System-level Sled Test Methodology to Optimize Restraints for Small Overlap Frontal Crash Tests

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ABSTRACT: Automotive manufacturers have developed a variety of countermeasures to optimize a vehicle’s performance under the Small Overlap Frontal Crash (SOFC) test. Generally, the SOFC test produces higher severity pulses and greater vehicle body intrusion than any other existing crash mode. Therefore, the primary focus of this research was to develop a system-level sled test methodology for the optimization of vehicle restraints, dummy kinematics and head protection through the analysis of primary control factors. For this study, a universal sled buck was specially designed to accept a variety of vehicle interior components and to adapt to varying vehicle packaging conditions.

KEY WORDS: Safety, Sled, Small Overlap Frontal Crash (SOFC) Testing, IIHS, Restraint Optimization, Countermeasures, Universal Buck [C1]

1. Introduction

In the early 1990s, much emphasis in the research community was placed on analyzing real world crashes. From this research, frontal crashes at various speeds and overlap conditions were identified. This research led to the development of the Severe Partial Overlap Collision test method, which focused on 20-40% overlap collisions against a fixed rigid barrier and initial velocities up to 65kph. Currently, there are two major consumer evaluation programs that assign ratings for new US market vehicles. The National Highway Traffic Safety Administration (NHTSA) uses a star rating from 1 to 5, while the Insurance Institute for Highway Safety (IIHS) categorizes the overall vehicle performance as good, acceptable, marginal, or poor. On August 14, 2012, IIHS released the first Small Overlap Frontal Crash (SOFC) test results, where 25% of the front end of the vehicle was subjected to a rigid barrier impact at 64kph. According to research from Brumbelow and Zuby in 2009, the SOFC mode accounted for 24% of the 116 real world frontal crashes with serious injuries in their study. Additionally, the SOFC tends to produce higher levels of intrusion as compared to the narrow center or moderate overlap crash. Small overlap crashes have been identified as a significant contributor to occupant injuries and fatalities in frontal crashes.

The SOFC test is evaluated through three categories: restraint and dummy kinematics, dummy injury and vehicle structural performance. The dummy injury category is divided into four body regions: head and neck, chest, thigh and hip, legs and feet. The primary focus of this research is to develop a sled test methodology for the optimization of vehicle restraints and their interaction with the kinematics of the dummy. By controlling the dummy kinematics and their interaction with the restraint system, it should be possible to control two of the three performance categories for determining the vehicle rating.

Moreover, many automotive manufacturers in the industry traditionally rely heavily on full-scale crash testing. As this may suggest, this traditional methodology incurs significant costs and longer developmental periods.

Therefore, the intent of this research is to introduce a system-level sled test methodology to reduce development costs by optimizing the number of full-scale crash tests and expediting the development period, which overall, may reduce the total production cost of the vehicle.

2. Sled Test Methodology for Optimizing Restraints for IIHS SOFC

2.1. Key milestones

The proposed sled test methodology is an incremental approach to assessing the performance and optimization of vehicle restraint systems and countermeasures for the IIHS SOFC test. Therefore, in the study, heavy emphasis was placed on reproducing dummy kinematics from the full-scale crash test. Secondary considerations were placed on correlating Head Injury Criteria (HIC) and other injury values.

Key milestones for producing the sled test methodology were as follows:
- Developing of a universal test buck
- Developing a sled pulse
- Reproducing the vehicle’s structural dynamic response characteristics during a SOFC test
2.2. Universal Buck Development

It was understood early on in the process that in order to consistently and efficiently perform each sled test, a specialized tool needed to be developed - this was the universal buck. The universal buck allowed for an incremental assessment of each restraint’s performance under a variety of packaging conditions. For ease of use, all parts were installed using bolts. The overall design concept included a consistent hole pattern throughout, which allowed for the adaptation of multiple vehicle platforms of varying sizes. The base plates were designed with a slot and included transfer bearings, which allowed an infinite selection of yaw angles between 0 to 30 degrees clockwise. The design of the buck also included the ability to install collapsible, production level steering columns that could be rotated, translated and yawed relative to the chassis in order to simulate dynamic intrusion resulting from the SOFC. Further, the universal buck design allowed for the installation of full length curtain airbag (CAB) attachments and a variety of seats and seat belt restraint systems. Additional design considerations included the installation and adjustment of the knee bolster, footrest, windshield, roof and A/B pillars. The drawings in Figures 1 and 2 reflect the adjustability and overall design considerations of the universal buck.

2.3. Pulse Development

In the development of the sled pulse, much consideration was focused on determining the phase of the pulse which would yield the greatest effect on reproducing vehicle behavior and dummy kinematics. As shown below in Figure 3, the vehicle behavior was divided into 3 phases.

