

# A SLED TEST METHOD FOR SMALL OVERLAP CRASHES AND FATAL HEAD INJURIES

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## ABSTRACT

A large portion of fatal crashes are characterized by passenger cars being hit at the front but without engaging the drive train or longitudinal structural beams. The objective of this paper was to describe a cost-effective sled test method developed to address the issue of small overlap crashes and fatal head injuries. A real-life small overlap crash and literature review revealed that, in most cases, fatal injuries were multiple and the dominating injury mechanisms were head impacts with the inboard side, A-pillar, or external objects. Full-scale crashes with the THOR dummy confirmed this. A sled test method was developed replicating the critical events in the full-scale crashes. In additional tests with the HIII dummy there was no indication of head contact with the inboard side.

In conclusion, sled tests with the THOR dummy may be used in the evaluation of restraints' ability to protect occupants in small overlap types of crashes.

## INTRODUCTION

Passenger cars have probably had frontal crashes with other cars with a partial, narrow or small overlap since the beginning of car history. Nevertheless, to date, there is no standardized procedure of evaluating a car's ability to protect occupants from injury in these types of crashes. A first step towards such standardization is to clarify and define relevant crash circumstances. Examples of definitions used in the literature include frontal crashes with less than 1/3 overlap (O'Neill et al 1994), without drive train (Lindquist 2004) or longitudinal structural beam engagement (Scullion 2009).

In order to evaluate a car's ability to protect an occupant in a standardized test there is a need to understand injury distribution, mechanisms and causations. 1968 Mackay (1968), using UK data, noted that the benefit of a belt was greatly reduced in frontal corner impacts, presumably because the A-

pillar and door structure played a greater role in generating injury compared with non-corner frontal impacts. According to Kullgren et al. (1998) 22% of all frontal impacts in Sweden and 42% of severely injured (MAIS3+) drivers had an overlap below 30%. Lindquist (2004) showed that a large part of Swedish fatal crashes were characterized by cars being hit at the front without engaging the drive train or longitudinal beams. Moreover, in this group of fatal crashes, occupants died of head and/or thorax injuries caused by interaction with the side interior (Lindquist 2006). Lindquist concluded in his thesis (2007) that the injury mechanism in this configuration was characterized by an oblique movement and interaction with the outboard side. Pintar et al (2008) analyzed narrow offset frontal crashes in NASS and CIREN databases and concluded that countermeasures designed with standard large overlap frontal crashes may not address the specific injuries associated with narrow overlap crashes. The authors continue: "Rotation of the vehicle and subsequent occupant movement lateral to the airbag could be a factor in less severe impacts". Based on NASS/CIREN analysis and modeling, NHTSA performed a series of small overlap, vehicle-to-vehicle, and vehicle-to-pole THOR crash tests. The research dummy THOR (Test device for Human Occupant Restraint) has been shown to be more biofidelic compared to the dummy HIII (Shaw et al. 2000). At the 2010 Government-Industry meeting Saunders (2010) noted that the THOR head was in contact with the A-pillar, door or instrument panel in all NHTSA tests in accordance with real-life case reviews. Hollowell (2011), in an overview of NHTSA's compatibility and frontal impact activities, noted, after analyzing the vehicle-to-vehicle (Taurus) small overlap tests, that the THOR dummy rolled off the bag resulting in head-door contact.

Planath et al (1993) developed a test method addressing severe partial overlap collisions (0-30 degrees frontal impacts, <50% overlap and extensive deformation) where a full-scale car impacts a fixed rigid barrier with a 20-40% overlap at speeds of up to



**Figure 1 – To the right, post crash photos of the CCIS case chosen for vehicle-to-vehicle crash replication, to the left, the post crash photos of the vehicle-to-vehicle crash test. The photos of the CCIS car have been mirrored.**

65 km/h. Recently, the Insurance Institute of Highway Safety (IIHS) presented arguments for and proposed a test concept that would make it possible to address fatal injuries in small overlap types of crashes (IIHS 2009, Sherwood 2009). In the IIHS research program the Institute has performed vehicle-to-vehicle and vehicle-to-pole/-barrier crash tests where the overlap was approximately 25%. In the 2011 Government-Industry meeting Sherwood (2011) presented research progress where the Institute started with a 10-inch diameter pole, continued with a flat barrier with a 2-inch radius and then went on to a 20-inch diameter pole. They have now started with a flat barrier with a 6-inch radius THOR and HIII tests for better understanding compromise of vehicle and occupant dynamics.

