Effect of Impact Configuration Variance in Oblique Frontal Offset Tests on Driver and Passenger Injury Risk

Rudolf Reichert, Cing-Dao Kan

Abstract Oblique impacts account for a significant amount of real-world accidents. Compared to co-linear frontal crashes, these impacts produce different occupant kinematics and vehicle intrusion patterns. Consequently, a new frontal oblique impact test is being evaluated by NHTSA. Variations in impact conditions and occupant seated positions are immanent in full-scale testing. The aim of this research was to understand how repeatable the test procedure is when relevant parameters are changed within defined test tolerances and how sensitive vehicle and occupant results are, when parameters are varied beyond such tolerances. Finite element simulations and Design of Experiment methods were used to determine the importance of parameters and their individual and combined effect on vehicle and occupant criteria. A point-based rating scheme was used to calculate the overall occupant ratings. A *Test Procedure Study*, which is described in this paper, evaluated the effect of variations in Offset Moving Deformable Barrier impact angle, misalignment, overlap, mass, and velocity for ranges within (repeatability study) and beyond (sensitivity study) defined test tolerances. The study resulted in an extended database that allowed to analyse how kinematics and loads measured by THOR dummies are affected by a wide range of oblique impact configuration parameters. This research showed overall good repeatability with respect to vehicle kinematics and occupant loads, when relevant parameters were changed within defined tolerances. Far-side occupant loads were more sensitive to test setup variances.

Keywords DOE Analysis, finite element simulation, NHTSA's frontal oblique impact, test tolerances.

I. INTRODUCTION

Consumer information rating crash tests, such as the National Highway Traffic Safety Administration's (NHTSA's) New Car Assessment Program (NCAP) full frontal impact and the Insurance Institute for Highway Safety (IIHS) small and moderate frontal overlap impacts, have contributed to advance vehicle safety and reduce injury risks. Recent studies, such as [1], have indicated that oblique offset crashes are a common real-world accident pattern related to belted occupant fatalities. Another study compared the number of annual driver Maximum Abbreviated Injury Scale (MAIS) 3+ injuries by body region for oblique and co-linear frontal impacts [2]. It was observed that drivers in left oblique impacts experienced more MAIS3+ injuries in almost all body regions than drivers in co-linear crashes. Oblique impacts capture real world accidents, and the development of countermeasures for restraints and vehicle structures will potentially further improve vehicle safety and reduce injury risk.

NHTSA has developed a laboratory test procedure for oblique offset moving deformable barrier impacts [3]. Figure 1 depicts a schematic of the new oblique test configuration. An Offset Moving Deformable Barrier (OMDB) was optimised to produce realistic target vehicle crush patterns. It has a weight of 2,486 kilograms (kg) and impacts a stationary vehicle at a speed of 90 km/h. The vehicle is placed at a 15-degree angle from the OMDB longitudinal axis. The impact is set up such that a 35 % overlap occurs between the OMDB and the front end of the struck vehicle at initial contact.

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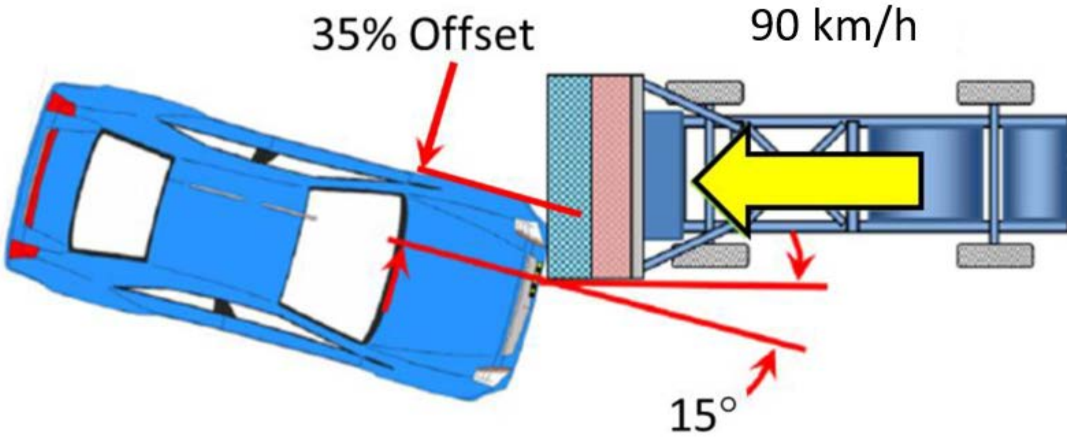

Fig. 1. NHTSA's Oblique Impact Configuration.

When developing the oblique test procedure, NHTSA has defined tolerances for test parameters, since they cannot be completely controlled. A finite element (FE) study using available models for vehicle, barrier, interior, restraints, and the respective Anthropomorphic Test Device (ATD), i.e. the Test device for Human Occupant Restraint (THOR) occupants was conducted to evaluate the effect of test configuration tolerances, such as small differences in impact angle, impact location, barrier mass, and velocity (repeatability study). To understand, how vehicle and occupant outcomes are affected when parameters are changed beyond current test tolerances, a sensitivity study was conducted. Evaluated parameters included: impact angle, OMDB horizontal misalignment (overlap), OMDB mass, and impact speed. The effect of each parameter, as well as combinations of these parameters, was investigated. Variations in vehicle and occupant (driver and passenger) responses were studied.

II. Methods

Baseline Simulation

A baseline simulation for NHTSA's left oblique impact condition was conducted with an FE model of a mid-size sedan vehicle with a THOR occupant in the driver and front passenger seat. THOR ATDs were positioned in the baseline simulation model using coordinate measuring machine data provided by the Vehicle Research Technical Center of NHTSA. Occupants were seated according to the latest seating procedures [3]. Figure 2 shows the final seated position for the driver (a) and passenger (b).