Phase 1 shows the initial contact where the front bumper begins to engage the barrier and deform. During this phase, the vehicle and dummy are stable due in part to the low impact energy over a short duration. In phase 2, the front left wheel begins to engage the barrier and deform. This asymmetrical loading induces some increased lateral motion. However, it is not until phase 3 that the primary factor in the behavior of the vehicle is defined. In phase 3, the barrier has engaged the wheel rim and has forced it into the back of the wheel well and corresponding side sill. As long as the vehicle does not slip over the face of barrier, this increased asymmetrical loading along the X axis will cause the vehicle to rotate counterclockwise. Phase 3 is the main driver which characterizes the vehicle behavior during a SOFC and as a result, primarily influences the dummy kinematics. As such, the main focus of the sled pulse generation was set on the reproduction of key elements in phase 3.

A comparison of the acceleration and velocity profiles for the sled and full-scale SOFC test are shown below in Figure 4.
Initially, a simple setup was used to determine the optimal pretest sled condition for reproducing the head excursion from a full-scale SOFC test. In the full-scale SOFC test, the maximum head excursion was obtained when the vehicle achieved about a 25 degree yaw angle. Due to the complexities of reproducing a dynamic yaw angle, a short experiment was developed to determine the static yaw angle which produced an equivalent head excursion to the target SOFC test. For this, a test series was conducted where the yaw angle was adjusted in 5 degree increments. The tests were performed using a Hybrid III 50th percentile Male dummy. The dummy was instrumented with three axis head, chest, pelvis accelerometers, head angular rate sensors, and a six axis upper neck load cell. Lap and shoulder belt load cell transducers were installed to understand the occupant and restraint loading profile and timing. The anchor and retractor pretensioners were fired remotely in sync with the timing found from full-scale SOFC tests. Additionally, photometric analysis was also used to track the head path of the dummy.

According to these results, a static yaw angle of 20 degrees - which is 80% of maximum yawed angle of vehicle – has similar dummy kinematic responses to the target full-scale SOFC test. Photos of the test setup are shown in Figure 5 and 6.

Using the same approach, the A-pillar deformation was reproduced by measuring the driver door opening pre and post-crash as shown in Figure 8. To reproduce the A-pillar intrusion on the universal buck, the forward tether anchor mounting location on the CAB was altered to control the inflation of the forward-most chamber.
2.5. Comparison of sled and full-scale SOFC test

Successful optimization of the restraint system configuration of the sled tests were based on improving the occupant head protection as compared to the IIHS official SOFC test results for the 2015 model year mid-size vehicle platform, for which the vehicle received an “Acceptable” rating in the dummy kinematics category.

Initially, a baseline sled test was performed with production vehicle content to qualify the reproducibility of the methodology. After successful completion of this test, incremental changes to the restraint system were applied to improve occupant head protection. Some countermeasures included the substitution of critical components, such as the load limiter of the shoulder belt retractor or by shifting the CAB Time To Fire (TTF) for example. A full-scale SOFC test was performed with the new countermeasures applied to confirm the effectiveness of the change. The results of the occupant head protection correlation between the sled and full-scale SOFC tests are summarized in Figures 9 and 10.

The IIHS official SOFC test produced a peak head excursion of 428mm, while the sled baseline test produced a head excursion of 433mm. Furthermore, the final configuration, as determined by the sled test methodology, for producing the optimized restraint system yielded a reduced peak head excursion of 300mm, which was confirmed by the full-scale SOFC test of which yielded a head excursion of 331mm. Therefore, it was postulated that there is a positive correlation between the sled test methodology and the reproducibility of dummy kinematics during a SOFC test, especially as it pertains to improving occupant head protection.

3. Analysis of The Primary Control Factors for Providing Occupant Head Protection

For this research, four major variables were analyzed for effectiveness in improving occupant head protection: seat belt restraint systems, CAB volume (thickness) of forward-most chamber, gas flow control within the CAB and TTF of CAB. For this analysis, a variety of tools were adopted to measure the dummy head kinematics. These included the IIHS head excursion calculation template, head accelerometers, head angular rate sensors and two string potentiometers attached directly to the dummy’s head. A comparison of the resulting head excursion data is shown by Figure 11.
According to the variables analyzed in this research, the effectiveness of each of the primary control factors can be represented in Equation (1).

\[
A \gg C \gg B \approx D
\]

\(A\): Seat belt restraint system effective
\(B\): CAB Volume (Thickness) effective
\(C\): Gas Flow Control of CAB effective
\(D\): TTF of CAB effective

While increasing the load limiter on the shoulder belt retractor yielded the most effective reduction of dummy head excursion, it also increased the risk of chest deflection injury.