With standardized full-scale car tests at hand there is a need for cost-effective tests in order to understand potential benefits of traditional and new occupant restraints such as airbags and belts. Also, such a resource- and purpose-limited test could be used to evaluate the applicability of using dummies such as the HIII and THOR.

The objective of this paper was to describe the developed sled test method as a tool to evaluate differences between dummy kinematics as well as the ability of restraint systems to protect the head in a set of fatal small overlap or narrow offset types of crashes.

## METHOD

A simple cost-effective sled test method needed to be developed with the complex reality of real-world crashes in mind. More specifically, simplicity should only be directed toward the purpose of the test. The purpose of the test method proposed and discussed in this paper was to evaluate the applicability of dummies and restraint systems regarding fatal head injuries. Therefore, as a first step, a real-life data analysis and literature review were performed to gain an understanding as to which type of small overlaps were both frequent in fatalities but capable of mitigating the consequences. Also, this review/analysis was meant to get an idea of the most frequent AIS3+ injury mechanisms. The data analysis was previously documented in an internal report by Kruse (2008). Thereafter, a test series of small overlap vehicle-to-vehicle and vehicle-to-barrier crashes with a THOR dummy were performed. Based on free flying mass trajectories and A-pillar/instrument panel intrusion a sled test method including a set of linkage arms was developed. The development was previously documented in an internal report by Kruse (2009). The sled test method was used in a series of THOR and HIII tests. The test specifications were similar for the two dummies which were restrained by a retractor-pretensioned load-limiting belt and a driver airbag. The pre-test nose-rim and chest-center hub distances were 470 and 310 mm for the HIII and for THOR (w/o nose) 490

and 370 mm. The THOR-NT was equipped with the second generation of shoulder modification developed by Tornvall et al (2006).

The real-life analyses were performed using fatal frontal crashes (direction of force 11-01), no roll, with belted occupants in CCIS (1998-2006) including 247 fatalities and NASS (1995-2005) with 390 fatalities. The inclusion criterion used in this study was drivers and 33% of overlap with accurate data.

## RESULTS

### Real-life analysis

The 247 and 390 frontal/no roll/belted CCIS and NASS fatal cases were reduced to 34 and 60 drivers respectively exposed for well documented small (<33%) overlap cases. Among the 60 NASS cases there were 327 AIS3+ injuries. The most common injury of the small overlap NASS cases were brain

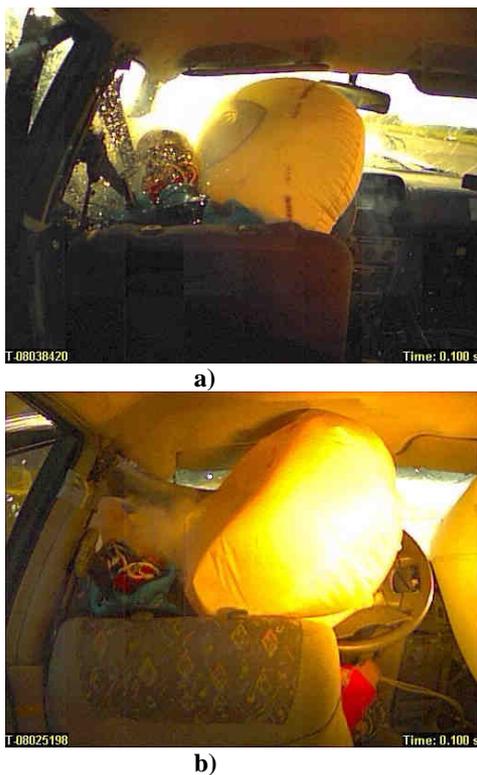
injuries (35%) followed by ribcage, femur, heart/aorta injuries (10% respectively) and lung injuries (7%). The most common injury cause was side structure (35%) followed by exterior object (25%) and A-pillar (12%) and steering wheel (7%). Among the CCIS and NASS small overlap cases most occurred on roads with a posted 60 and 45 mph limit, respectively. Of the 34 CCIS cases one representative case was chosen to be replicated in a vehicle-to-vehicle and a vehicle-to-barrier crash test. While negotiating a left hand bend the target vehicle (right hand side driven) in this case collided with a another car travelling in the opposite direction resulting in a 22% overlap, crash CDC code 12FREE4, and no longitudinal beam engagement. According to the report the driver sustained severe head and neck injuries in contact with the A-pillar, severe thorax injuries in contact with the steering wheel and severe lower extremity injuries in contact with the intruded door and instrument panel. See Figure 1 for post-crash photos of the car (right hand side).