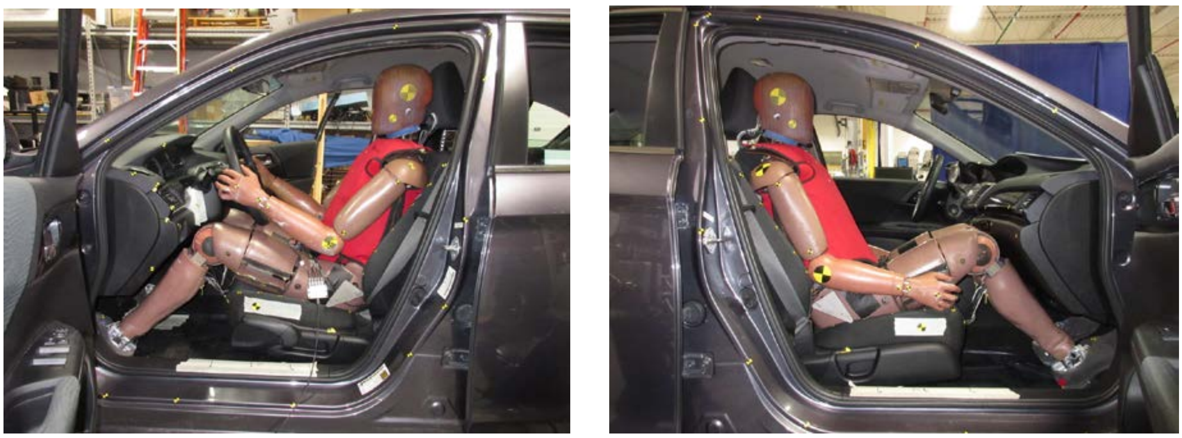

Fig. 2. THOR in (a) Driver Seat, (b) Passenger Seat.

The initial Baseline Model (BM) was setup by another organisation and provided by NHTSA [4]. Vehicle kinematics, vehicle pulse, occupant kinematics and injury criteria were compared with results from a full-scale test of the same vehicle [4, 5]. Kinematics and injury criteria compared reasonably well with the specific test results for all body regions, as described in [4, 10]. For example, maximum chest deflection for the driver was 49 mm in the test and 47 mm in the simulation; maximum chest deflection for the THOR in the passenger seat was 39 mm in the test and 38 mm in the simulation. Values for the Head Injury Criteria (HIC), the neck, pelvis, and lower extremities of the driver were all below the lower boundary injury thresholds, as defined in Appendix A2, in test and simulation. The Center for Collision Safety and Analysis at the George Mason University has analysed 65 oblique impact tests for a vehicle manufacturer. The tests were conducted by NHTSA and are available from their crash test database (www.nhtsa.gov). It was found that kinematics and injury values were in a range that can been seen in many full-scale tests of similar sedan vehicles. For example, most full-scale tests showed the highest chest deflection on the driver side for the upper right measurement location due to interaction with the seat-belt during the oblique forward motion of the occupant towards the A-Pillar. Kinematics of THOR in the passenger seat, where the seat-belt slipped over the shoulder and allowed significant movement of the upper body, was also observed in the simulation, as seen in more than 90 % of the analysed full-scale tests for the far-side occupant.

Figure 3 (a) shows the typical occupant kinematics of the near-side occupant, i.e., the occupant closer to the impact, in test and simulation. The driver's motion is controlled by the seat-belt and the driver and side curtain airbag. Figure 3 (b) represents the far-side occupant in test and simulation. It can be noticed that the passenger upper body slides out of the shoulder-belt and the head moves towards the middle of the vehicle with significant head rotation due to the interaction with the passenger airbag.

Fig. 3. THOR Kinematics in Test and Simulation (a) Near-Side, (b) Far-Side.

. Figure 4 shows a comparison of the lower extremity kinematics in test and simulation for the near-side occupant. Initial position of the feet and eversion of the right foot due to interaction with the pedals was well captured in the simulation model.

Fig. 4. Lower Leg Kinematics in Test and Simulation.

Vehicle kinematics, pulse, and intrusion characteristics were also well captured as described in [4, 10]. For example, maximum toe-pan intrusion in the test was 142 mm compared to 150 mm in the simulation; vehicle delta-v in x-direction was 15.5 m/s in the full-scale test compared to 14.8 m/s in the baseline simulation. Vehicle delta-v in y-direction was 5.3 m/s in the test and 5.5m/s in the baseline simulation.

The baseline simulation can therefore be considered a good FE model to conduct parametric studies to understand the effect of different test configuration parameters.

Injury Risk Assessment

Injury risk was analysed by calculating injury criteria for the head, neck, chest & abdomen, and femur & lower extremities. For each injury metric, an upper and lower boundary was defined, as shown in Appendix A2. The table lists values for the different body regions and how they relate to Abbreviated Injury Scale (AIS) injury risk, as described in [2]. A point-based system with a total of 100 points, resulting from a maximum of 25 points for each of the four body regions, as defined in Appendix A2, was used. Injury assessment values (IAVs) below the lower boundary received 25 points; IAVs above the upper boundary received 0 points; and IAVs between the lower and upper boundaries were calculated using linear interpolation, according to Equation 1.

$$Score = \left[1 - \frac{IAV - lower\ boundary}{upper\ boundary - lower\ boundary}\right] \times 25\ points \quad , \qquad (1)$$

where IAV is the injury assessment value and Score is the total point received for the respective body region.

