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Yi Yang Tay [α], Rasoul Moradi [σ] & Hamid M. Lankarani [ρ]

Abstract- Airbag systems such as frontal and side-impact airbags are developed to reduce occupant injuries during vehicle collisions. Yet, such systems have caused serious injuries to out-of-position occupants especially to smaller females and children. The primary objective of this study is to examine the different influential factors such as mass flow rate, fabric permeability ratio, fabric maximum inflated depth that contribute to OOP occupant injuries in airbag-related accidents. A mathematical model of Heidelberg stationary test, vehicle interior and seat mounted side-airbag is developed using the MADYMO code 7.4.2. The mathematical model of the airbag used in this study is a torso-only seat-mounted side-impact airbag (SAB). The airbag model is validated against similar study conducted by Hallman et al. and the results are found to be in good agreement. Once the airbag model is validated, the airbag and the anthropomorphic test dummy are positioned in a vehicle environment to better predict the occupant injuries in a static environment. The ATD test configurations are performed in accordance to the recommendations by The Side Airbag Out-Of-Position Injury Technical Working Group. Lastly, a set of parametric equations to predict the OOP occupants' injuries are developed using the full factorial design.

Keywords: out-of-position occupants; side-impact airbags; injury biomechanics; design-of-experiment; full-factorial design; injury prediction.

I. Introduction

The safety of road vehicle has improved remarkably in recent years. A study conducted by the National Highway Traffic Safety Administration (NHTSA) shows that in year 2009, the fatality rate has been reduced to 1.14 people per 100 million vehicle miles travel as opposed to 1.55 fatalities 10 years ago [1]. Even with this promising result, the ultimate common goal in the automotive industry and government regulations is to reduce occupant injuries and fatalities to nearly zero in all crash scenarios. The vastly improved occupant safety rating cannot be made possible without the technology enhancement in vehicle safety. One of the widely used safety features which have shown to have the highest effect in reducing occupant injuries in recent vehicles are the frontal and side-impact airbags. A study published in 2007 by NHTSA shows that torso only side-airbag reduced fatality by approximately 17% compared to vehicle without side airbags, while the combination of torso and head side airbag further reduce fatality by approximately 35% [2]. Hence, it is evident that airbags provide tremendous amount of occupant safety in vehicle side collisions.

The increasing utilization of airbags on vehicles has also seen a rise in injuries caused by deploying airbags on out-of-position (OOP) and in-position occupants. The earliest recorded airbag related injuries dated back to early 1990, some of the most common injuries or fatalities caused by airbag are rib fractures, fractured sternum, head injuries, minor bruises, abrasions to the upper limbs and face and eyes injuries from chemical keratitis [3, 4]. OOP occupants are considered more prone to injuries from deploying airbags compared to in-position occupants due to the fact OOP occupants can be exposed to significant amount of force imposed by a deploying airbag. An occupant is considered as an OOP occupant if the occupant is in the path of a deploying airbag by either leaning or seating too close to the side structure or front panel that houses the airbag mechanism. If the occupant is initially positioned correctly but displaced closer to the airbag during the course of a collision, the occupant is also considered as an OOP occupant [5].

In 2003, NHTSA's Special Crash Investigation (SCI) conducted a study on 242 cases of airbag related injuries; it was shown that out of the 242 cases considered, 227 occupants were fatally injured by airbags. Besides that, out of the 242 cases, approximately 60% comprised of children fatalities [5]. Although NHTSA has amended its regulations to allow automotive makers to reduce airbag deploying force in 1997, the study conducted by NHTSA's SCI showed that children are more vulnerable to airbag related injuries and fatalities. In 2002, NHTSA Transportation Research Center conducted a set of experiments on airbag aggressivity using static side impact seat-mounted and door mounted airbags on 3 year-old, 6 year-old and 12 month CRABI dummy using a fleet of model years 1999 to 2001 sedan cars. It was observed from the test

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results that 80% of the seat mounted and all door mounted airbag for 3-year old dummy exceeded the injury reference values (IARV) [6]. For the 6 year-old dummy, 60% of all seat mounted and door mounted airbags conducted exceeded the IARV. This shows that advance airbags installed in recent vehicles can still, albeit lower risks, cause serious injuries to OOP occupants.

