A VALIDATED OBLIQUE POLE SIDE IMPACT SLED TEST METHOD FOR ANALYZING OCCUPANT RESPONSE

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Paper Number 09-0466

ABSTRACT

This paper describes a new test methodology for evaluating occupant injury response in a near side oblique pole impact per FMVSS 214. Given the complexity, time, and cost of using full vehicle pole impact crash tests to develop occupant restraint systems, it is desirable to have a simple test method that allows engineers to develop an optimized restraint system in a timely and cost effective manner. The authors will present a new sled test method that accurately simulates a full vehicle oblique pole side impact test using only minimal vehicle components. This test method was validated using both the ES2-RE representing an AM50 occupant and a SID IIs representing an AF05 occupant. The authors will provide data showing correlation with full scale oblique pole impact vehicle tests. Furthermore, to demonstrate the effectiveness of this test methodology a case study will be presented showing a restraint system that has been optimized for both AM50 and AF05 occupants in an oblique pole impact.

INTRODUCTION

In the mid 1990's, restraint system suppliers and vehicle manufacturers began implementing side impact restraint systems for head protection in side impact crashes involving narrow objects such as utility poles and trees. Starting with MY1999 passenger vehicles, the NHTSA made accommodations for this technology in the FMVSS 201 "Occupant Protection in Interior Impact" with the inclusion of an optional 24 km/h vehicle side impact (90 degrees) into a 254mm diameter rigid pole for vehicles equipped with a "dynamically deployed upper interior head protection system" [1]. On September 11, 2007 the NHTSA published a Final Rule incorporating a 32 km/h oblique (75 degree) lateral pole impact crash test into the FMVSS 214 "Side Impact Protection". In addition to head protection, this new regulation requires thorax, abdomen, and pelvis protection in lateral impacts for both 50th percentile male and 5th percentile small female drivers beginning with some MY2011 passenger vehicles [2]. Most recently (July 8th, 2008) the NHTSA issued a Final Notice of enhancements made to the USNCAP (New Car Assessment Program) to include the oblique pole impact crash test results with the 5th percentile small female in its 5-Star vehicle safety rating – beginning with MY2011 passenger cars [3].

Since the initial pole impact test requirement in FMVSS 201P evaluated only head injury potential; development of countermeasures for head protection could be accomplished through the use of linear impact tests with a full scale crash test used for final validation. As such, full scale sled testing was not required. A majority of side impact sled tests during this time were performed for the purpose of developing and evaluating side impact restraint systems for thorax, abdomen, and pelvic injury protection in a vehicle to vehicle crash. One such method, developed in 1994-95 [4] utilized an acceleration type sled with a sliding dolly affixed to simulate the rapid door intrusion into the passenger compartment; while also simulating the important characteristics of dummy-to-door trim geometry, gap closure timing, and door stiffness.

With the additional requirements of the oblique pole side impact test outlined in the upgraded FMVSS 214 regulation to include thorax, abdomen, and pelvis injury, a new pole side impact sled test method was developed. This sled test method can provide engineers a tool to develop optimized side impact countermeasures, such as side airbags, prior to conducting a full scale vehicle test. This new test method is, to a large degree, based on this earlier test device and the experience gained in more than 13 years of use, as well as those experiences from many full scale side impact crash tests and the development of side impact restraints for both the moving barrier and pole impact test conditions.

TEST METHOD

This section describes the sled test method and apparatus in general terms only. It does not include significant detail on mounting the test specimen hardware or tuning the system to achieve the desired level of correlation. As is typical for side impact sled testing, these details are, to a large degree, dependant on the subject vehicle geometry and crush characteristics. The following section titled "Test Setup" will describe the process used to understand these variables and account for them in the test configuration.

Before discussing the sled test method, it is important for the reader to first consider certain characteristics of the full scale crash test (FMVSS 214 Oblique Pole Impact):

At the time of impact (T=0):

- the vehicle is traveling at a 15 degree crabbed angle (front angled toward pole) at a constant velocity of 32 km/h,
- the test dummy is traveling at a constant velocity of 32 km/h (same as vehicle) with it's head (center of gravity) aligned, in the direction of travel, with the centerline of the pole.
- the pole is fixed rigidly to earth. We could say that the pole is traveling at a constant velocity of zero.

