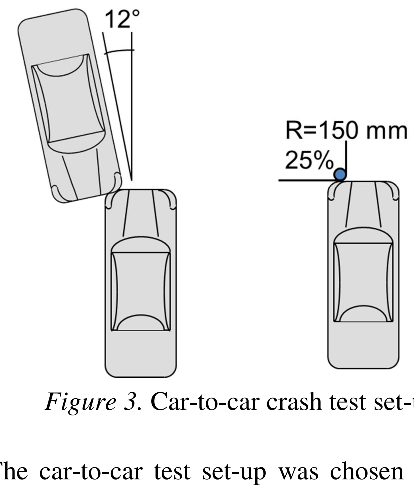
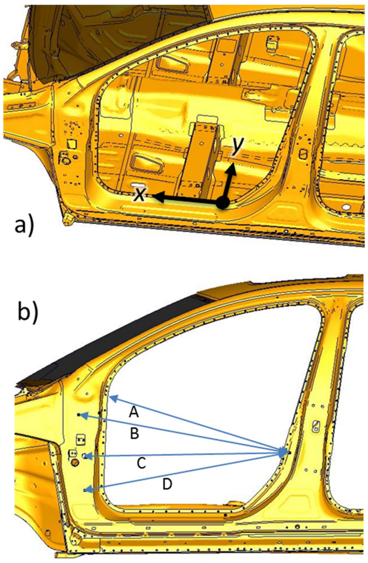


Figure 3. Car-to-car crash test set-ups.

The car-to-car test set-up was chosen based on the crash simulations and the car-to-barrier test was chosen based on correspondence to the car-to-car crash test results. The structural and occupant performance seen in the real world cases were aimed for in the tests. The desired performance was to expose the occupant area for both longitudinal and lateral accelerations in order to promote an oblique motion of the driver against the A-pillar.

The lateral and longitudinal accelerations were measured in the door sill as shown in Figure 4a. The door aperture deformation was measured in four different points as illustrated in Figure 4b, as a measure for structural deformation.



Figures 4. a). Location of accelerometer. b) Door aperture deformation measurement points.

A THOR dummy with modified shoulder enabling more humanlike motion in oblique loading conditions (Törnvall et al. 2008) was used.

RESULTS

Real world data

The distribution of 4,770 frontal impact cases with belted drivers are presented in Figure 5 with respect to the extent of frontal deformation; full overlap, 2/3 overlap and 1/3 or less overlap. It can be seen that 20% of the frontal impacts have driver side (left) overlap of 1/3 or less, while 15% and 25% is 2/3 driver side and full overlap respectively.

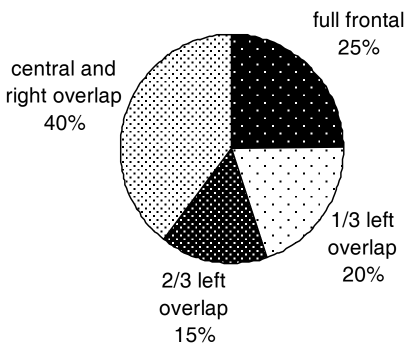


Figure 5. Distribution of horizontal deformation extent in frontal impacts with belted drivers.

For the frontal impact configurations analyzed, the distribution of some AIS2+ injured body regions of 274 injured drivers in total, is compared. Figure 6 displays the distribution of MAIS2+ injuries to the drivers' head and face, chest, lower extremities and upper extremities, respectively, per horizontal deformation extent.

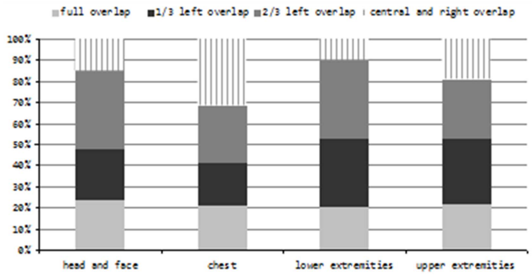


Figure 6. Distribution, by group of frontal horizontal distribution extent, of drivers MAIS2+ injuries to head and face (n=127), chest (n=95), lower extremities (n=112) and upper extremities (n=90).

Less than 1/4 of each of the drivers' injured body regions studied occur in full overlap frontal impacts, indicating that partial overlap account for a relatively higher injury outcome, Figure 6. The two driver side partial overlap groups hold a relatively higher frequency of MAIS2+ injuries. The injured drivers that were exposed to a 1/3 left side frontal impact, sustained 24% of the head and face injuries, Also, this group holds 20% out of chest injuries 35% of the MAIS2+ lower extremity injuries, and 31% of the upper extremities.