For example, Head Injury Criteria (HIC) values below 500 would be considered low risk of injury and received 25 points. A HIC value of 500 correlates with a 4.7 percent risk of an AIS 3+ skull fracture described in Appendix A2, based on the respective injury risk curve outlined in [2]. HIC values above 700 were considered high risk of injury and received 0 points. A HIC value of 620 would fall between the upper and lower boundaries and would receive 10 points based on linear interpolation. Where more than one criterion is available for an individual body region (for instance, HIC and BrIC for the head), the minimum score from the available criteria was used for the given body region. A star rating ranging from 0-stars to 5-stars in ½-star increments, as outlined in Appendix A1, was calculated based on the overall points using Equation 2:

$$Star\ Rating = f(Overall\ Score) = FLOOR\left(\frac{Overall\ Score + 5}{20}, 0.5\right) \quad , \qquad (2)$$

where *Overall Score* is the total amount of points for all body regions; and FLOOR is an Excel function that rounds a given number to the nearest specified multiple.

Design of Experiment

The flow chart of the test procedure study is shown in Figure 5. The procedure includes four main components: Design of Experiments (DOE), Finite Element Method (FEM) simulations, Response Surface (RS) construction, and data analysis and comparison.

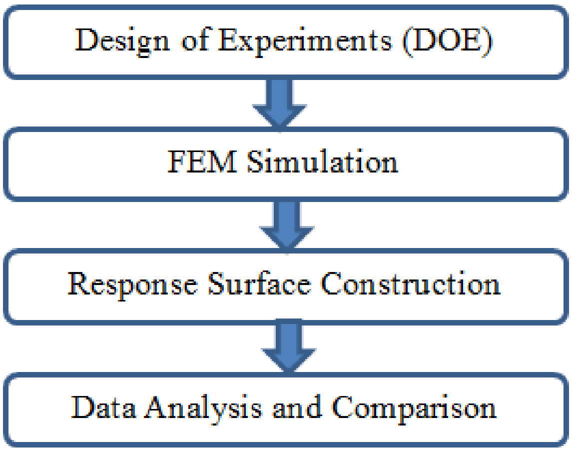

Fig. 5. Simulation Study Flow Chart.

To evaluate the effects each parameter and combinations of these parameters have on the outcome of the vehicle and THOR(s), the design of experiments (DOE) based method was adopted. Specifically, the Box-Behnken method was used to define which combination of parameter values were used for the conducted simulation runs. The Box-Behnken approach is an independent quadratic design in which the treatment combinations are at the midpoints of edges of the process space and at the centre. These designs are rotatable and require three levels for each factor.

Response Surface Construction

Response surfaces, also called surrogate models, approximate models, or machine learning models, were used to estimate the representation of the real objective function, which is unknown. Thus, the obtained response surface can be used for the prediction of the objective function. There are many different types of response surface models, such as linear surface, polynomial surface, radial basis function model, Kriging model, support vector machine model, and neural network model. In the present study, the open source python machine learning library *scikit-learn* was used to build the response surfaces. A set of response surfaces were constructed based on the data obtained from the FE simulations.

During the process of the response surface construction, two main types of models were used: second order polynomials and support vector machine regression models. The K-fold cross-validation strategy was adopted to optimise the response surface for each parameter and combination of parameters. Cross-validation is a resampling procedure used to evaluate response surface models on a limited data sample. The procedure has a single parameter, called k, that refers to the number of groups that a given data sample is to be split into. As such, the procedure is often called k-fold cross-validation. When a specific value for k is chosen, it may be used in place of k in the reference to the model, such as k=5 becoming 5-fold cross-validation.

The general procedure for the k-fold cross-validation is conducted in four steps. (1) The dataset is randomly shuffled. (2) The dataset is split into k groups. (3) For each group (a) use the group as a hold out or test data set, (b) take the remaining groups as a training data set, (c) fit a response surface model on the training set and evaluate it using the test set, (d) obtain the evaluation score or predict value and discard the model. (4) Summarise the skill of the model using the sample of the model evaluation scores or predict values.

If the obtained model was accurate enough according to the cross-validation scores, the model was kept and used in the data analysis stage. Otherwise, the model was discarded, and different models were applied.

Data Analysis and Comparison

In the stage of data analysis, comparisons of responses were conducted for each parameter, with varied ranges between baseline results and simulation cases. Response curves obtained from variation of single design factors were calculated. Parameters were evaluated one at a time, keeping the other values at the baseline value. Response surfaces were constructed to describe the variation of two design factors.

In addition, the ANalysis Of VAriance (ANOVA) method [6] and other sensitivity analysis methods [7] were used to quantify the importance of each parameter based on the response surfaces. In the present study, an open source library, *SALib*, was used for implementation of the sensitivity analysis.

The Parameter Importance Index (PII) describes the relative importance of a parameter compared to the other evaluated parameters for the respective vehicle or occupant responses. For example, when conducting a DOE study with five parameters, a PII of 20 % for all the parameters would mean that they are of equal importance for the respective outcome, such as chest deflection or toe-pan intrusion. The sum of all PII for five parameters is 100 %. The more significant the effect of changing a parameter, the larger the PII.

CORA - Objective Correlation Method

The objective curve correlation rating tool *CORA* (CORrelation and Analysis) was used to quantify differences in time history results between select parametric cases and the baseline simulation. The CORA tool was developed by the Partnership for Dummy technology and Biomechanics (PDB, Gaimersheim, Germany) and takes phase shift, size, shape, as well as the comparison of values at each time increment, into account [8]. Using these criteria, an *objective rating* is given that indicates how well a curve, e.g., parametric simulation, compares to a reference curve, e.g., baseline simulation. Rating results range between 0 and 1, where 0 means no correlation and 1 means (close to) perfect correlation. For the current study, a CORA value above 0.8 was considered *GOOD* and values between 0.6 and 0.8 were considered F*AIR* or *ACCEPTABLE* correlation or repeatability. The used rating scheme is adopted from [9].