In order to successfully minimize the injuries mitigated by deploying airbag on various occupants on future vehicles, a systematic and widely used experimental procedure has been developed by *The Side Airbag Out-of-Position Injury Technical Working Group* (TWG) to evaluate airbag aggressivity [7]. The purpose of TWG is to recommend a standard procedure and injury assessment for testing the aggressivity of deploying airbag on various test configurations and occupants. Therefore, the TWG recommendations and test configurations are used as a guideline in this study.

The main objective of this paper is to present a set of prediction model in predicting injuries to OOP occupants from a deploying airbag. The multi-body dynamic software, MADYMO 7.4.2 is used exclusively to evaluate the occupant's injury response and the Design-of-Experiment's (DoE) full factorial design is used to develop the injury prediction model. To achieve this objective, three main influential parameters or factors on affecting OOP occupant injuries have been identified and categorized into factorial design's high and low levels. Next, three OOP test configurations which comprised of TWG's testing configurations for the Hybrid III 3-year old, Hybrid III 6-year old and SID IIs are selected. Finally, a set of prediction equationsfor each OOP test configurations is obtained using the DoE regression model to represent the occupant injury level. This computational and DoE study can provide future researcher with a new dimension in designing and analyzing newer airbags by providing a platform for estimating the injury response of OOP occupants from future airbags design.

II. Mathematical Evaluation of Airbag Model

The mathematical approach used in determining the governing factors that define the characteristics of the airbag model is presented in this section. In the design of airbag system, the occupant injury is significantly affected by many governing factors. As such, it is important to develop the airbag model based on accurate mathematical model that represents the dynamics of the airbag.

The airbag chamber(s) temperature, T can be formulated based on the constant pressure heat capacity, c_p parameter. According to the entropy of gases, for monatomic gases such as Helium (He) and Argon (Ar), the c_p is nearly equal to $\frac{5}{2}R$ while the c_p for diatomic gases such as Hydrogen (H_2) and Oxygen (O_2) is equals to $\frac{7}{2}R$ [8]. R is the universal gas constant or 8.3145 $Jk^{-1}mol^{-1}$. The National Institute of Standards and Technology (NIST) model and Poling model can be used to formulate the temperature dependency on thec_p. The NIST model is recommended for gases with relatively high temperatures, while the Poling model is applicable to low temperature gases [9]. Both NIST and Poling equation is described as Equation (1) and Equation (2) respectively:

$$c_p = a_0 + a_1T + a_2T^2 + a_3T^3 + \frac{1}{T^2}a_4 \tag{1}$$

$$c_p = b_0 + b_1T + b_2T^2 + b_3T^3 + b_4T^4 \tag{2}$$

Where the T for both model is the absolute temperature of the gases, and the a_0 - a_4 and b_0 - b_4 is the heat capacity coefficients for the NIST and Poling model respectively. Both models can only be used to accurately represent the c_p if the inflated gas consist of only one type gas. In order to properly predict the c_p of a mixture of gas, the Amagat's law of the partial volumes can be used to describe the $c_{p,mixture}$ and the NIST model can be further modified to Equation (3):

$$c_{p,mixture} = \sum a_0 x_i + T\sum a_{1_i} x_i + T^2 \sum a_{2_i} x_i + T^3 \sum a_{3_i} x_i + T^4 \sum a_{4_i} x_i \tag{3}$$

The relationship between the constant volume heat capacity, c_v and c_p is $R = c_v - c_p$. Similarly, the ratio of heat capacity is governed by $k = \frac{c_p}{c_v}$. Hence, the c_v can be calculated by knowing the value of c_p. Also, the temperature in the chamber can be formulated by solving the quartic equation, Equation (3).

The airbag can be considered as a closed system in which the bag is inflated by a uniform internal pressure. Once the temperature of the chamber is determined from Equation (3), the internal pressure acting on the membrane of the airbag can be formulated using the ideal gas law:

$$p = \frac{nRT}{V\!\!\!/} \tag{4}$$

Where n is the amount of moles; p is the airbag internal pressure; and $V\!\!\!/$ is the airbag instantaneous volume. The ideal gas law can also be represented based on mass:

$$p = \frac{m\underline{R}T}{V\!\!\!/} \tag{5}$$

with $\underline{R} = \frac{R}{MW}$; MW is the molar weight of the gases.