### Full-scale car tests

The chosen circumstances for the vehicle-to-vehicle test were two identical cars (the same as the target vehicle in the chosen CCIS case) colliding collinearly with both cars traveling at a speed of 80 km/h. The circumstances for the first vehicle-to-barrier tests were chosen to be same type of car colliding at a speed of 80 km/h with a barrier at a 150 mm (approximately 6-inch) radius corner. Tests were carried out on an airfield with remote controls and the car engines as driving forces. The two tests resulted in 25 and 28% overlaps and both tests resulted in crash deformations typical for what the tests should replicate. In Figure 1 post crash photos of the vehicle-to-vehicle test and the chosen CCIS case are shown.

In both tests driver injury causations in the real-life case were more or less replicated. The head of the THOR dummy missed the driver airbag (see Figure 2) and the lower extremities interacted with the severely intruded toe-pan. Two critical events or features of this type of crash were identified, the intrusion of the instrument panel and the lateral motion of the occupant relative to the compartment during the crash.

The vehicle in the CCIS case and the full-scale tests were not available numerically (FE-code) to the authors. In order to vary crash circumstances in a cost-effective way two more vehicle-to-barrier crash tests were performed with a numerically available car model. Two Ford Taurus models from 2001 were crashed into a barrier with a 150 mm radius corner at



**Figure 2 – Interior rear-view snapshots 100 ms into the a) vehicle-vehicle test replicating the CCIS case and b) barrier tests. The tests showed two critical small overlap features, the lateral motion of the dummy and the intrusion of the steering wheel and instrument panel.**



**Figure 3 – Lateral view of the  $\Delta V$  50 km/h 26% overlap Taurus test 80 ms after contact with the flat barrier with the 150 mm radius corner.**

a speed of approximately 80 km/h with resulting overlaps and  $\Delta V$  of 19% and 32 km/h and 26% and 50 km/h respectively, (see Figure 3 for a lateral view 80 ms into the crash in the 26 % overlap  $\Delta v$  50 km/h test).

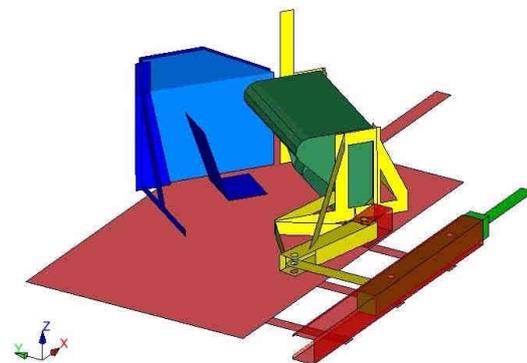
For all crash tests the ratio of lateral and longitudinal displacements of the cars during the event were calculated. These calculations showed that a free flying mass in the car during the first tens of milliseconds would move less than 50 mm straight ahead in the car and thereafter stabilize to move at an specific angle ranging between 19 and 37 degrees in the four tests. This specific angle was used as a set-up angle in the sled test method. Also, the (resultant) crash pulse and change of velocity in this direction, was used as the  $\Delta V$  in the sled test method.

### Sled test development

According to the limited overlap literature, real-life analyses and the four full vehicle crash tests, the intrusion of the instrument panel/steering wheel and the lateral movement of the occupant with consequent injurious head contact with the side/A-pillar/external object were simulated in a sled test addressing protection of fatal head injuries. The sled test method was developed with a seat and door set-up at a specific angle to the track direction.

The angle should be equal to the set-up angle as defined above. The sled pulse, created by means of a combination of iron-bar bending and pneumatic brake is tuned to mimic the crash pulse of the full-scale test in this direction. Moreover, the toe-pan, instrument panel and steering wheel were guided by means of a set of linkage arms. After a specific time of the sled

pulse, calculated from the full-scale crash to be replicated, the toe-pan, instrument panel and steering wheel is forced by means of a separate friction break system to rotate to a certain angle (see Figure 4). The range of rotation angle enabled intrusion-simulation of up to 300 mm of A-B pillar closure.