Repeatability Study

For the test procedure repeatability study, parameters were varied *within defined test tolerances*. The OMDB impact angle was varied by +/- 1 degree, i.e., between 14 and 16 degrees relative to the vehicle longitudinal centreline. The vertical position (z) of the OMDB was evaluated at level to the vehicle and 50 mm higher and lower relative to the target vehicle. A range of +/- 50 mm was also used for the horizontal misalignment (MA) of the OMDB. This represents an overlap of 33 % and 38 % compared to the 35 % overlap of the OMDB with the target vehicle in the baseline simulation. The OMDB mass was varied by +/- 50 kg. Finally, the impact speed was evaluated for a range of +/- 1 km/h. Using a Box-Behnken DOE method with five parameters and three levels, a total of 41 simulations were run to determine the effect and importance of the different parameters.

An accelerometer was placed at the far-side rear sill to record the vehicle pulse during the impact. Intrusion into the occupant compartment was recorded at the brake pedal and at five rows with four points each on the toe-pan. Intrusions were also evaluated for the steering column and the left and right Instrument Panel (IP).

Sensitivity Study

A *Sensitivity Study* was conducted, where parameters were varied *beyond full-scale test tolerances* to understand how vehicle characteristics, occupant kinematics, and injury risks of the driver and front passenger are affected by a wider range of impact conditions. The impact angle was changed by +/- 5 ° relative to the 15 ° baseline value, resulting in impact angles between 10 ° and 20 °. The overlap percentage was varied by +/- 5 % compared to the 35 % baseline value, resulting in a range of 30 % to 40 % overlap of the OMDB and the target vehicle. The OMDB mass was evaluated for a range between 2000 kg and 2500 kg. A value of 2250 kg was chosen as the mid-level for the conducted DOE analysis. The impact speed was evaluated for a range between 80 km/h and 90 km/h, with 85 km/h being the mid-level for the DOE analysis. Using a Box-Behnken DOE method with four parameters and three levels, a total of 25 simulations were run to determine their relative importance and the effect each parameter and combinations of parameters have on the vehicle and occupants seated in the driver and front passenger seat.

III. RESULTS & DISCUSSION

Repeatability Study

Parameters relevant for NHTSA oblique test setup were varied within defined test tolerances for the repeatability study. Figure 6 shows a top view of the configuration for two extreme cases. The OMDB shown in green represents a case where the barrier was positioned at a 14 ° angle and a 38 % overlap relative to the target vehicle. The OMDB shown in red represents a case where the barrier was positioned at a 16 ° angle and a 33 % overlap relative to the target vehicle.

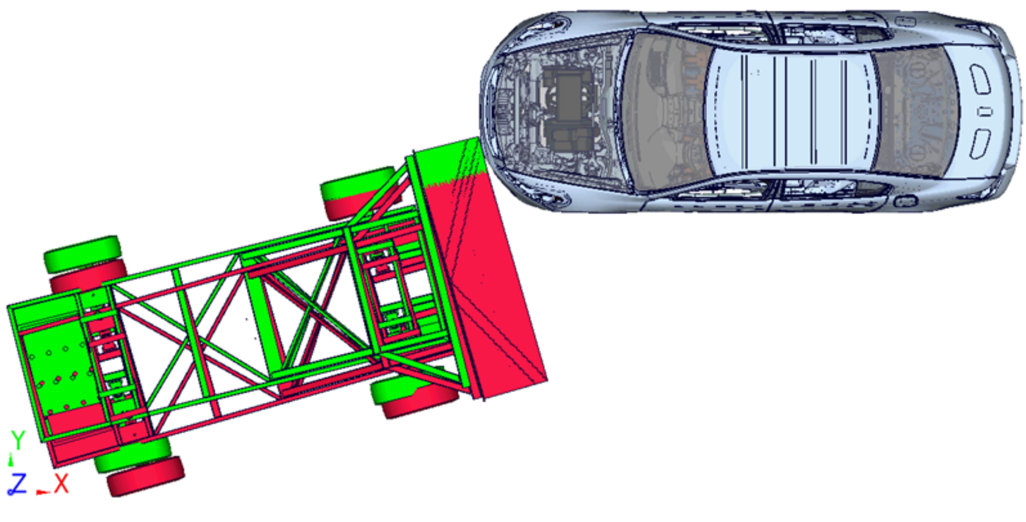

Fig. 6. Repeatability Study – Extreme Cases.

Deformation in the longitudinal vehicle x-direction was the dominant component and was used to compare occupant compartment intrusions. Impact speed was found to be the most important parameter for the vehicle x-pulse, represented by a 46 % PII. Higher impact speed tended to show marginally higher delta-v in longitudinal vehicle direction. Values ranged from 14.5 m/s to 15.1 m/s. Impact angle was found to be the most significant parameter for the vehicle y-pulse, represented by a 49 % PII. Larger impact angle, i.e., more oblique configuration, tended to show marginally higher delta-v in vehicle y-direction. Values ranged from 5.6 m/s to 6.2 m/s. Varying parameters within the test tolerance showed good test repeatability with little effect on the vehicle pulse.

Horizontal misalignment was found to be the most significant parameter for the maximum toe-pan intrusion, represented by a 26 % PII. More overlap tended to show lower maximum toe-pan intrusion. Maximum values ranged from 128 mm to 157 mm. Varying parameters within the test tolerance showed good test repeatability with little effect on the occupant compartment intrusions. It was also observed that a more oblique impact angle, higher OMDB mass, and higher impact speed caused marginally higher values. Respective points at the toe-pan and instrument panel were also evaluated on the far-side occupant compartment, relevant for the front passenger seating position. Maximum intrusion was considerably smaller than for the near-side. Differences when varying parameters within test tolerances were not significant, ranging from 14 mm to 25 mm.

The effect of varying parameters within defined full-scale test tolerances (repeatability study) was evaluated by analysing occupant kinematics and injury metrics for a *50th percentile THOR in the driver seat.* The THOR moves towards the A-Pillar and is being restrained by the seat-belt, driver airbag and side curtain airbag. Relative head movement ranged from 396 mm to 408 mm in x-direction and from 167 mm to 188 mm in y-direction. Occupant loads and related injury risk was analysed using upper and lower boundaries, as defined in Appendix A2. Overall points, when using all combinations of parameters, ranged from 54 (3 stars) to 70 (3.5 stars). The combination of smaller overlap and higher impact speed was the most critical with respect to overall occupant rating.