As a typical severe partial overlap real-world crash the following case was selected. A Volvo XC70 of model year 2008 impacted by a modern passenger vehicle of similar size with a narrow left side, slightly oblique (17% to the right) interaction. The car's speed at impact was approximately 80 km/h and the vehicle rotated substantially during impact. The driver of the vehicle was a 79 year old male. He sustained concussion with unconsciousness during 15 minutes, bruises on the chest and neck from the belt as well as bruises on the thighs. A photo of the exterior deformation is seen in Figure 7. The structural integrity was well maintained, resulting in an almost un-deformed foot-well area, see Figure 8. Based on vehicle kinematics as well as the head injury sustained, it is likely that the driver's head impacted the areas of the A-pillar and door structure. The frontal airbag was deployed, but not the Inflatable Curtain, which was in accordance with the specification of the vehicle.

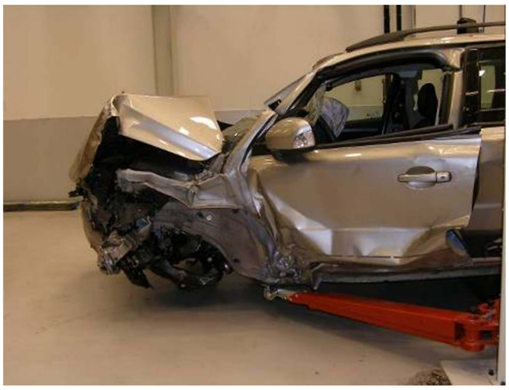


Figure 7. Exterior view of the in-depth real world case. Note, the pillars were cut for extrication purposes by the rescue squad at scene.

Figure 8. Photo of driver foot-well area of the in-depth real world case.

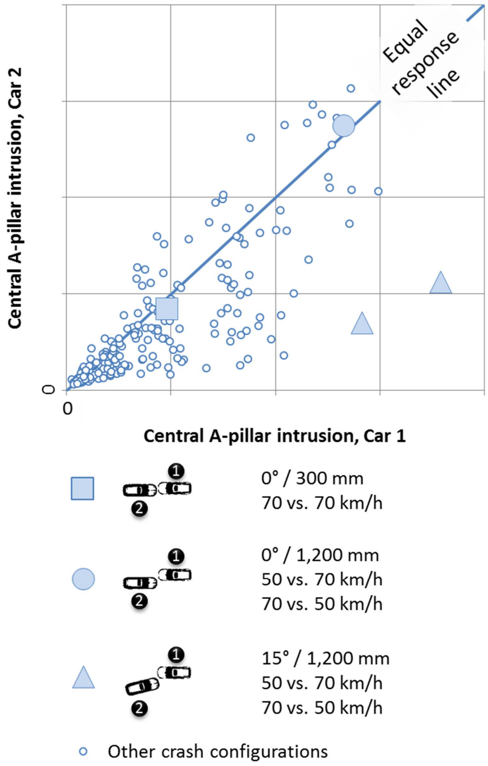


Figure 9. Central A-pillar intrusions for the two cars, respectively. Three specific load cases are highlighted.

Tests

Crash simulations, In terms of passenger compartment intrusion, a high degree of correlation between the central A-pillar intrusion and other measured intrusion areas was observed. The A-pillar intrusion was therefore proposed as a good indicator of the overall intrusion into the passenger compartment, and when this intrusion was compared between the different crash scenarios, the largest intrusions occurred at 15° oblique angle and 1,200 mm lateral offset, Figure 9. The findings from the simulation study were found to correspond well to the knowledge gained from real-world data as well as crash testing, indicating situations around 10-20° oblique angle and approximately 1/3 left overlap to represent the worst case structural loading in car-to-car situations.

Full scale crash tests, Exterior views of two cars tested in car-to-car and car-to-barrier configuration, respectively, are shown in Figure 10.

Figure 10. Exterior view of two cars tested in car-to-car (top) and car-to-barrier (bottom).