The airbag inflation process can be modeled as the instantaneous gas mass available in the airbag system. The available mass is influenced by the mass flow rate injected to the system by the inflator minus the gas flowing out of the airbag system through holes and permeable surfaces. Hence, the gas mass of the system can be formulated as:

$$\dot{m} = \dot{m}_{in,flow} - \dot{m}_{out,flow} \tag{6}$$

The $\dot{m}_{out,flow}$ can be calculated in terms of fabric permeability as shown in Equation (7):

$$\dot{m}_{out,flow} = A_{pores}\sqrt{2\rho\Delta p} \tag{7}$$

where ρ is gas density in the airbag chamber, Δp is the pressure difference between the airbag chamber and the ambient environment and A_{pores} is the total area of pores.

The A_{pores} can be formulated by multiplying the free area coefficient and the total airbag area, A_{total} :

$$\eta = \frac{A_{pores}}{A_{total}} \tag{8}$$

and, the Δp can be calculated as shown in Equation (9):

$$\Delta p = \frac{1}{2(\eta^2)}\rho v^2 \tag{9}$$

In order to accurately estimate the mass flow rate supply into the airbag chamber, the gas jet model must be calculated. By considering the inlet flow to be adiabatic flow, the inlet velocity can be calculated as:

$$v_0 = \sqrt{c_p(T_{exit})(k-1)} \tag{10}$$

where, c_p is the constant pressure heat capacity, T_{exit} is the constant temperature of the exit gas and k is the heat capacity ratio. The estimated mass flow rate supply to the gas chamber can then be formulated as:

$$\dot{m}_{in,flow} = A_i v_0 \rho_0 \tag{11}$$

where, the area of the inlet jet is represented as A_i and the gas density in the inlet represented by ρ_0. By combining Equations (6), (10) and (11), the mass flow rate in the system is formulated as:

$$\dot{m} = A_i\rho_0\sqrt{c_p(T_{exit})(k-1)} - A_{pores}\sqrt{2\rho.\Delta p} \tag{12}$$

It is known that the ambient pressure is 101.3kPa, Equation (12) can then be further expanded by combining Equation. (5) and (12) as:

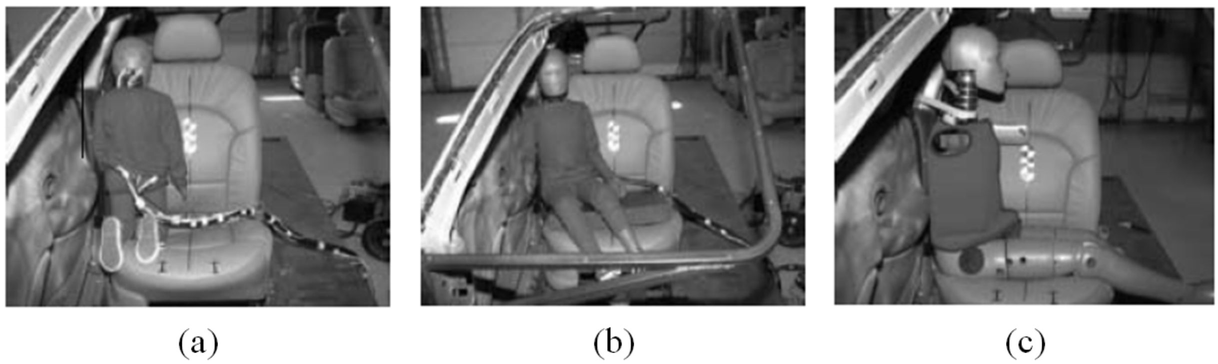
$$\dot{m} = A_i\rho_0\sqrt{c_p(T_{exit})(k-1)} - A_{pores}\sqrt{2\rho.\left(\frac{mRT}{V} - 101.3\right)} \tag{13}$$

The preceding formulations can be used to accurately represent the airbag model. It can be seen that these equations must be solve simultaneously and no factors can be used to independently define the airbag mathematical model.