After initial contact:

- The entire vehicle undergoes a change in velocity, with certain subcomponents (door, door trim, seat, roof rail, etc…) changing more quickly than others (accelerating toward the non-struck side of the vehicle).
- The test dummy also experiences a change in velocity, but not until it is acted on by certain other components (door trim, seat, roof rail, side airbag, curtain airbag, and pole).
- The pole does not change velocity. It maintains the constant speed of zero km/h throughout the duration of the test and beyond.

The device described here is designed for use with an acceleration type sled, but can be easily adapted for use with a deceleration sled application – the basic test method remains the same with respect to the configuration of the door, trim, seat, and test dummy. When used with an acceleration sled, the sled must be capable of achieving the impact test speed (32 km/h) then maintaining that speed for the duration of the test (up to 100 msec). The device used by the authors is an acceleration sled retrofitted with a servo-controlled carriage braking system.

As illustrated in Figure 1, the device consists of the main sled carriage with a rigid pole attached to it (a); a sliding dolly to which the door element, seat, and dummy are mounted (b); a seat slider for attaching the seat to the dolly (c); various crush elements (d), (e), and (f), and a position switch (g).

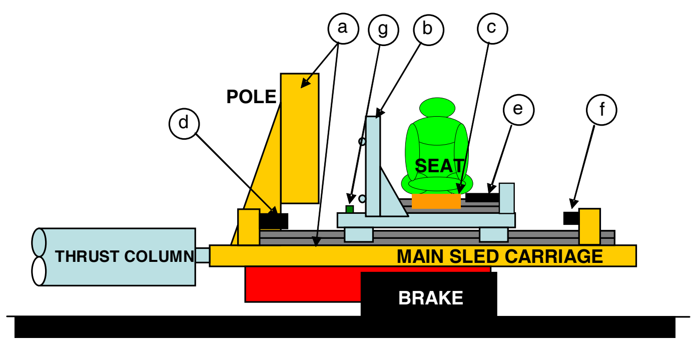

Figure 1. Schematic of test device

The test method proceeds as follows:

The main sled carriage and pole are accelerated to 32 km/h over a stroke of about 200mm, and then maintained at that speed under velocity based servo-control braking to counteract the thrust column forces still trying to accelerate the sled. The resulting velocity profile is shown in Figure 2.

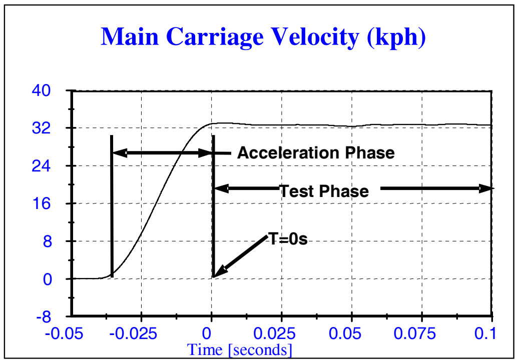

Figure 2. Sled carriage and pole velocity profile

The sliding dolly, in addition to the seat slider and seat, is built with two vertical pillars used to support the struck door components. The door components are supported by two (or more as needed) horizontal bars (1 inch electrical conduit) that are attached at each end to the vertical pillars using a sliding swivel arrangement, which allows the bars to deform toward the seat and occupant when struck by the pole. Once the door components are mounted to this structure, the seat is positioned on the slider such that its orientation with the door trim simulates the target vehicle geometry. A crush element (e) is then added to ensure the seat remains in contact with the door once it is struck, while still allowing the seat to travel with the door relative to the dolly to which they are both mounted (Figure 3).

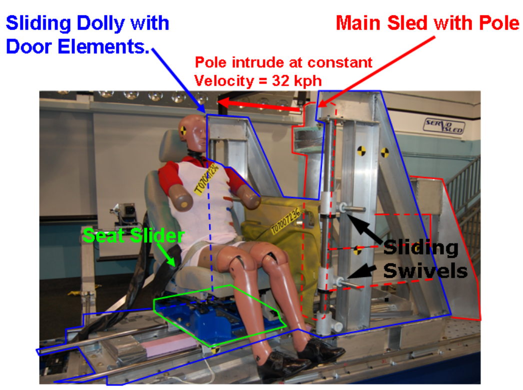

Figure 3. Test setup showing sliding swivel arrangement for mounting door components

This dolly assembly remains essentially motionless during the acceleration of the main sled due to its inertia and the low friction linear bearings used to attach it to the main sled.

