Occupant Behavior in Small Front Overlap Event – A Parametric Study

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ABSTRACT

Frontal crash tests have always been at the forefront of vehicle safety evaluation. However, the full frontal testing and 40% oblique testing that is included in the National Highway Traffic Safety Administration (NHTSA) and the Insurance Institute for Highway Safety (IIHS) rating system does not represent some of the severe crashes recorded in the field. NHTSA and IIHS have been investigating frontal oblique impacts with narrow, offset objects to increase the coverage of replicating real world crashes with controlled testing procedures.

The objective of this paper is to study and understand the effect of vehicle structural performance on the occupant kinematics and related injury during small front overlap crashes. As occupant kinematics and injuries are directly influenced by structural response of the vehicle, this paper focuses on effect of various structural responses with corresponding intrusions and rotations. It also investigates effectiveness of the restraint system to reduce the occupant injuries.

MADYMO software was used to create a small front overlap environment. A driver occupant was represented by 50th percentile Hybrid III dummy model. All the intruding parts (floor, dash, hinge pillar, IP, steering column, A-pillar, door, door trim) were represented by planes and hyper-ellipsoids. Time based intrusions were extracted from the small front overlap test data and applied to all intruding parts. Seat belt system, driver airbag, side airbag and curtain airbag were modeled as part of restraint system. Longitudinal (X) and lateral (Y) structural responses were applied to the MADYMO dummy. A parametric study was then designed to understand the effect of various vehicle structural responses, restraint system deployment timing, seat belt load limiters and steering wheel lateral and vertical movements on occupant kinematics and injuries.

INTRODUCTION

In designing a small overlap test condition, the IIHS researched over 20 years of crash scene data. In 2009, Sherwood et al [1], stated that one-quarter of severe crashes had loading on less than 40% of the vehicle's front end structure. The test procedure consists of impacting a 6 inch diameter rounded barrier at 64 km/h with a 25% overlap of the front width of the vehicle. There are three categories for the rating evaluation; (1) restraints and dummy kinematics, (2) dummy injury measures, (3) and vehicle structural performance. The restraints and dummy kinematic assessment allows for further evaluation besides injury measurements from the test dummy, and can be applied to occupants of other sizes and seating positions. This category uses a demerit system for Frontal Head Protection, Lateral Head Protection, Frontal and Lateral Chest Protection, and Occupant Containment. Four groups of dummy injury ratings utilize the instrumentation in the dummy's (1) head and neck, (2) chest, (3) hip and thigh, and (4) legs and feet. Each of these body regions receives one of the ratings, Good, Acceptable, Marginal, or Poor, based on the performance. The lowest score of the four regions is used as the overall dummy injury rating. The vehicle structural rating is based upon the pre-test and post-test measurements of seven various locations. It is further divided into upper and lower occupant compartment regions. The upper region includes measurements of the steering column, upper hinge pillar, upper dash, and left instrument panel (knee bolster). The lower region includes lower hinge pillar, footrest, left toe-pan, brake pedal, parking pedal, and rocker panel. Each region receives a sub-rating, and the overall structural rating is based upon the worst performing region.

METHOD

Model

In this paper, correlation refers to the kinematic and injury comparison between CAE model and test data. Baseline vehicle refers to the in-house test that was conducted on one of the vehicles.

The data in this paper was gathered using a MADYMO small overlap simulation model (Figure 1). A correlated NCAP model was used to develop a small front overlap baseline model. Hybrid III 50th percentile dummy was used as a driver occupant. This model used driver airbag, retractor pretensioner and anchor pretensioner as a part of restraint system. A generic finite element model of curtain airbag was included. Multi-Body (MB) surface planes were created for the upper and lower interior door trim, along with the armrest. A-pillar segments and the side rail were represented by cylinders. Hinge pillar and dash were modeled using planes. Each surface was given a translational joint in the primary direction of relevant movement; dash, a-pillar, and side rail in the X direction, and hinge pillar and door trim in the Y direction. The steering column joint was given Y rotation capabilities to replicate the vehicle test.

Structural intrusion data was extracted from a full vehicle test and from an LS-DYNA structural simulation model. The intrusions of surfaces were derived from pre and post test measurements, along with a dynamic estimation based on the LS-DYNA model and baseline comparison injury results.