Vertical misalignment, impact angle, and impact velocity were the most important parameters, represented by a 24 % to 30 % PII for the driver Brain Injury Criteria (BrIC), as shown in Figure 7(a). Values ranged from 0.85 to 0.96, where higher values were associated with higher angular head velocity around the head local y-axis. The influence for each individual parameter was small, when keeping the other parameters at the baseline simulation value, as shown in Figure 7(b). A more oblique impact configuration and higher OMDB position tended to show higher driver BrIC values.

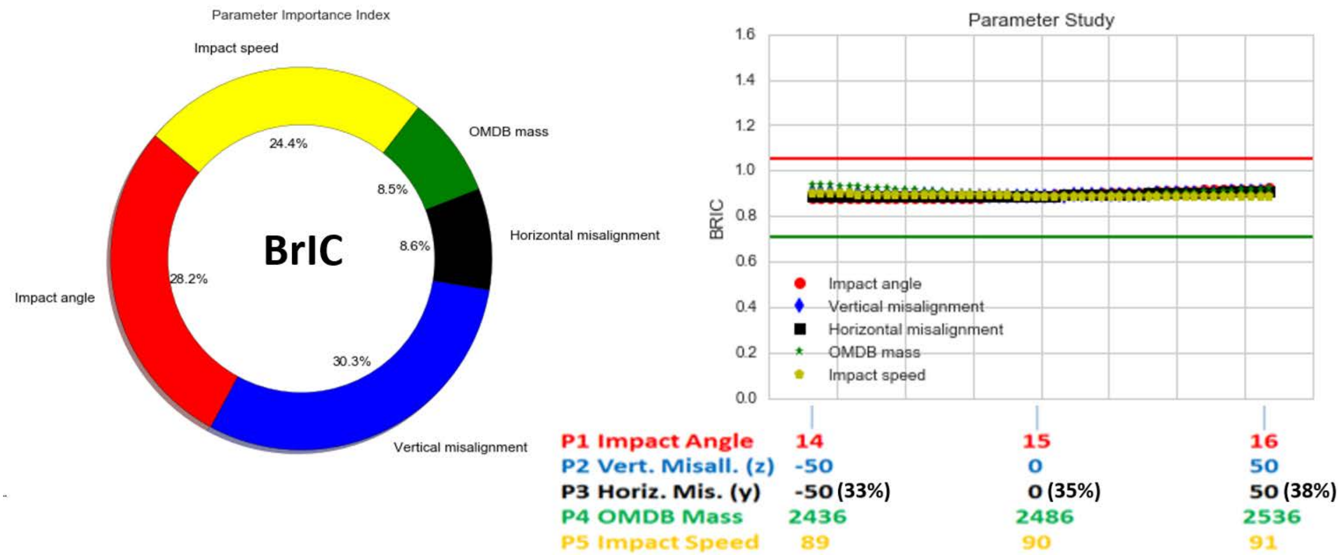

Fig. 7. Driver BrIC (a) PII, (b) Effect of Parameters.

Impact speed was found to be the most important factor for the maximum chest deflection, which occurred at the upper right measurement point for the THOR in the driver seat due to interaction with the seat-belt. Higher impact velocity correlated with higher chest deflection, while differences were small with values ranging from 47 mm to 49 mm. Horizontal misalignment was the most important factor for the left femur load. Less overlap tended to show higher values. Higher impact velocity and higher OMDB mass also correlated with higher femur loads. When taking all combinations of parameters into account, values for the maximum femur load ranged from 3421 N to 5324 N.

Time history data compared well between simulations with varying parameters and the baseline simulation, represented by overall *GOOD* CORA scores of 0.85 to 0.96 for all simulations.

The effect of varying parameters within defined test tolerances (repeatability study) was also evaluated by analysing occupant kinematics and injury metrics for a *50th percentile THOR in the passenger seat*. The THOR typically moves towards the middle of the vehicle, sliding out of the seat-belt, which slips over the shoulder and down on the upper right arm, resulting in little interaction between shoulder-belt and chest. Since there is no head curtain airbag in the middle of the vehicle and most current passenger airbags are not capable of controlling the head motion in a far-side oblique impact condition, higher angular velocities of the head can be observed. Significant head yaw motion, i.e., high angular velocity around the local z-axis of the head, lead to high BrIC values in many cases. Relative head motion was larger in x- and y-direction, when compared to the near-side occupant on the driver side.

Injury risk was analysed using upper and lower boundaries, as defined in table A2. Impact speed was the most important parameter, represented by a 27 % PII. Lower impact speed tended to show smaller overall dummy loads. The combination of lower OMDB position and higher impact speed was the most critical with respect to overall occupant loads. BrIC values were above the upper limit, resulting in 0 points for the head. Maximum chest deflection values were lower than for the driver due to the limited interaction with the shoulder-belt. They ranged from 37 mm to 41 mm. The overall rating was therefore mostly influenced by varying neck and lower extremity criteria. Neck values varied noticeably due to different head motion, which is less controlled by restraints compared to the driver. It was found that differences in overall occupant kinematics for the far-side passenger, i.e., larger amount of head and upper body motion, contributed to these observations. Lower extremities also showed a significant difference, ranging from 6 to 23 points.

All five evaluated parameters were of similar importance for BrIC. Vertical misalignment was found to have the highest (27 %) and OMDB mass the lowest (14 %) PII. In contrast to the near-side driver seating position, small changes in parameters resulted in noticeable differences in BrIC. All values were above the upper limit, ranging from 1.11 to 1.57. Higher impact speed and lower OMDB vertical position correlated with higher BrIC values.