When the pole (a) has achieved the impact speed and is at the initial vehicle contact position (measures the same distance from dummy head to pole as in full scale crash at T=0) a position switch (g) triggers T=0 for the data acquisition system and the airbag deployment timer. At this position (or slightly later – depending on the target vehicle characteristics) the sled/pole engage a crush element (d) sized to accelerate the dolly to simulate the motion of the target vehicle's center of gravity during the crash, thus simulating the body-side and floor structure stiffness. During this time the pole surface will also engage the door components and begin to deform them toward the test dummy. As the door components and conduit supports used in this method are not structurally significant the force required to deform them has very little influence on the acceleration of the dolly.

From there, the pole surface, and deformed door components continue at constant velocity (32 km/h) as the vehicle's dummy-to-door "gap closure" is reproduced, and finally – the seat and test dummy are impacted. When the relevant portion of the test is complete, the on-board brakes for the carriage safely stop the entire assembly, with the crush element (f) allowing the dolly to gently couple with the sled carriage during this deceleration phase.

TEST SETUP

A primary goal of this activity was to develop a test method that was reasonably simple and economical to setup and use with a minimum of vehicle components required. In order to achieve this goal the following assumptions were made.

1. As noted in the introduction, the purpose for the development of this test method was to provide a way to evaluate restraint systems to reduce thorax, abdomen, and pelvis injury. Because head injury performance can be more easily evaluated using linear impact component testing, this sled test method is not recommended for developing the curtain airbag. As such, the curtain airbag was included in the sled test only to provide the correct occupant kinematics, and was simplified as follows:

    a. The curtain airbag was modeled as a bladder that was constructed from the front row chambers of the inflatable curtain airbag for each of the tested vehicles.

    b. The bladder was unrolled in the pre-test condition, and pressurized to the correct pressure using shop air before the test.

c. The bladder was tethered to the front and rear uprights on the sliding dolly in the correct location relative to the vehicle in the fore and aft position.

2. The coupling between the occupant and the vehicle through the seatbelt was assumed to be negligible. Therefore, the seatbelt was omitted in order to simplify the test fixturing and setup. As a result the occupant kinematics during rebound is not valid.

3. In a full vehicle test the door structure is crushed and stopped by the pole before significant loading of the restraint system by the occupant occurs. Therefore, it is assumed that door structure can be simplified as follows

    a. Provide the door trim and its mounting structure only.

    b. Include any hard components that the dummy may interact with (i.e., window regulator motor, …)

4. In order to reproduce the side airbag deployment path in the vehicle; a piece of foam was used to represent the surface of the B-Pillar trim (ES2-RE).

Reference Table 1, for a summary of the components used for this correlation activity.

Table 1.
Components included in testing.

	Curtain Airbag	Seat	Seat-belt	Side Airbag	B-Pillar	Door Trim	Door
Vehicle Test	O	O	O	O	O	O	O
Sled Test	Δ	O	X	O	Δ*	O	Δ

* For ES2-RE setup only.
O Included
Δ Simplified Structure
X Not included

Figure 4 shows the test setup used for this testing for each of the test configurations considered; ES2-RE and SID IIs dummies as well as SUV and Sedan vehicles.

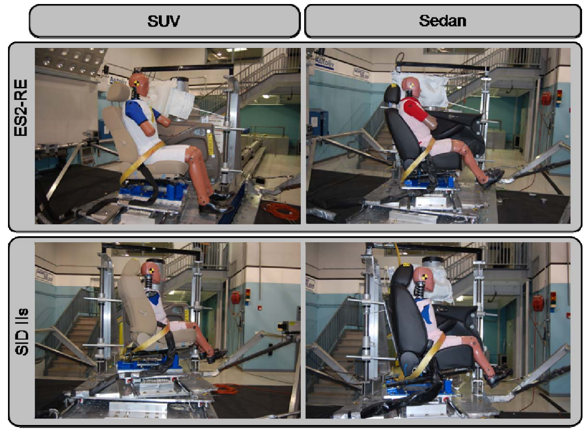

Figure 4. Test setup

In order to achieve the correct gap closure between the door trim and the seat for the side airbag deployment the stiffness of crush element (d) (reference Figure 1) was tuned such that the velocity of the sliding dolly (to which the door components and the seat are mounted) matched the test vehicle's velocity measured at the center of gravity. Injury for the vehicle tests being correlated to occurred at ~50 ms; therefore, the sliding dolly velocity was correlated to the vehicle test through 60 ms to ensure correlation during dummy loading.