III. Computational Methodology

This study is conducted using multi-body software, MADYMO 7.4.2 and the results is analyzed using Design-of-Experiment software, Design Expert 7. To achieve the objective of developing a prediction model, this study consists of two parts. First, the testing scenario consisting of a Heidelberg stationary test is presented. The ATD used for the Heidelberg stationary test is a MADYMO 50th percentile facet dummy model. The purpose of the Heidelberg stationary simulation is to validate the airbag model against the simulations by Hallman et al. [10] and to provide a foundation to test the linearity of the selected factors on occupants' injuries. The linearity of the factors will then be used to provide high and low values for the DoE factorial test. The Heidelberg test is extremely useful in providing high/low values for the DoE factorial design, because it isolates the effect of each factor on occupant injuries. The DoE test methodology is further explained later.

Second, due to the inability of the Heidelberg test to properly predict occupant injury in a vehicle environment, a Ford Taurus interior is modeled to represent a generic vehicle environment. By utilizing a vehicle environment in the static airbag test, occupant injuries can be better predicted by factoring in the effect of the airbag, vehicle geometry and placement of the ATD. As mentioned in the introduction section, The Side Airbag Out-of-Position Injury Technical Working Group suggested a list of recommended OOP test configurations for evaluating ATD's injuries from deploying side airbags as well as the optimal placement of ATD with respect to the vehicle geometry. The vehicle test procedures used in this study are in accordance with the TWG's test sections, namely, TWG's section 3.3.3.2, TWG's section 3.3.3.5 and TWG's sections 3.3.3.6 [7]. The test procedures are carefully selected to represent a wide variety of occupants in terms of age, size and position. Table 1 represents the selected TWG test procedures and Figures 1(a) – (c) are the graphical representation of the TWG's recommended test configurations.



Figures 1 : OOP test configurations [7].
(a) 3-year old dummy rearward facing and leaning on back seat; (b) 6-year old dummy forward facing and leaning on door panel; (c) small females inboard facing

The TWG 3.3.3.2 procedure places the Hybrid III 3-year old (3yo) in a rearward facing kneeling position is a procedure to measure injuries to the chest of a 3-year old OOP occupant. The TWG 3.3.3.5 where the Hybrid III 6-year old (6yo) is forward facing and seated on a booster cushion is a procedure to measure the loads on the head and neck region of a 6 year old due to the direct load acting on the back and shoulder. Lastly, the TWG 3.3.3.6 is a procedure to measure injuries to the SID-IIs or small females in which the dummy is positioned inboard facing with its ribs fully exposed to the deploying airbag.

Table 1 : TWG selected test procedures

ATD	TWG Section	Test Position	Body Region of Interest
Hybrid III 3-Year Old	3.3.3.2	Rearward Facing	Head, Neck, Thorax
Hybrid III 6-Year Old	3.3.3.5	Forward facing on booster seat	Head, Neck
SID-IIs	3.3.3.6	Inboard facing	Head, Neck, Thorax, Abdomen, Pelvis

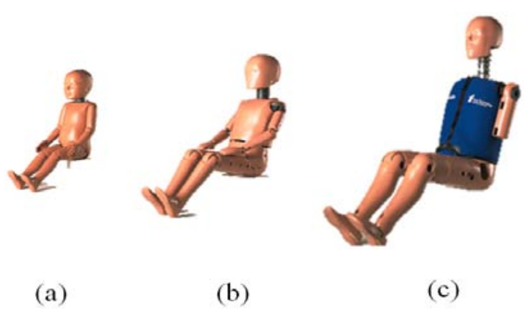


Figure 2 : Humaneticscrash dummies [11].
(a) Hybrid III 3yo; (b) Hybrid III 6yo; (c) SID-IIs

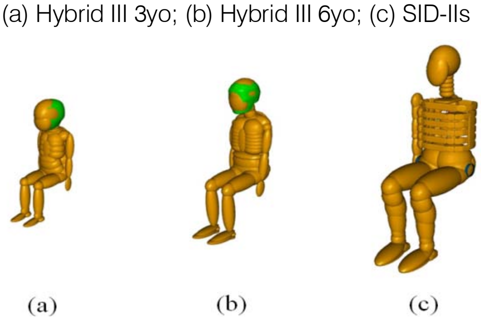


Figure 3 : MADYMO ellipsoid ATD.
(a) Hybrid III 3yo; (b) Hybrid III 6yo; (c) SID-IIs

In order to fulfill the TWG recommended procedures, the ATD used for these test procedures are MADYMO validated ellipsoid models. For comparison purposes, Figure 2(a) – (c) represent the Humanetics Crash Dummies and Figure 3(a) – (c) represent the MADYMO dummies.

a) Airbag Model

Due to the complexity of the airbag system in affecting the occupant's injury, the airbag model must be validated to ensure good accuracy in the airbag model. The ATD's viscous criterion and rib deflection is validated against study conducted by Hallman et al. [10].