Vertical misalignment was the most important factor (44 %) for the maximum chest deflection. Differences were small, with values ranging from 37 mm to 41 mm. No significant trend was observed for any of the parameters when evaluating the effect of individual parameters while keeping the others at the baseline simulation value. Impact speed was the most important factor for the passenger femur forces, represented by a 42 % PII. Values ranged from 3847 N to 5623 N. Higher impact speed, higher OMDB mass, and larger overlap percentage correlated with higher femur loads.

Vertical and horizontal misalignment were the most important parameters for the maximum resultant moment of the tibia, with 33 % and 29 % PII, respectively. The values ranged from 174 Nm to 231 Nm. The observed variations in lower extremity dummy loads was caused by differences in overall far-side occupant kinematics rather than toe-pan intrusion, which was small.

Sensitivity Study

Parameters relevant for NHTSA oblique test setup were varied beyond defined test tolerances for the sensitivity study. Figure 8 shows a top view of the configuration for two extreme cases. The OMDB shown in green represents a case where the barrier was positioned at a 10° angle, having a 40 % overlap relative to the target vehicle. The OMDB shown in red represents a case where the barrier was positioned at a 20° angle, having a 30 % overlap relative to the target vehicle.

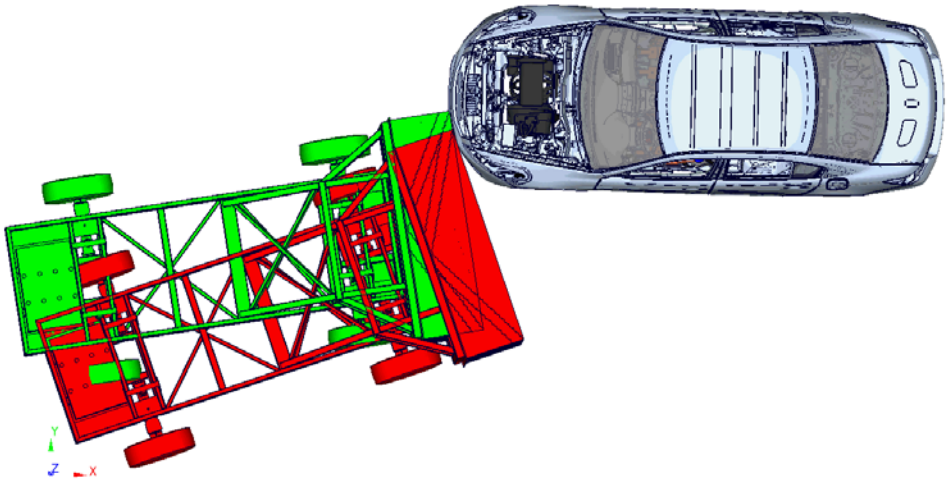

Fig. 8. Sensitivity Study – Extreme Cases.

Impact speed and OMDB mass were found to be the most important parameters for the vehicle x-pulse, represented by a 46 % and 41 % PII, respectively. Higher impact speed and higher OMDB mass tended to show higher delta-v in longitudinal vehicle direction. Values ranged from 11.8 m/s to 14.8 m/s. Impact angle was found to be the most significant parameter for the vehicle y-pulse, represented by a 64 % PII. Larger impact angle, i.e., more oblique configuration, showed higher delta-v in vehicle y-direction. Values ranged from 4.2 m/s to 6.4 m/s. A more oblique impact at higher speed showed the highest delta-v in vehicle y-direction and vice versa.

Impact speed was found to be the most significant parameter for the maximum toe-pan intrusion, represented by a 62 % PII. Higher OMDB speed and higher mass correlated with higher maximum toe-pan intrusion. More oblique configurations and more overlap tended to show marginally lower maximum intrusions. Values ranged from 91 mm to 150 mm. Respective points at the toe-pan and instrument panel were evaluated on the far-side occupant compartment, relevant for the front passenger seating position. Maximum intrusion was considerably smaller than for the near-side, ranging from 4 mm to 20 mm.

Occupant kinematics and injury metrics for a *50th percentile THOR in the driver seat* were analysed for parameter ranges beyond defined full-scale test tolerances. THOR head movement towards the A-Pillar was more significant than for the cases analysed in the repeatability study. At the same time, the near-side occupant was well restrained by the seat-belt, driver airbag, and side curtain airbag for all analysed cases and no contact with the A-Pillar or other interior parts of the vehicle was observed.

Impact speed was the most important parameter for the overall dummy loads, represented by a 49 % PII. Higher impact speed correlated with higher overall occupant loads. Overall points ranged from 57 (3 stars) to 79 (4 stars). The combination of smaller overlap and high impact speed was the most critical.

Impact angle and impact velocity were the most important parameters, represented by a 41 % to 40 % PII for the driver BrIC. Values ranged from 0.85 to 1.08, where higher values were mainly associated with a higher yaw component, i.e., higher angular head velocity around the local z-axis. Especially the impact angle showed a significant effect, where more oblique conditions created higher BrIC values. This can also be noticed when analysing the combined effect of impact angle and overlap percentage: BrIC values were highest for a more oblique condition with smaller overlap percentage.

Impact speed (72 % PII) was the most important factor for the maximum chest deflection, which occurred at the upper right measurement point for the THOR in the driver seat due to interaction with the seat-belt. Values ranged from 30 mm to 47 mm, when taking all combinations of parameters into account. Higher speed correlated with higher chest deflection. The combination of higher mass and higher impact speed created the highest chest deflection values and vice versa. Abdomen deflection was not critical for any of the conducted simulations with values around 50 mm, which is significantly less than the critical value of 89 mm.