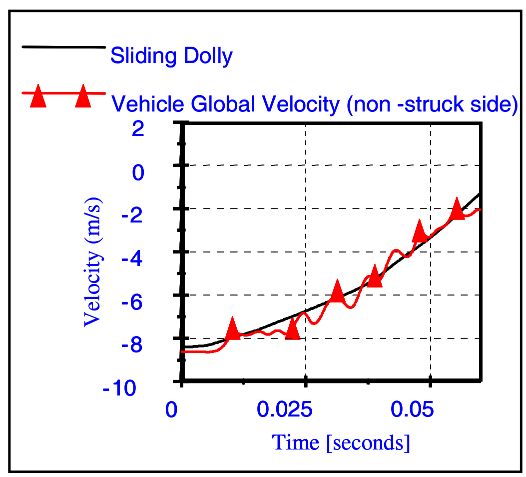

Figure 5. Sliding dolly velocity

CORRELATION

Correlation was achieved using both SID IIs and ES2-RE dummies for both an SUV and a sedan vehicle. The two vehicles were confirmed in order to verify that this test method can be applied to a wide range of vehicle architectures.

Agreement between the sled and vehicle tests was confirmed by normalizing the sled test result with respect to the vehicle test with 1.0 being a perfect agreement between the two tests. For the purposes of this paper a normalized injury of between 0.8 and 1.2 (+/- 20 percent) was judged to be an acceptable agreement. Overall both the SUV and sedan vehicles' normalized injury for the SID IIs dummy was within the acceptable range (Figure 6). The only exception was the iliac force in the SUV environment; which was significantly more than the vehicle test (2.35 normalized injury). The acetablum matched the vehicle test very well for both peak values as well as the shape of the curve. Furthermore, the pelvis acceleration for both the sled and vehicle tests also matched very well indicating that the total loading on the pelvis was very similar in the sled and vehicle tests. The SID IIs dummy used in the SUV vehicle test was instrumented with a build level 'C' iliac wing and did not have the enhancements, which correct the potential of the load cell under reporting the force level [5]. The dummy used in the sled testing was instrumented with a build level 'D' iliac wing. It is believed that the reason for the differences in the iliac load between the sled and SUV vehicle test is due to the load cell under reporting the force level in the vehicle test. This is further supported by the fact that the pelvis loading in the sedan environment agreed very well with the vehicle test as can be seen in Figure 7. In the case of the sedan vehicle, both the vehicle and sled tests were conducted with a dummy instrumented with the level 'D' iliac load cell.

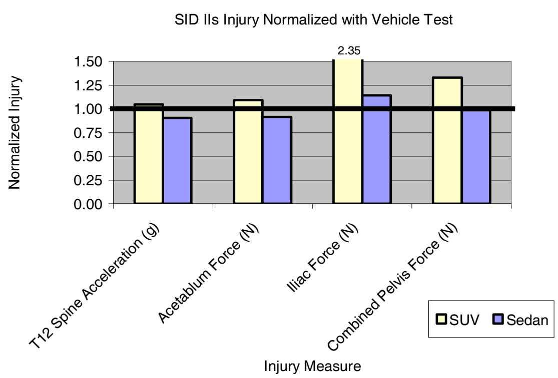

Figure 6. SID IIs injury agreement

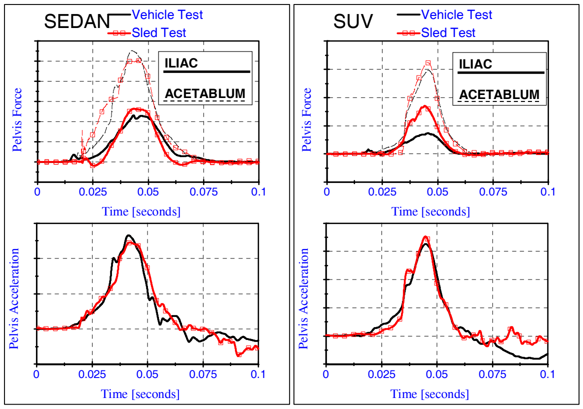

Figure 7. SID IIs pelvis loading time history

Figure 8 summarizes the results of the ES2-RE testing. The abdominal force for both vehicle environments as well as the pubic force for the sedan environment achieved the acceptable normalized injury range of 0.8 to 1.2. However, the rib deflection for both vehicle environments as well as the pubic force for the SUV environment was not within the acceptable range.