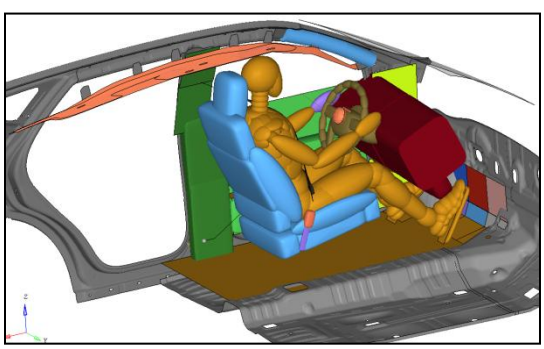


Figure 1. Baseline Small Overlap Model

Parameter Study

The parameter study of adjustable component characteristics and performance assessment was used to understand the resulting effects on the kinematics of the dummy. IIHS has shared the structural responses from the small overlap tests performed in the last year. Vehicles were selected from all performance categories of the IIHS rating system. The vehicles' structural responses were analyzed and used in the model for any notable contributions of peak, duration, timing, and trends based on the accelerometer data. Restraint system deployment timing, seat belt load limiters and steering wheel lateral and vertical movements were varied to understand their effect on occupant kinematics and injuries.

RESULTS

The baseline model used for this study demonstrated good correlation with NCAP test. For small front overlap test condition, occupant kinematics showed good correlation with the small front overlap test. Due to generic curtain airbag used in the model, injury correlation was not performed. Injury correlation showed some trends and peak as per the test though. This correlation is displayed in Figure 2, with the test vehicle data displayed in blue, and the simulation data in red.

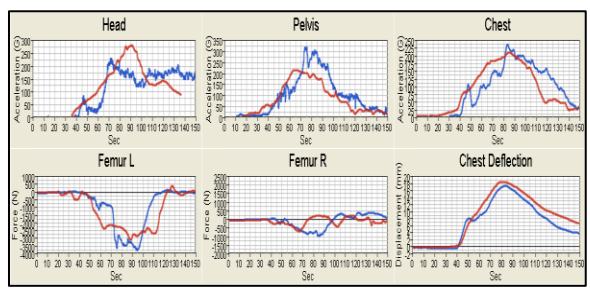


Figure 2. Baseline Correlation

With this correlation, focus of the study was to understand occupant kinematics, injury trends and associated demerits with variation in parameters.

Following injury reference values were used to compare injury percentage in the paper.

HIC: 700
Chest Acceleration: 60 G
Chest Deflection: 50 mm
Femur Force: 10,000 N

Parametric study:

1) Vehicle structural response

In-house full vehicle small front overlap test showed that the upper body injury values were

low and had more than 50% margin for a Good rating. Lower body injury values were high due to excessive structural intrusion. For Good or Acceptable structural performance for this test, structural countermeasures have to be developed.

These structural countermeasures can be divided into 2 categories.

Category 1: Deflection strategy where vehicle rotates at the point of contact and deflects away from the barrier, and

Category 2: Energy absorption and occupant cage protection strategy where vehicle rotation occurs when barrier contacts occupant cage.

For this parametric study, a wide variety of vehicle structural response data was analyzed using baseline model. Due to unavailability of the data, structural intrusions were maintained constant. This structural data was divided into 2 categories defined above. These two categories were simplified and represented by step function. Figure 3 shows vehicle X acceleration in G's versus time in seconds. Acceleration data was collected from accelerometer located at the bottom of B-pillar.

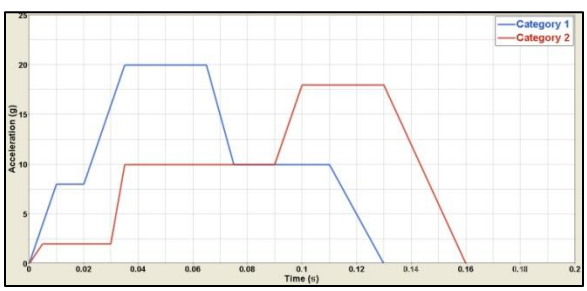


Figure 3. Simplified Acceleration versus Time Data based on Vehicle Categories

It was observed from the data that category 1 vehicles showed more rotational tendency about Z axis. This rotational tendency of the vehicle resulted into more lateral motion of the occupant.

Figure 4 compares injuries for these 2 categories. HIC value and chest acceleration were higher for category 1 vehicles. Chest deflection was very similar for both the categories.

Early loading of the vehicle for category 1 initiated early occupant motion. Occupant had more energy to dissipate. This excessive energy resulted in higher upper body injuries. Note that, lower body injuries are not compared here due to constant intrusion values. Category 2 vehicles experience higher structural intrusions and higher lower body injuries.