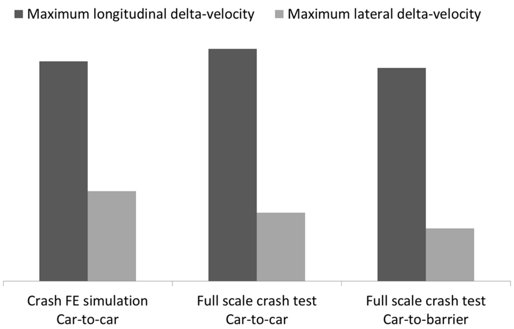


Figure 11. Longitudinal and lateral maximum delta-velocity at door sill, comparing the two full scale crash tests with the crash FE simulation.

Figure 11 shows a comparison of the longitudinal and lateral change of velocities measured at the door sill (as indicated in Figure 4a) for the two full scale tests and the car-to-car crash test simulation of 15° oblique angle and 1,200 mm lateral offset. The car-to-car and car-to-barrier full scale crash tests both include components of longitudinal as well as lateral change of velocity, in a similar magnitude. The values are also in line with the measurements from the car-to-car crash FE simulation, Figure 11. This provides an indication that the vehicle kinematics in the two test set-ups involves longitudinal as well as lateral acceleration affecting the occupant movement in line with the mechanism identified in real world situations. It is also an indication that the energy absorption and thus deformation pattern between the two test set-ups are similar.

Another measure of deformation is the door aperture opening measurement as shown in Figure 12, comparing the two full scale crash tests with the crash FE simulation of 15° oblique angle and 1,200 mm lateral offset. As can be seen in Figure 12, the deformations are overall minor and comparably similar between the two full scale crash test set-ups and the car-to-car crash FE simulation.

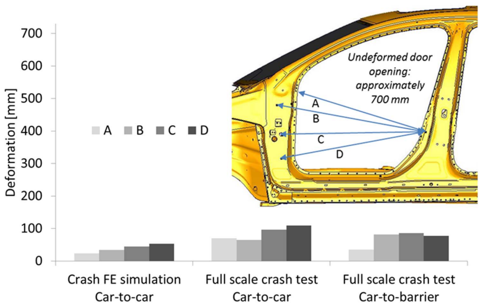


Figure 12. Deformation of door aperture deformation, comparing the two full scale crash tests with the crash FE simulation

In Figures 13 and 14, the maximum forward displacement of the driver dummy is shown, for the car-to-car and car-to-barrier full scale crash test, respectively. The crash test dummy in both tests, is the mid-size male dummy THOR, with modified shoulder as described in Törnvall et al. (2008). As can be seen in Figure 13, the driver dummy in the car-to-car full scale crash test has moved into a lateral position when in its maximum forward displacement position. The similar dummy kinematics is seen in the car-to-barrier crash test as well, illustrated with a photo of the maximum forward dummy displacement in Figure 14

Figure 13. Interior view on occupant maximum forward displacement in car-to-car test set-up.

Figure 14. Interior view on occupant maximum forward displacement in car-to-barrier test set-up.

DISCUSSION

Based on real world data, crash testing and simulations, this study confirms the crash test method which was presented already in 1993 by Planath et al. (1993). The method, called Severe Partial Overlap Collision (SPOC), addressing 25% overlap against a fixed rigid barrier was found representative for a variety of car-to-car frontal impact scenarios and a good complement to conventional frontal impact test methods. Over the years, frontal impact protection has been improved, however mostly focusing full frontal overlap and 40% overlap in regulatory and consumer information crash testing procedures. In more recent years, the significance of small overlap crashes in relation to protection in other frontal crashes has been highlighted (IIHS, NHTSA). Using the SPOC method for more than three decades, the development of Volvo cars have improved with respect to small overlap frontal impacts. Jakobsson et al. (2013) presents real world data of Volvo cars showing continuous improved occupant protection in full frontal as well as 1/3 overlap frontal crashes.

Frontal crashes can occur in numerous different configurations. This study highlights one test configuration representative for evaluating structural integrity for a variety of crash situations of partial overlap and oblique frontal impacts, providing a valuable supplement to regulatory frontal impact test set-ups. Besides aspects concerning structural integrity, equally important is the determination and replication of occupant kinematics for reflecting real world situations with small overlap as well as oblique frontal impact scenarios. This is essential for structural performance around the occupant as well as restraint activation logic and robustness.