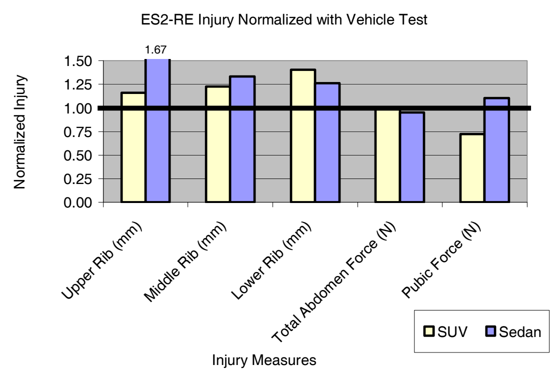

Figure 8. ES2-RE injury agreement

Sled testing of both the SUV and the sedan environments consistently showed higher rib deflections for the ES2-RE Dummy. Analysis of the dummy kinematics for the vehicle and sled testing indicated that the seatbelt affected the kinematics of the thorax. In the sled test the dummy torso rotates counterclockwise in the plan-view towards the pole as the dummy is impacted. However, in the vehicle test the seatbelt tended to restrict this motion. Based on these findings the test fixture for the SUV was modified to include the seatbelt. With the addition of the seatbelt the dummy kinematics matched the vehicle test much better, reducing the amount of torso rotation in the plan-view (Figure 9). Furthermore the rib deflections matched the vehicle test well (Figure

10 & 11). As a result it was concluded that the seatbelt must be included in the sled test in order to achieve acceptable agreement of the rib deflection.

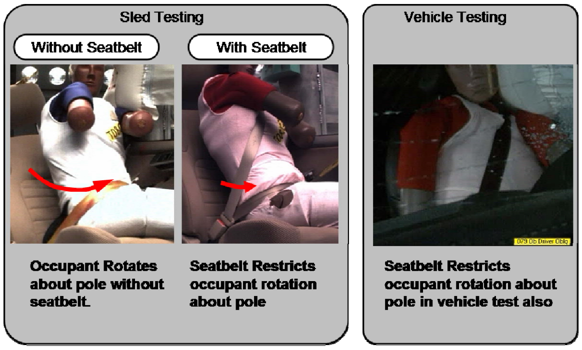

Figure 9. Seatbelt influence on ES2-RE dummy kinematics

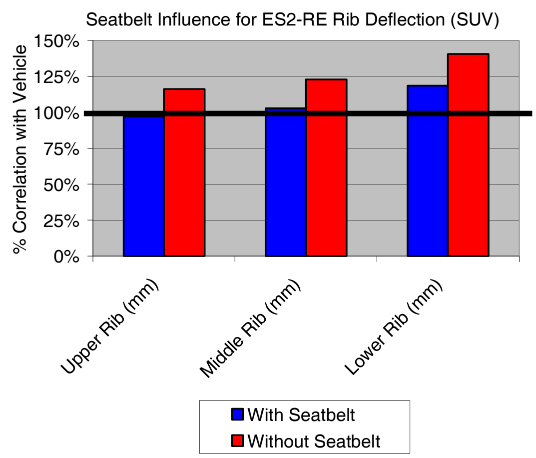

Figure 10. Seatbelt influence on ES2-RE rib deflections (SUV)

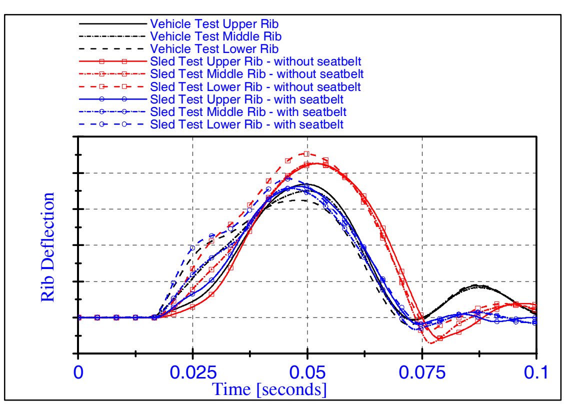

Figure 11. Seatbelt influence on ES2-RE rib deflections time history (SUV).