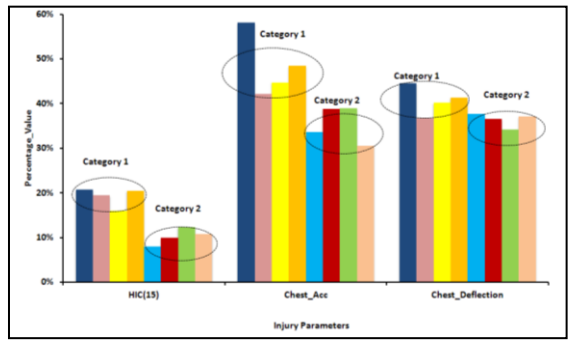


Figure 4. Occupant Injury based on Structural Response

Vehicles with category 1 structural response experienced higher lateral motion for the occupant. Based on the lateral motion, occupant showed partial or no driver airbag interaction (figure 5). This led to 1 or 2 demerits respectively.

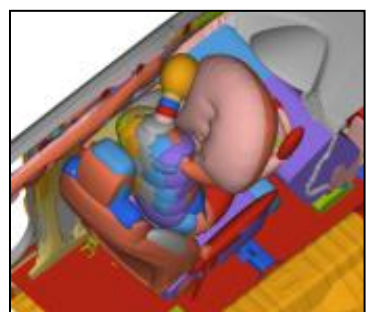


Figure 5. Partial Driver Airbag Interaction

2) Time-to-fire (ttf)

For the baseline model, time-to-fire for retractor pretensioner, driver airbag and curtain airbag was 34 ms. This time was based on in-house small front overlap test conducted.

The purpose of this parameter study was to understand the effectiveness of the restraint system based on its time-to-fire. To achieve this, restraint system ttf was varied starting from 15 ms till 65 ms at every 10 ms step (ttf: 15, 25, 34, 45, 55, 65 ms).

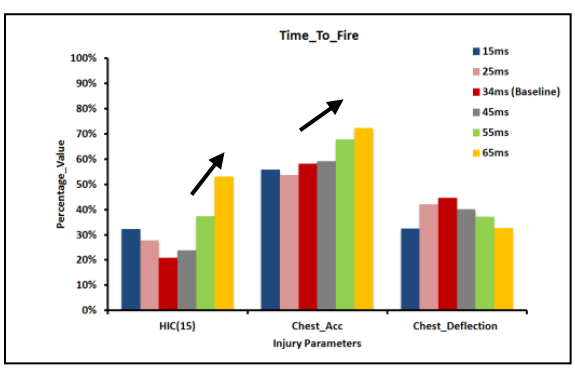
Figure 6 compares HIC, chest acceleration, chest deflection, head and chest displacement for various ttf.

Time-to-fire variation analysis showed that due to nature of the event, occupant did not have much energy to dissipate during first 30 ms. Deploying restraint system during this time period (15 and 25 ms) ended up driver interacting with deflating driver airbag. Driver head slid over the airbag with partial contact (demerit) and went closer to the A-pillar. Higher head and chest X travel demonstrated this motion.

Restraint system deployment at 34 proved to be the most efficient deployment. Due to structural response, occupant experienced energy transfer at 30 ms and started gaining momentum. Part of the occupant energy was dissipated immediately through fired retractor pretensioner and anchor pretensioner. Driver started interacting with driver airbag when it was in position and inflating. Most of the driver energy was dissipated through driver and curtain airbag. HIC and chest acceleration showed lower values. Head and chest displacements were minimum.

When restraint system was deployed at 45, 55 and 65 ms, driver already had gained the momentum from vehicle structural response. Delayed restraints did not help to dissipate energy efficiently. HIC value, chest acceleration, head displacement and chest displacement showed increasing trend with delay in time-to-fire.

Driver head moved into the gap between driver and curtain airbag (demerit). It went very close to the A-pillar.



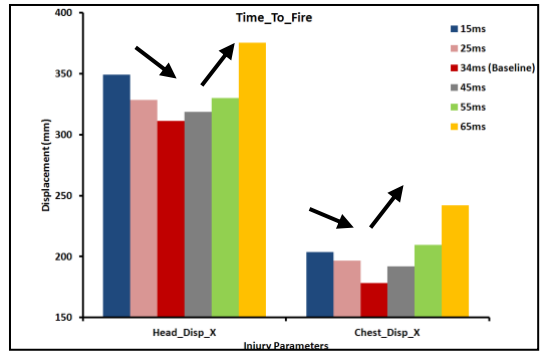


Figure 6. Occupant Injury based on Time-to-fire

3) Seat Belt Load Limiter

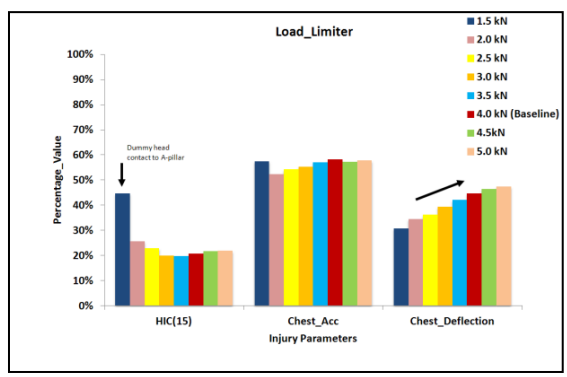
Seat belt load limiter plays a vital role in dictating dummy chest deflection which in turn dictates vehicle USNCAP front star rating. With the stringent criteria to achieve 5 star rating, it is observed that many vehicles use lower load limiter values.