The knowledge regarding small overlap crash situations based on simulations of vehicle structures has been quite limited until recently, mainly for two reasons: simulation resources and model detail level. Since the response in small overlap situations by definition does not engage the main energy absorbing members of the front structure, chassis components represent the main load paths in this type of situation. This means that the FE tools, developed for axial buckling and bending of sheet metal, needs to be expanded to cover also deformation and possibly material failure of chassis components. By requiring detailed models in combination with a large set of impact configurations, exploring car-to-car robustness in small overlap situations becomes particularly intensive in terms of computer resources. The methodology developed by Wågström et al. (2012) represents an initial attempt to combine a high level of model detail with a comprehensive scope of impact configurations. However, updates to FE models appear to be needed based on the knowledge from small overlap situations; these updated models can then be employed to make even more detailed predictions on worst case scenarios and structural robustness.

Two full scale crash test set-ups were presented in this study. In total seven different full scale crash test set-ups were run. Two addition car-to-car tests were run to evaluate the sensitivity in test set-up with respect to overlap and impact point. None of them provided the structural interaction as desired. In one of the tests, too narrow overlap resulted in a side-swipe with low acceleration and too little structural interaction. In the other one, the longitudinal members just reached but did not overlap. In addition, four variations of car-to-barrier / pole were run. These tests provided information that a barrier radius smaller than 150 mm gave high structural deformations but not the desired kinematics of the driver. In a test set-up with a barrier radius of 250 mm the vehicle glanced off the barrier thus giving too low structural deformations although the desired driver kinematics were achieved.

In small overlap real world crashes, the injury causation mechanisms are often related to oblique occupant upper body movements caused by the oblique pulse direction, a large portion of glance off forces and rotation of the vehicles, increasing likelihood for injuries from outboard components such as the door and A-pillar (Lindqvist 2007, Scullion et al. 2010, Rudd et al. 2011). The driver in the in-depth real world crash described in the present study likely impacted his head due to his oblique outboard motion. In the full scale crash tests, the THOR dummy used was equipped with a modified shoulder specifically designed for oblique motions (Törnvall et al. 2008) and showed similar head impact areas as in the real world situations (Figures 13 and 14). Humanlike occupant kinematics leading to realistic head impact areas are important in order to drive the development of occupant protection technology in a real world effective way.

This study provides a wide overview including detailed analyses of car-to-car frontal collisions in oblique and small overlap situations, combining updated real-world crash data with full scale crash testing as well as state-of-the-art computer simulations. It provides insight into vehicle design for structural performance and occupant protection for these situations, offering important information on a representative test method, corresponding structural prerequisites as well as the mechanisms of injury for severe car to car frontal impacts. The car-to-barrier test set-up evaluated is found representative for a variety of real world frontal impact scenarios.

CONCLUSIONS

The Severe Partial Overlap Collision (SPOC) crash test method, addressing 25% overlap against a fixed rigid barrier with a radius of 150 mm is found representative for a variety of car-to-car frontal impact scenarios and reflects mechanisms identified in real world crash situations. This method provides a good complement to conventional frontal impact test methods especially driving the development of structural performance around the occupant as well as restraint activation logic and robustness.

REFERENCES

Association for the Advancement of Automotive Medicine (AAAM), The Abbreviated Injury Scale, 1985 Revision, Des Plaines IL, USA, 1985

AMS (Auto Motor und Sport). Die Sekunde der Wahrheit. Issue 19, page 127, 1990

Bean JD, Kahane CJ, Mynatt M, Rudd RW, Rush CJ, Wiacek C. Fatalities in Frontal Crashes despite Seat Belts and Air Bags - Review of all CDS Cases - Model and Calendar Years 2000-2007 - 122 fatalities, DOT HS 811 102, National Highway Traffic Safety Administration, Washington, DC, 2009

Brumbelow ML and Zuby DS. Impact and Injury Patterns in Frontal Crashes of Vehicles with good Ratings for Frontal Crash Protection, Proc. of the 21st ESV Conference, Paper No. 09-0257, Stuttgart, Germany, 2009

Eichberger A, Schimpl W, Werber C, Steffan H A New Crash Test Configuration for Car-to-Car Frontal Collisions with Small Lateral Overlap. Int. Journal of Crashworthiness, 2007: 12(2), 93-100

Hackney JR and Kahane CJ. The New Car Assessment Program: Five Star Rating System and Vehicle Safety Performance Characteristics. SAE Paper No. 950888, Warrendale, 1995

Hobbs C. The Need for Improved Structural Integrity in Frontal Car Impacts. Proc. of the 13th ESV Conference, Paper no. S9-O-12, 1991

IIHS (Insurance Institute for Highway Safety), "Status Report, Small Overlap Crashes", Vol. 47, No. 6, 2012