The pubic force for the SUV environment was slightly below the acceptable range with a normalized injury of 0.73, 27 percent lower than the vehicle test. It is believed that the reduced pubic force level observed in the sled test is due to the lack of the interior components and floor structure included in the sled test. In the vehicle test there are two forces applied on the dummy pelvis. The first being (F_1) the external force applied on the dummy pelvis by the pole impact. The second force (F_2) is the reaction force resulting from the inboard side of the dummy interacting with the vehicle interior components such as the center console. In the vehicle test the net force measured by the ES2-RE pubic load cell is the summation of these two forces ($F_{Total} = F_1 + F_2$). In the sled test the reaction force F_2 is not accounted for because the vehicle's interior components and floor are not included resulting in a lower pubic force (Figure 12).

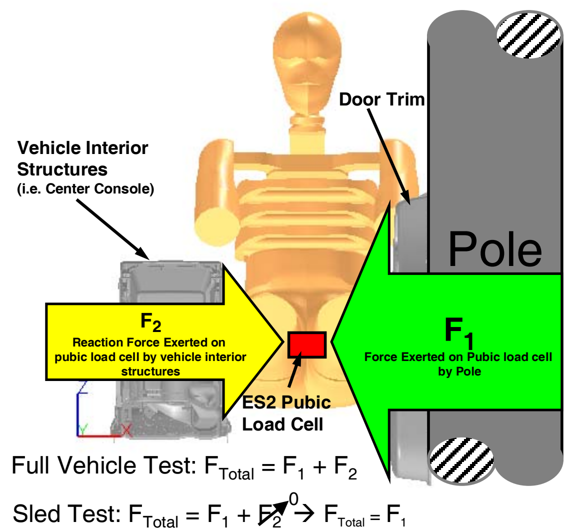

Figure 12. ES2-RE pelvis loading

Further testing is required in order to verify if this theory is correct. It may be possible to improve the agreement of the pubic force by including the center console structure in the sled testing. However, given the desire to maintain the simplicity of the test setup the authors feel the current level of correlation is acceptable especially given the agreement level of the pelvis acceleration (Figure 13) which can be used to predict the pubic force in the vehicle test. However, care should be taken to understand the relationship between the pubic force and the pelvis acceleration for the subject vehicle, as it may vary from vehicle to vehicle depending on the vehicle layout.

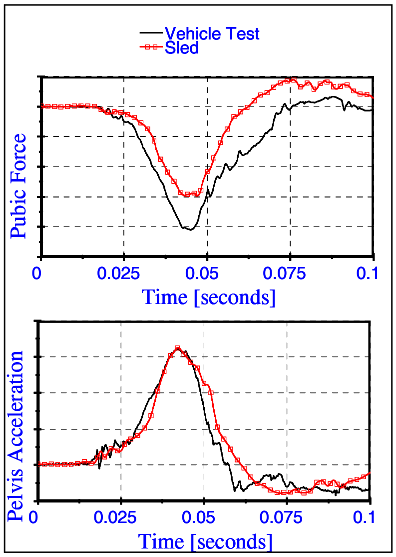

Figure 13. ES2-RE pubic force (SUV)

SIDE AIRBAG OPTIMIZATION CASE STUDY

In order to demonstrate the effectiveness of this test methodology, a case study using the SUV environment was conducted. The goal of this study was to optimize the side airbag to reduce the ES2-RE average rib deflections by 20% while reducing the injury levels for the other ES2-RE body regions as well as for the SID IIs by as much as possible. A design of experiments approach was used for this testing with the following variable being considered:

1. Three inflators were considered for this study which will be referred to as inflators: A, B, and C (inflator 'A' is the baseline inflator)

2. Two side airbag cushion types were considered for this study. The first being a single chamber cushion that provides coverage to the thorax and pelvis (baseline). The second type of cushion considered was a dual chamber pelvis – thorax cushion. The two chambers were created by the addition of internal baffle in the single chamber cushion that was positioned between the thorax and pelvis portions of the airbag. The intent is to maintain a higher pressure in the pelvis chamber to increase the energy absorption of the pelvis. Figure 14 shows the two cushion shapes evaluated.

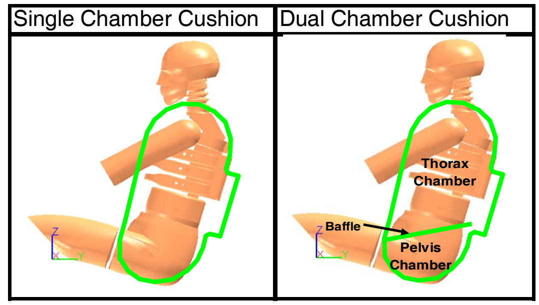

Figure 14. Side airbag cushion configurations evaluated

3. The third variable considered was the vent size to determine the optimal stiffness considering both the AM50 and AF05 occupants.