**Figure 4- The seat and door (blue parts) are pre-set to a predetermined angle. The slewing bracket arrangement (yellow parts) allows rotation of the instrument panel (green) to a predetermined angle.**

A series of sled tests were performed and results showed the method sufficiently robust to be used as a cost-effective method. Included in these tests was a validation test with the Taurus full-scale barrier test where the THOR dummy in the sled test was shown to move accordingly and hit the side structure with a resulting comparable HIC value (1707 compared to

1813). See Figure 5 for a snapshot at the moment of head contact with the door. In the sled test an inflatable curtain was added (in contrast to the Taurus tests) but the curtain had a negligible influence on the dummy head motion for this specific test condition.



**Figure 5 – The THOR head 110 ms after start of the sled pulse. Accordingly, with real-life analysis and the full-scale tests, the head recorded a high HIC value.**

### **THOR versus HIII**

HIII and THOR comparison tests were also carried out for a test set-up simulating more conservative (less lateral motion) small car conditions. The tests were carried out with a set-up angle of 15 degrees (compared to 26 degrees in the previous sled tests). Even with less pronounced lateral motion the THOR reached about a head length farther than the HIII. The interaction with the driver airbag was also critically different. While the THOR head rolled off the bag with the face directed towards the bag the HIII head forward motion was obstructed and delayed by the bag. See also Figure 6 for lateral, front and top-views at 150 ms after impact and Appendix for shoulder, lap belt and femur force-time histories.

### **DISCUSSION**

According to the literature and the executed real-life analyses, one of the injury mechanisms in small or

narrow offset crashes is the head forced laterally outboards colliding with side or external structures. This paper presented a sled test method which simulated the lateral motion of the occupant in combination with the intrusion of instrument panel with the steering wheel and the frontal airbag. The HIII dummy was shown less flexible compared to the THOR dummy during this oblique loading. The THOR head moved a head-length's greater distance compared to the HIII in the comparison tests carried out at a moderate set-up angle. This was in accordance with HIII versus THUMS numerical simulations (Bostrom et al 2009, Mroz et al 2010) where the human body model in frontal collision conditions without lateral movement, moved a considerably greater distance compared to the HIII model (see Figure 7).

The sled test method, far more cost-effective compared to full-scale tests may be used in extensive development test series in order to develop, optimize or tune occupant restraints to be able to handle the situation when the occupant is forced outboards (actually, the car is forced) and the A-pillar, instrument panel and steering wheel intrude into the compartment. Examples of such occupant restraints are belts and frontal and side airbags.

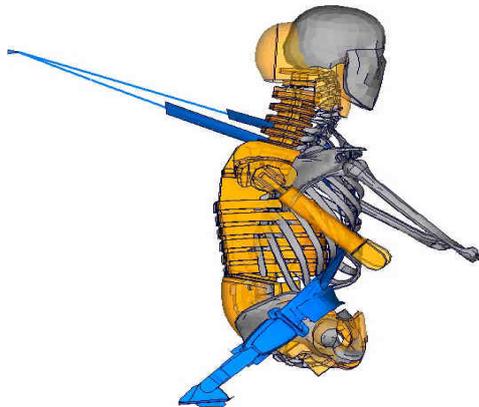
As small overlap crashes include a high variety of circumstances both for the cars and occupants involved, the sled tests are still limited in incorporating all aspects of this important yet ill-defined crash type.

As the focus of the method was on fatal head injuries the method and the paper did not address important mechanisms such as thorax interaction with the side structure and lower extremity injuries due to extensive intrusion. Neither does the paper address the situation where the B-pillar is engaged in the striking car (one type of injury causation found by Lindquist (2006)).

If cars are designed to reduce the amount of intrusion in small overlap types of crashes the need for using the full performance capacity of the proposed method is reduced. On the other hand, when considering the laws of physics, avoiding intrusion will likely lead to higher lateral or longitudinal forces on the car. Thus, even with cars glancing off the collision partner, occupant restraints still need to be tested for their ability to protect an occupant from moving sideways and colliding with side structures.



Figure 6 – Lateral, top and front views 150 ms after impact of the tests with THOR (left) and HIII (right). The  $\Delta v$  was 60 km/h, the angle was set to 15 degrees and the amount of intrusion at the A-pillar base was almost 300 mm.