Impact speed was the most important factor for the left (50 % PII) and right (65 % PII) femur load of the driver. Higher speed correlated with higher femur loads. Axial force of the lower right tibia was mostly influenced by the impact angle, represented by a 54 % PII. Values ranged from 2598 N to 4042 N when taking all combinations of parameters into account. More oblique impact conditions caused higher maximum tibia loads.

Time history data showed more differences between simulations with varying parameters and the baseline simulation than observed in the repeatability study. Overall CORA scores fell between 0.71 and 0.87, which would be rated *FAIR* or *ACCEPTABLE* according to the ISO reference.

The effect of varying parameters within a wider range compared to full-scale test tolerances was evaluated by analysing occupant kinematics and injury metrics for a *50th percentile THOR in the passenger seat.* Head trajectory in y-direction ranged from 146 mm to 271 mm. Head trajectories with higher y-displacement were mainly correlated with more oblique impact conditions. The extent of THOR movement towards the middle of the vehicle was more significant than for the cases studied in the repeatability study and more significant than for the near-side seating position. The far-side occupant slides out of the shoulder seat-belt and is being restrained mainly by the pelvis-belt and the passenger airbag. Consequently, larger movement of the upper body and head can be observed, making it more likely to have contact with the interior of the vehicle and experience less controlled head motion.

Impact speed was the most important parameter for the overall injury risk, represented by a 49 % PII. Higher impact speed correlated with higher overall injury risk. Overall points ranged from 56 (3 stars) to 83 (4.5 stars). A combination of more oblique impact angle and higher impact velocity showed the highest overall injury risk.

Impact speed was also the most important parameter for passenger BrIC, represented by a 69 % PII, as shown in Figure 9(a). BrIC ranged from 0.89 to 1.3, where higher values were mainly associated with a higher yaw component, i.e., higher angular head velocity around the local z-axis. Higher impact velocity resulted in higher contact forces of the head with the passenger airbag, which generated higher head angular velocities and BrIC values, as shown in Figure 9(b). BrIC values were highest for a more oblique condition with higher impact speed.

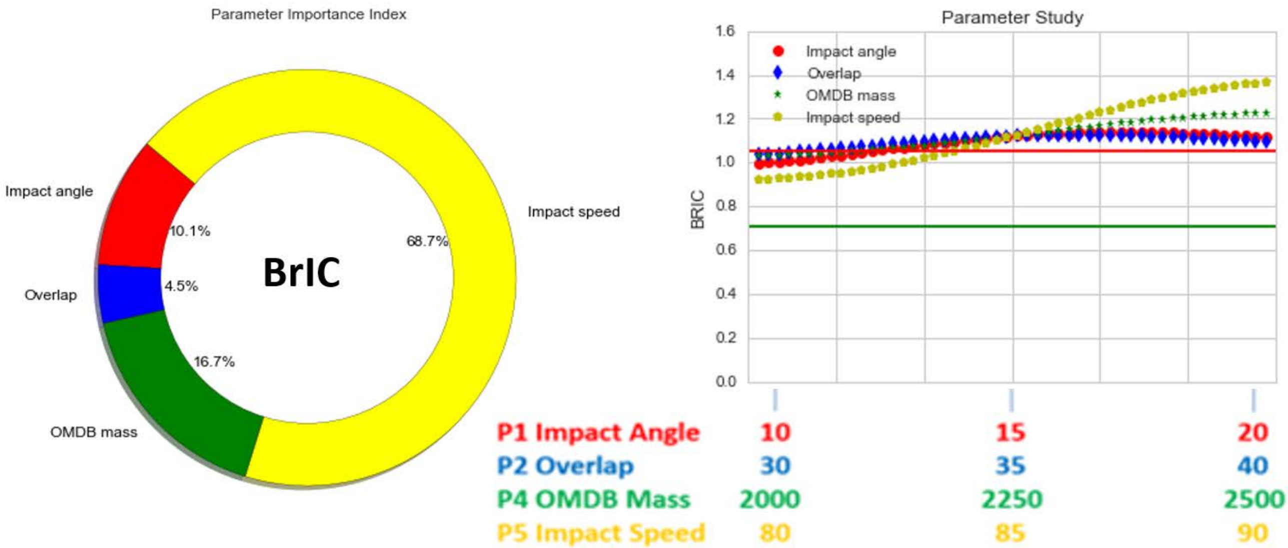

Fig. 9. Passenger BrIC (a) PII, (b) Effect of Parameters.

Impact angle (72 % PII) was the most important factor for the maximum chest deflection. Highest values occurred at the lower left measurement point for the THOR in the passenger seat due to limited interaction of the seat-belt with the upper torso. More oblique impact angle correlated with lower chest deflection. Differences were small, ranging from 35 mm to 40 mm. Abdomen deflection was not critical for any of the conducted simulation, with values around 60 mm, which is significantly less than the critical value of 89 mm. The most important factor (55 % PII) for the abdomen was the impact velocity.

Impact speed was also the most important factor for the left femur load, with a 70 % PII of the far-side passenger. Higher femur loads correlated with higher velocities. Maximum femur loads ranged from 1241 N to 4142 N. Resultant moment of the upper right tibia at the passenger side was mostly influenced by the impact angle, with 58 % PII. Values ranged from 163 Nm to 220 Nm. More oblique impact conditions caused higher maximum tibia loads. Differences occurred in the absence of significant toe-pan intrusion.

Time history data showed more differences between simulations with varying parameters and the baseline simulation than for the repeatability study. Overall CORA scores ranged between 0.73 and 0.90.

Table 1 summarises the PII of the overall score. Impact speed was the most important parameter for the

THOR on the driver seat (49 % PII) and passenger seat (38 % PII) when parameters were varied beyond defined test tolerances (sensitivity study). Vertical misalignment of the OMDB (31 % PII) was the most important parameter for driver and impact speed (27 % PII) was the most important parameter for the THOR on the passenger seat, when parameters were varied with defined test tolerances (repeatability study).