The test matrix for the ES2-RE dummy was conducted first to determine the optimal bag configuration to reduce the rib deflections (inflator, cushion type, and vent size). Once this was completed a small test series was completed for the SID IIs varying the vent size to determine the optimal bag stiffness for the ES2 and SID IIs dummies. Table 2 outlines the approach used for the sled testing.

Table 2.
Testing approach.

Occupant			Series 1 AM50 (ES2-RE)	Series 2 AF05 (SID IIs)
Side Airbag Parameters	Inflator	'A' (Baseline)	O	
		'B'	O	
		'C'	O	
	Cushion Type	Single Chamber *(without baffle)*	O	
		Pelvis / Thorax Dual chamber *(with baffle)*	O	
	Vent Diameter		20 mm 25 mm 30 mm 35 mm 40 mm	20 mm 30 mm 40 mm

For the purpose of this study all injuries were normalized with respect to the baseline test results to allow for easy comparison. The baseline side airbag specification is as follows:

- Inflator ‘A’
- Single chamber cushion
- Vent = 32mm Diameter

Inflator ‘B’ showed better performance for all body regions with the largest improvement in the average rib deflection (Figure 15). Therefore, Inflator ‘B’ was chosen as the optimal inflator. The Dual chamber cushion showed a slight improvement for the pelvis injury (4%). However, both average rib deflection and abdominal force were worse with the dual chamber cushion (8%, and 11% respectively). Since average rib deflection was the primary criteria being optimized the single chamber cushion was selected as the optimal cushion type (Figure 16). From the sensitivity analysis it was found that vent sizes ranging from 27mm to 37mm diameter achieved the target of 0.8 normalized injury for the ES2-RE average rib deflection (Figure 17). Furthermore the abdomen and pelvis injury was better for the ES2-RE with the smaller vent sizes. Therefore the optimal vent sized for the ES2-RE was determined to be a 27mm diameter based on achieving the 0.8 normalized injury for the ES2-RE average rib deflection and minimizing the injuries to the other body regions.

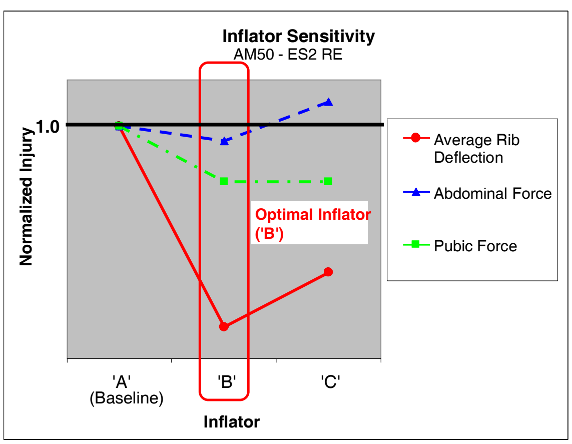

Figure 15. Inflator sensitivity for the ES2-RE injury measures.

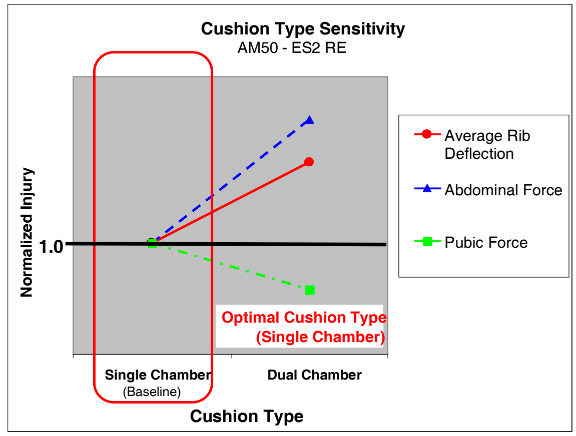

Figure 16. Cushion type sensitivity for the ES2-RE injury measures.