The effect of diverting the gas flow control within the CAB was found to be a useful mechanism for reducing lateral head excursion. That is, if the chambers that comprise the CAB could be positioned to intersect the dummy head, optimal lateral head protection could be achieved. Additionally, adjusting the CAB volume of forward-most chamber had the same effect as applying an earlier TTF. Setting an earlier TTF allows the CAB to engage the occupant’s head at an earlier stage, stabilizing and guiding it through the event. The diagram in Figure 12 below shows this interaction.

![Fig. 12 CAB gas flow direction comparison](image)

The effect of increasing the CAB volume (thickness) of the forward-most chamber was to reduce the gap produced between the CAB and DAB deployments. Figure 13 shows an example of the increased CAB volume (thickness).

![Fig. 13 Comparison of CAB chamber thickness](image)

This research showed that with the proper gas flow in an optimized CAB, the dummy’s head is pushed inboard when it is deployed at the initial stage and guided away from the A-Pillar. This was not the case as found in the baseline tests. The CAB engaged the head late and without enough force to redirect the head’s lateral movement. The increased head excursion was further perpetuated by the lack of volume (thickness) and decreased inflation rate of the forward-most chamber as shown in location (2) of Figure 14.

![Fig. 14 Comparison of head to CAB engagement for 2 types](image)

Therefore, these test results show that proper gas flow and dummy head to CAB engagement are critical factors for providing proper occupant head protection in SOFC tests.

### 4. Optimization of Restraint System

According to this research, the primary factors of head excursion control are: an increased seat belt restraint tension, deeper chamber depth and proper gas flow direction with an earlier TTF. The results of these countermeasures are summarized in Figures 15 and 16.

![Fig. 15 Comparison of head excursion for baseline and optimized restraint configuration](image)
Fig. 16 Comparison of restraint specifications for baseline and optimized restraint configuration

The results shown in Figure 15 were calculated using the 3 axis accelerometers and angular rate sensors in the dummy’s head, whereas, the results shown in Figure 16 were calculated using the IIHS small overlap excursion template.

5. Summary and Conclusion

The purpose of this research was to develop a sled test methodology that was capable of reproducing dummy kinematics from a full-scale SOFC test. The intent of the study was to determine the primary restraint components that could be used to optimize occupant head protection.

In the process of creating this research study, a universal buck was developed to reproduce the structural dynamic response characteristics of the vehicle during a SOFC test. Some of these characteristics include vehicle yawing, steering column intrusion, and A/B pillar deformation. Moreover, the universal buck was designed to accept components from multiple vehicle platforms of varying packaging condition.

This research suggests sufficient correlation results with good consistency between the sled and full-scale SOFC tests. Therefore, it was postulated that the universal buck may be an influential tool for providing an incremental assessment of each restraint’s performance for optimizing occupant protection during the SOFC test. However, more research will be needed to fully understand the effectiveness of this tool. The next steps for evaluating this tool moving forward will be to apply the concepts learned from this research to other vehicle platforms.

According to these research results, occupant head protection can be optimized using deeper CAB chamber volumes (thickness), improving CAB gas flow and increasing seat belt tension. An earlier TTF can also help to engage the dummy head earlier in the event and guide the head inboard, away from the A-Pillar.

It is understood that though the increase in seat belt tension had the greatest effect on the reduction of head excursion, it is a key contributor to the risk of higher chest deflection injury during the 56kph full frontal impact or 40% offset deformable barrier (ODB) crash test. In order to reduce this risk, a restraint system with an adapter load limiter is recommended, which would alter the load control under various crash modes.

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References

(1) Jakobsson, L., McNally, G., Axelson, A., Lindman, M. et al.: Severe Frontal Collisions with Partial Overlap - Two Decades of Car Safety Development : SAE Technical Paper 2013-01-0759, 2013, doi:10.4271/2013-01-0759 (2013).
(2) Samaha, R., Digges, K., Fesich, T., and Authaler, M. : Frontal Crash Testing and Vehicle Safety Designs: A Historical Perspective Based on Crash Test Studies : SAE Technical Paper 2010-01-1024, doi:10.4271/2010-01-1024 (2010).
(3) Munjurulimana, D., Nagwanshi, D., and Marks, M. : Small Overlap Impact Countermeasures for Automobiles : SAE Technical Paper 2015-01-1491, doi:10.4271/2015-01-1491 (2015).
(4) IIHS Status report news letter Vol. 47, No. 6 August 14, (2012).
(5) Brumbelow, M.L. and Zuby, D.S. : Impact and injury patterns in frontal crashes of vehicles with good ratings for frontal crash protection : 21st ESV Conference (2009), Paper no. 09-0257.
(6) Sherwood, C., Nolan, J., and Zuby, D. : Characteristics of small overlap crashes : 21st ESV Conference (2009), paper number 09-0423
(7) Insurance Institute for Highway Safety : Small Overlap Frontal Crashworthiness Evaluation Rating Protocol (Version III) (2014).