TABLE 1
PII OVERVIEW FOR THE OVERALL

		Impact Angle	Vertical Misalignment	Overlap	OMDB Mass	Impact Speed
Repeatability Study	Driver	20	31	25	13	11
	Passenger	12	23	18	20	27
Sensitivity Study	Driver	21	n/a	17	13	49
	Passenger	17	n/a	15	30	38

IV. LIMITATIONS

The documented results and conclusions are based on finite element simulations with a validated FE model of a mid-size sedan vehicle and existing THOR occupant models. Findings do not necessarily apply to other vehicle structures and restraint systems.

DOE immanent limitations apply. Validated response surfaces and trend-lines were used determine the relationship between factors affecting NHTSA's oblique impact test procedure and the output represented by vehicle and occupant injury metrics. A *Box-Behnken* DOE approach was used to generate surrogate models, which are based on fewer design points, i.e., simulation runs, compared to full factorial methods.

V. CONCLUSIONS

A validated integrated occupant-vehicle model with relevant restraints was used to conduct parametric studies to understand the effect of different parameters relevant for NHTSA's oblique test procedure. Parameters included the impact angle, OMDB vertical misalignment, OMDB overlap, OMDB mass, and impact speed.

Two studies were conducted to understand the importance of the different parameters and their effect on the vehicle and occupants. (1) In the *Repeatability Study*, parameters were varied within defined test tolerances when conducting full-scale tests. (2) In the *Sensitivity Study*, parameters were varied within a range that is beyond defined test tolerances.

Good test repeatability was found when changing parameters within the small ranges used as test tolerances. Vehicle delta-v varied by less than 1 m/s and maximum intrusion varied by less than 30 mm. Impact speed was the most important factor for the vehicle pulse in x-direction and impact angle was most dominant for the vehicle y-pulse. The overall CORA score for time-history data of the THOR in the driver seat and front passenger seat ranged from 0.81 to 0.94, when compared to the baseline simulation.

More significant effects were seen when evaluating wider ranges of parameters in the *Sensitivity Study*. Vehicle delta-v in x- and y-direction varied by more than 3 m/s and 2 m/s, respectively. Maximum toe-pan intrusion varied by up to 60 mm. The overall CORA score for time-history data of the THOR in the driver seat and front passenger seat ranged from 0.71 to 0.90, when compared to the baseline simulation. Impact speed was the most important factor for the driver and passenger. Impact angle was found to be especially relevant for far-side occupant results.

The conducted studies, using integrated occupant vehicle simulations with relevant restraints, enabled valuable insight into the effect of different test parameters for the frontal oblique impact condition. In summary, NHTSA's oblique frontal offset impact test showed overall good repeatability with respect to vehicle kinematics and dummy loads, when relevant parameters were changed within defined test tolerances.

VI. ACKNOWLEDGEMENT AND DISCLAIMER

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The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Department of Transportation or the National Highway Traffic Safety Administration.

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VIII. APPENDIX

TABLE A1
5 STAR RATING SCALE (100 POINT SCALE)

Lower Total Point Score (Greater than or equal to)	Crashworthiness Stars	Upper Total Point Score (Less than)
0	No stars	5
5	0.5	10
10	1	20
20	1.5	30
30	2	40
40	2.5	50
50	3	60
60	3.5	70
70	4	80
80	4.5	90
90	5	100

TABLE A2

INJURY CRITERIA WITH UPPER AND LOWER BOUNDARIES AND RELATED INJURY RISK [2]

Body Region		Injury Criteria	Lower Boundary	Related Injury Risk [%]	Upper Boundary	Related Injury Risk [%]
1	Head	HIC15	500	4.7 (AIS3+)	700	11.2 (AIS3+)
		BrIC	0.71	10 (AIS4+)	1.05	50 (AIS4+)
2	Neck	Ntf	0.39	10 (AIS2+)	0.85	25 (AIS3+)
		Ncf	0.39	10 (AIS2+)	0.85	25 (AIS3+)
		Nte	0.39	10 (AIS2+)	0.85	25 (AIS3+)
		Nce	0.39	10 (AIS2+)	0.85	25 (AIS3+)
3	Chest	Chest-UL [mm]	37.9	25 (AIS3+)	52.3	50 (AIS3+)
		Chest-UR [mm]	37.9	25 (AIS3+)	52.3	50 (AIS3+)
		Chest-LL [mm]	37.9	25 (AIS3+)	52.3	50 (AIS3+)
		Chest-LL [mm]	37.9	25 (AIS3+)	52.3	50 (AIS3+)
	Abdomen	ABDO-LE [mm]	n/a	n/a	88.6	50 (AIS3+)
		ABDO-RI [mm]	n/a	n/a	88.6	50 (AIS3+)
4	Femur	ACET-LE [N]	2583	10 (AIS2+)	3486	50 (AIS2+)
		ACET-RI [N]	2583	10 (AIS2+)	3486	50 (AIS2+)
		FEM-LE [N]	5331	10 (AIS2+)	8558	50 (AIS2+)
		FEM-RI [N]	5331	10 (AIS2+)	8558	50 (AIS2+)
	Lower Leg	FZ TI UL [N]	4235	10 (AIS2+)	5577	25 (AIS2+)
		FZ TI UR [N]	4235	10 (AIS2+)	5577	25 (AIS2+)
		FZ TI LL [N]	3573	10 (AIS2+)	5861	25 (AIS2+)
		FZ TI LR [N]	3573	10 (AIS2+)	5861	25 (AIS2+)
		MR TI UL [Nm]	178	10 (AIS2+)	240	25 (AIS2+)
		MR TI UR [Nm]	178	10 (AIS2+)	240	25 (AIS2+)
		MR TI LL [N]	178	10 (AIS2+)	240	25 (AIS2+)
		MR TI LR [N]	178	10 (AIS2+)	240	25 (AIS2+)