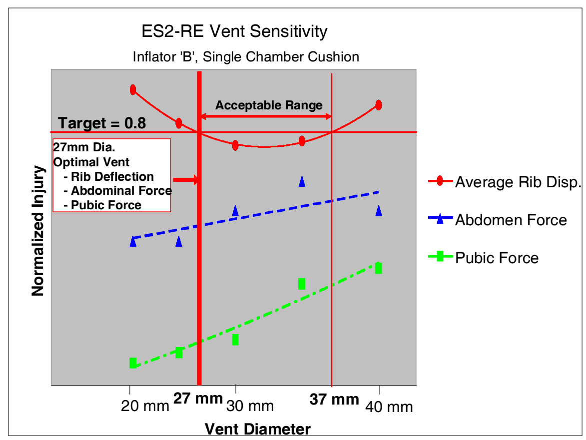

Figure 17. Airbag vent size sensitivity for the ES2-RE injury measures (inflator ‘B’, single chamber cushion data shown)

Once the optimal side airbag specification for the ES2-RE was determined a second test series was conducted for the SID IIs dummy. For this series the vent size was varied using Inflator ‘B’ with the single chamber cushion in order to determine the optimal vent size to minimize the injury for the SID IIs while achieving the target performance for the ES2-RE average rib deflection. Figure 18 shows the vent sensitivity for the SID IIs with the acceptable range for the ES2-RE average rib deflection (Inflator ‘B’, single chamber cushion). As with the ES2-RE dummy the injury results for the SID IIs were also found to improve with a smaller vent size. As a result the optimal vent size for the SID IIs was judged to be a diameter of 27mm (same as the ES2-RE). Therefore, the optimal side airbag specification considering both ES2-RE and SID IIs dummies was determined to be:

- Inflator: 'B'
- Cushion Type: Single chamber
- Vent size: 27 mm Diameter

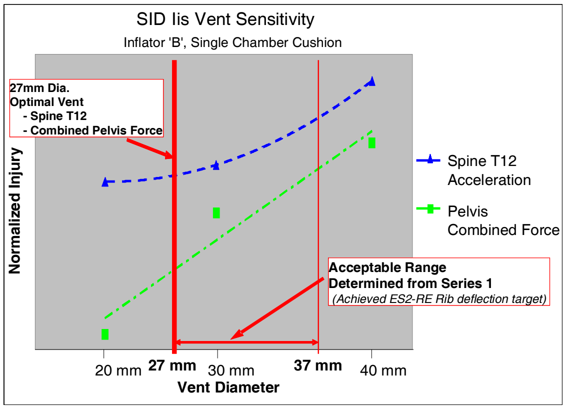

Figure 18. Airbag vent size sensitivity for the SID IIs injury measures (inflator 'B', single chamber cushion)

Through the use of this test method the target of reducing the ES2-RE average rib deflection by 20% while improving all other injury measures for both ES2-RE and SID IIs dummies was achieved with a minimum number to test components. Figure 19 summarizes the injury results of the optimized side airbag for both the ES2-RE and SID IIs dummies.

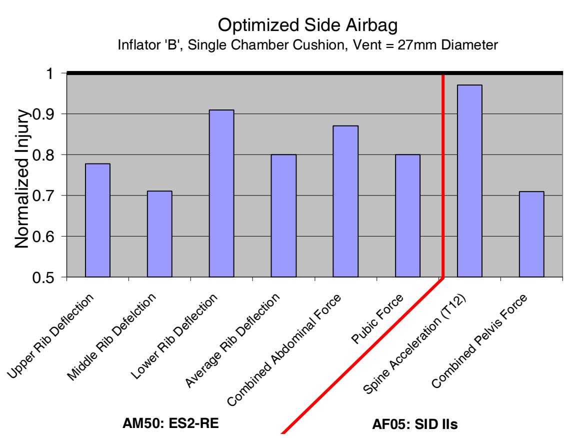

Figure 19. Optimized Side Airbag Normalized Injury for the ES2-RE and SID IIs dummies.

CONCLUSION

- This test method provides good correlation to vehicle testing while using a minimum number of components. Correlation was shown for a wide range of occupant sizes and seating positions as well as vehicle architectures.
- Through the case study presented the authors showed this test method to be an effective tool for developing optimized side impact restraint systems.

ACKNOWLEDGMENTS

The authors would like to thank our colleagues for their technical and analytical support. We would like to thank the following people in particular for their support on this project: Koichi Sagawa, Erik Robins, Dan Steimke, Lois Mueller, Christina Morris, Jennifer Pranke, and Analia Jarvis, Ron Parrott, Andy Young, Nate Schlis, Jim King, Mike Manicai, David Crumb, Kevin Stephen, and Chuck Sherwin.

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