**Figure 7 Lateral view of the HIII and THUMS models 100 ms after impact in a frontal collision (load limited belt and driver airbag) with no lateral movement. From Bostrom et al (2009).**

## CONCLUSIONS

The real-life small overlap crash and literature review revealed that in most fatal cases the AIS3+ injuries were multiple and the dominating injury mechanisms were head impacts with the inboard side, A-pillar or external objects. Full-scale crashes with the THOR dummy confirmed this. A sled test method was developed replicating critical events in the full-scale crashes. In additional tests with the HIII dummy there was no indication of head contact with the inboard side.

In order to protect the head in small overlap situations the structure of the car and the belt and airbag system may have to be enhanced. In conclusion, the paper offers an adjustable sled test method as a tool for understanding how to protect the head in a set of small overlap types of crashes.

## REFERENCES

- Bostrom O, Mroz K, Pipkorn B, Olsson J, "Influence of Belt Load-Limiting Force on Thorax Deflection, Rib Strain and Excursion in Frontal Impacts -A Numerical Evaluation using THUMS and HIII", Government/Industry Meeting, 2009.
- Hollowell W T, "Overview of NHTSA's compatibility and frontal impact activities", FIMCAR workshop, 2011.
- IIHS Status report Vol 42, No 2, March 7, 2009.
- Kullgren A., Ydenius A., Tingvall C."Frontal impacts with small partial overlap: Real-life data from crash recorders". ESV 1998, Paper No: 98-S1-O-13.
- Lindquist M, "Fatal car crash configurations and injury panorama- with special emphasis on the function of restraint system", PhD Thesis, Umeå University, 2007.
- Lindquist M., Hall A., Björnstig U. "Car structural characteristics of fatal frontal crashes in Sweden". IJCrash vol 9, 2004.
- Lindquist M, Hall R, Björnstig U, "Kinematics of belted fatalities in frontal collisions: a new approach in deep studies of injury mechanisms", Journal of Trauma 61: 1506-16, 2006.
- Kruse D, "Passenger cars in fatal small overlap frontal impacts, an in-depth study of injuries, injury causations and potential injury reductions for nearside impact positioned belted drivers", Autoliv internal report 2008.
- Kruse D, "Test set-up documentation and function description based on confirmative tests for Off-set overlap frontal impact test method", Autoliv internal report 2009.
- Mackay GM, "Injury and Collision severity". STAPP1968.
- Mroz K, Bostrom O, Pipkorn B, Wisman J, Brodin K, "Comparison of Hybrid III and human body models in evaluating thoracic response for various seat belt and airbag loading conditions", Ircobi2010
- O'Neill B., Lund A.K., Preuss C.A., Zuby D.S., "(IIHS/NASS 90-92): Offset Frontal Impacts – A Comparison of Real-World Crashes with Laboratory Tests". Paper No: 94-S4-O-19, ESV 1994.
- Planath I, Norin H, Nilson S, "Severe frontal collisions with partial overlap – significance, test methods and car design". SAE Technical report 930636, 1993.
- Pintar FA, Yoganandan N, Maiman DJ. "Injury mechanisms and severity in narrow offset frontal impacts". Ann Adv Automot Med 2008.
- Saunders J, "Evaluation of Small Overlap / Oblique Test Procedures", 2010 Government/Industry Meeting, January, 2010.

Scullion P, Morgan RM, Mohan P, Kan CD, Shanks K, Jin W, Tangirala R, "A reexamination of the small overlap frontal crash". Ann Adv Automot Med 2010

Sherwood C, Nolan J, Zuby D, "Characteristics of small overlap crashes", paper number 09-0423, ESV2009.

Sheerwood C, "An Update on the IIHS Small Overlap Frontal Crash Research Program", 2011 Government/Industry Meeting, January, 2011.

Shaw G, Lessley, D, Crandall J, Butcher J, "Biofidelity evaluation of the THOR advanced Frontal crash test dummy". Ircobi2000.

Tornvall FV, Holmqvist K, Davidsson J, Svensson MY, Haland Y, Ohrn H, "A new THOR shoulder design: A comparison with volunteers, the Hybrid III and THOR NT". Short paper Ircobi2006.

APPENDIX