Isaksson-Hellman I and Norin H. How Thirty Years of Focused Safety Development has Influenced Injury Outcome in Volvo Cars, Proc. of the 49th Annual Association for the Advancement of Automotive Medicine Conference (AAAM), Boston, USA, 2005

Jakobsson L, McInally G, Axelson A, Lindman M, Kling A, Broberg, T, Fermér M, Wågström L. Severe Frontal Collusions with Partial Overlap – Two Decades of Car Safety Development, SAE Car Congress, Paper No. 2013-01-0759, Detroit, 2013

Kullgren A and Ydenius A. Front Impacts with Small Overlap; Real Life Data from Crash Recorder", Proc. of the 16th ESV Conference, Paper No. 98-S1-O-13, Windsor, Canada, 1998

Lindquist M, Hall A, Bjornstig U. Car Structural Characteristics of Fatal Frontal Crashes in Sweden, Int. Journal of Crashworthiness 2004, 9(6), 587-597

Lindquist M. Fatal Car Crash Configurations and Injury Panorama - with Special Emphasis on the Function of Restraint System. Umeå University Medical Dissertations, New series No ISSN 0346-6612-1079, SBM 978-91-7264-247-8, Department of Surgical and Perioperative Science, Umeå University, Umeå, 2007

NHTSA (National Highway Traffic Safety Administration). Vehicle Safety Rulemaking & Research Priority Plan 2009-2011, Docket ID NHTSA-2009-0108-0023, Washington, DC, November, 2009

O'Neill B, Lund AK, Zuby DS, Preuss CA. Offset Frontal Impacts - a Comparison of Real-World Crashes with Laboratory Tests. Proc. of the 14th ESV, Paper No. 94-S4-O-19, Munich, Germany, 1994

Planath I, Norin H, Nilsson S. Severe Frontal Collisions with Partial Overlap - Significance, Test Methods and Car Design. SAE Technical Paper No. 930636, 1993

Rudd RW, Bean J, Cuentas C, Kahane CJ, Mynatt M, Wiacek C. A Study of the Factors Affecting Fatalities of Air Bag and Belt-restrained Occupants in Frontal Crashes, Proc. of the 21st ESV Conference ESV, Paper No. 09-0555, Stuttgart, Germany, 2009

Rudd RW. Scarboro M, Saunders J. Injury Analysis of Real-World Small Overlap and Oblique Frontal Crashes, Proc. of the 22nd ESV Conference, Paper No. 11-0384, Washington, DC, 2011

SAE International Surface Vehicle Recommended Practice Collision Deformation Classification (CDC) SAE Standard J224, 1980

Saunders J, Craig MJ, Suway J. NHTSA's Test Procedure Evaluations for Small Overlap/ Oblique Crashes, Proc. of the 22nd ESV Conference, Paper No. 11-0343, Washington, USA, 2011

Saunders J, Craig M, Parent D. Moving Deformable Barrier Test Procedure for Evaluating Small Overlap/Oblique Crashes, SAE Technical Paper No. 2012-01-0577, 2012

Scheunert D, Justen R Herrmann R, Zeidler F, Decker J, Kallina I. "What is Realistic Frontal Offset Test Procedure", International Conference on Biomechanics of Impacts (Ircobi), 1992

Scullion P, Morgan RM, Hohan P, Kan C, Shanks K, Jin W, Tangirala R. A Re-examination of the Small Overlap Frontal Crash, Proc. of the 54th Annual Association for the Advancement of Automotive Medicine Conference (AAAM), 2010

Sherwood CP, Nolan JM, Zuby DS. Characteristics of Small Overlap Crashes. Proc. of the 21st ESV Conference, Paper No. 09-0423, Stuttgart, Germany, 2009

Sherwood CP, Zuby DS, Nolan JM, Aylor DA. The Accuracy of Velocity Change Estimates in Small Overlap Frontal Crashes, ESAR Conference, Hanover, Germany, 2010

Sherwood C. Nolan J, Zuby D. Occupant Kinematics and Restraint Systems in Small Overlap Frontal Crashes, Airbag 2012

Törnvall FV, Holmqvist K, Davidsson J, Svensson MY, Gugler J, Steffan H, Haland Y. Evaluation of Dummy Shoulder Kinematics in Oblique Frontal Collisions, International Conference on Biomechanics of Impacts (Ircobi), 2008

Wågström L, Kling A, Norin H, Fagerlind H. A Methodology for Improving Structural Robustness in Frontal Car-to-car Crash Scenarios, submitted to the International Journal of Crashworthiness, 2012