For small front overlap, it is required to hold the dummy in place to avoid dummy excursion and dummy hard contact with occupant compartment. This requires higher load limiter.

The purpose of this parameter study is to understand effect of various levels of load limiters on dummy injury and dummy excursion.

The baseline model used a load limiter with 4 kN force. For the study, the load limiter level was varied by increments of 500 N from1.5 kN to 5.0 kN.

Figure 7 compares head and chest injury and its relative displacement due to variation of load limiter values.



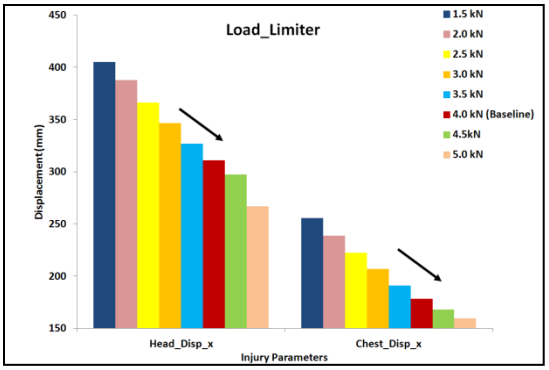


Figure 7. Occupant Injury based on Seat Belt Load Limiter Level

From the injury analysis, it was observed that with decrease in load limiter level, chest deflection was decreased significantly. It was seen at the lowest level for 1.5 kN load limiter and at the highest level for 5.0 kN load limiter.

Head and chest travel was increased with decrease in load limiter level. Since belt force was reduced, it allowed dummy head and chest to travel farther increasing the risk of dummy hard contact to occupant compartment. A head strike to the A-pillar was observed for 1.5 kN load limiter (demerit).

4. Steering Wheel Movement

IIHS rating includes a demerit qualifier for excessive vertical (>100 mm) and lateral (>150 mm) steering wheel movement. If steering wheel moves away from the occupant before occupant loads on the driver airbag, it fails to provide sufficient dummy coverage to dissipate energy through driver airbag. It may lead to higher injury values and a demerit.

This parametric study looked into 3 aspects of steering wheel:

a. Steering wheel lateral motion
b. Steering wheel vertical motion
c. Steering wheel lateral motion timing

a. Steering wheel lateral motion:

In the baseline model, steering wheel moved laterally by 55 mm. A study was conducted with 80 mm, 110 mm, 180 mm and 220 mm of lateral movement to understand its effect on dummy injury numbers. Figure 8 compares head and chest injury and its relative displacement due to variation of steering wheel lateral movement.

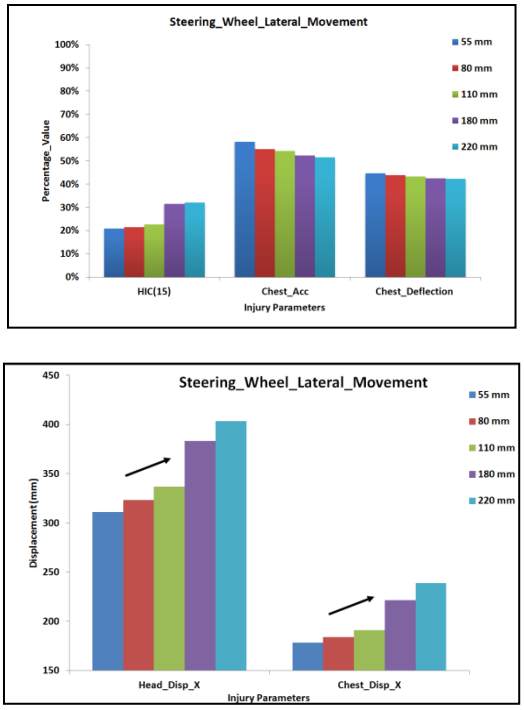
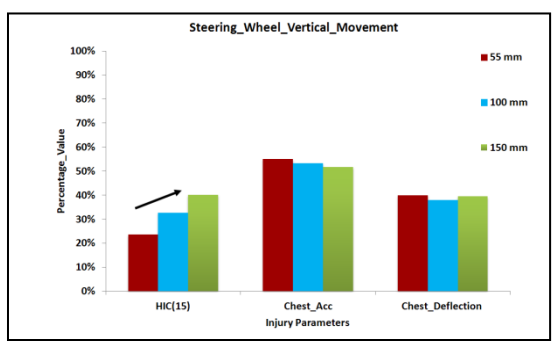