Since the airbag governing parameters or factors such as the mass flow rate, the volume, the allowable fully inflated depth, and fabric permeability of the airbag are of great important in influencing occupant injuries. The airbag is modeled and fine-tuned in closerelationship with the airbag model by Hallman et. al. to ensure an accurate validation[10]. The membrane of the airbag is of 0.5mm thickness. The inflator gases used in this study in terms of molar fraction are 0.4% Nitrogen, 0.3% Carbon Dioxide, 0.3% Water Vapor to approximate atmosphere air mixture. The fully inflated depth of the airbag is constrained by twelve 18cm elastic straps. The 3.44L airbag requires 20ms to reach fully inflated state and the maximum pressure is 168kPa.

The gas exits the inflator jet at 508.8m/s^2 and the inflator temperature is 7280^{0}K. The mass flow rate necessary to properly inflate the bag, as shown in Figure 4, is determined by performing a tank test analysis.

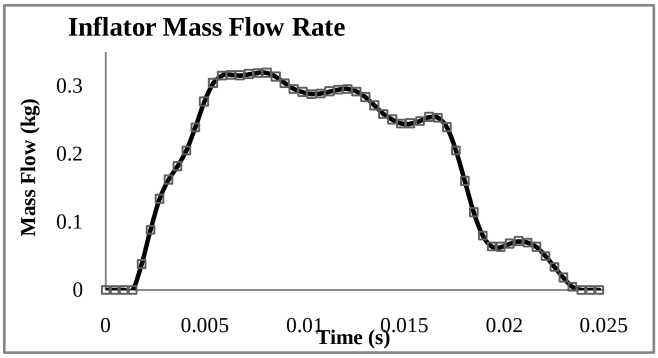


Figure 4 : Inflator mass flow rate

In the preceding formulations in Section I, it is shown that inlet mass flow rate is influenced by many parameters such as inlet velocities, geometry and inlet density. Besides that, the mass flow rate curve is also influenced by the selectionof chemical compositions. Therefore, it is important to note that the mass flow rate shown in Figure 4 is based on a mixture of chemical composition as well as other parameters. The inflator model and the chemical compositions are held constant in this study will not be discussed as it is not within the scope of this study.

b) Airbag Model Validation

A study conducted by Hallman et al. analyzed the effect of deploying a torso-only side impact airbags on out-of-position occupant's torso injury by utilizing MADYMO facet human model [10]. The torso injury evaluated in the study was occupant chest compression ratio and the viscous criteria. The method of evaluation was performed using Heidelberg stationary setup in which the ATD is placed in close proximity to the rigid impact wall.

Figure 6(a) – (c) show the Heidelberg stationary setup. The ATD is seated on a frictionless rigid seat fixed to the platform of the setup. A rigid wall is to provide surface support for the airbag and to simulate a vehicle side frame. The ATD's arms are raised to allow the thorax region to be fully exposed to the airbag and the rigid wall; the shoulder body region does not contact the rigid wall. The ATD initial position is 2cm relative to the rigid wall and displaced in an increment of 2cm until the airbag does not contact the ATD during inflation process. The chest % compression and viscous criteria are obtained and compared to the simulation results by Hallman et al.[10]. Figure 5 shows the MADYMO human ATD's rib placement in which level 4 represents the upper rib, level 2 and 3 represent the middle rib and level 1 represent the lower rib.