Figure 8. Occupant Injury based on Steering Wheel Lateral Movement

With the increase in steering wheel lateral movement, driver airbag coverage was significantly decreased (demerit). Lack of coverage led to increase in head and chest displacements. Lateral movements more than 150 mm affected dummy head acceleration considerably.

b. Steering wheel vertical motion:

Steering wheel vertical motion study was conducted with 55 mm, 100 mm and 150 mm vertical motion (55 mm being baseline). Figure 9 below compares head and chest injury and its relative displacements due to variation of steering wheel vertical movement.



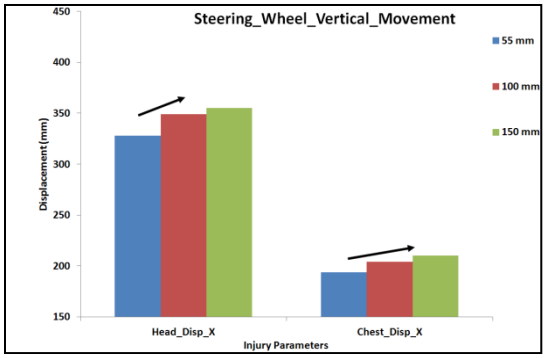
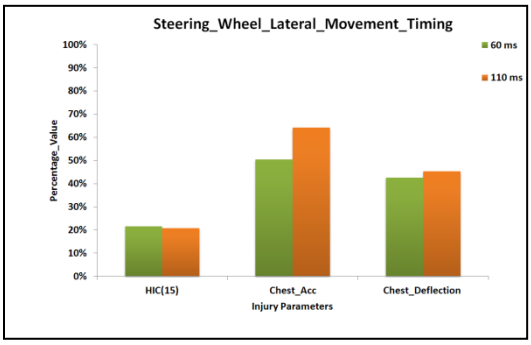


Figure 9. Occupant Injury based on Steering Wheel Vertical Movement

Driver head injury was mainly affected by steering wheel vertical movement. There was head strike to the steering wheel for 100 mm and 150 mm movement (demerit). Chest injury did not show significant change with the variation in steering wheel vertical movement.

c. Steering wheel lateral motion timing:

In the baseline model, steering wheel moved at 60 ms. In this study, steering wheel motion timing was delayed to 110 ms to understand its effect on occupant injury.



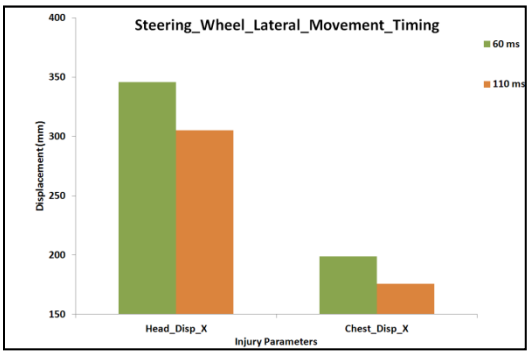


Figure 10. Occupant Injury based on Steering Wheel Lateral Movement Timing

Figure 10 compares the injury differences for steering wheel lateral movement timing. When steering wheel was moved at 110 ms, it supported dummy head and chest for longer time. This was demonstrated in reduced dummy head and chest displacements.

DISCUSSION AND CONCLUSION

- For vehicle structural response, vehicle deflection strategy leads to higher lateral and longitudinal dummy accelerations. Energy absorption and occupant cage protection strategy leads to higher structural intrusions in occupant cage. A well balanced vehicle structure and restraint system needs to be developed in order to mitigate impact energy efficiently

- Sensing strategy should complement to the structural and occupant performance

- With introduction of IIHS small overlap event, same seat belt load limiter has to comply with various impact event requirements. The strategy that is used to achieve highest STAR rating in frontal USNCAP event should be revisited and modified to comply with small front overlap event requirements

- IIHS rating includes a modifier for post test static position of steering wheel in lateral and vertical direction. If lateral or vertical motion occurs later in the event, it is not direct contributor to occupant injury. Efforts have to be taken to measure time history motion of steering wheel. A modifier has to be linked with time history data and video analysis

References

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