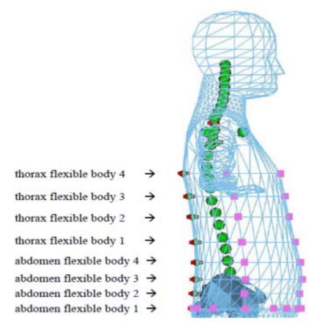


Figure 5 : MADYMO human ATD rib levels [12]

Figure 7 shows the ATD and airbag kinematics at different instances of time at 2cm from the rigid wall. It is shown that at 0-20ms, the ATD is in the path of the deploying airbag and the 1st to 4th ribs are fully exposed to the deploying airbag. The comparison graphs for the simulations and results from Hallman et al. [10] are shown in Figure 8 and Figure 9. The comparison results for the thorax viscous criteria and peak rib compression showed reasonable agreement. Once the airbag model is validated, the airbag model can then be used for the TWG's OOP simulations.

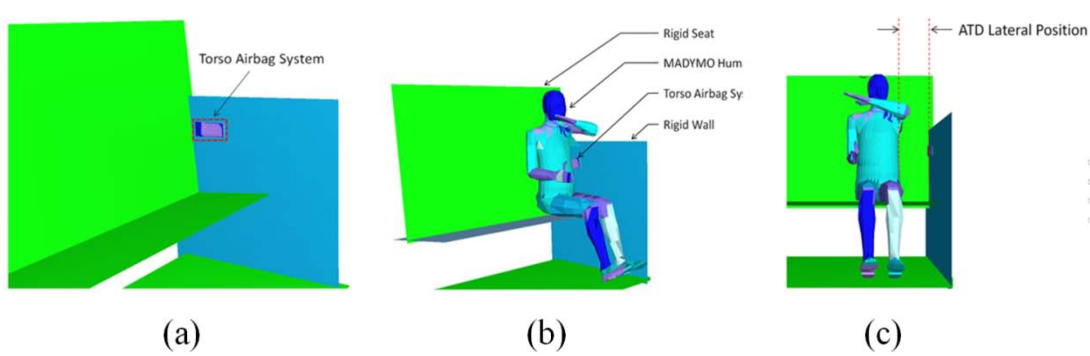


Figure 6 : (a) Heidelberg stationary setup showing torso airbag model; (b) 3D view of Heidelberg stationary setup; (c) ATD lateral position

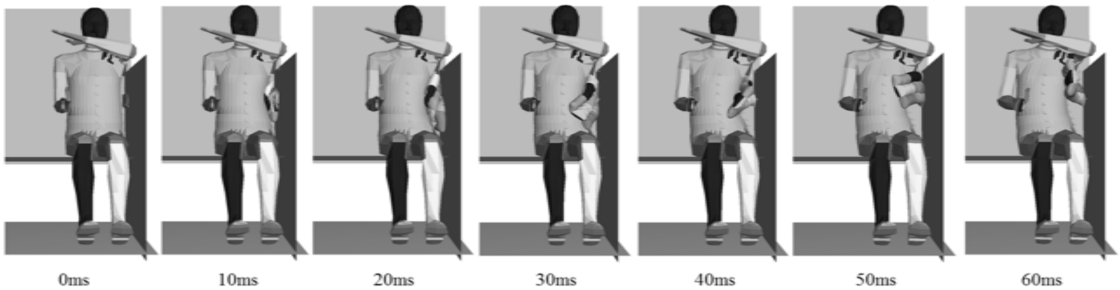


Figure 7 : Simulated kinematics of ATD and torso-only airbag at 2cm relative to rigid wall for stationary test

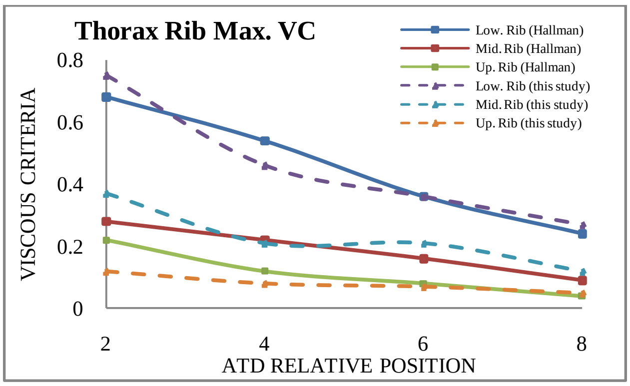


Figure 8 : Comparison of ATD viscous criteria against results by Hallman et al

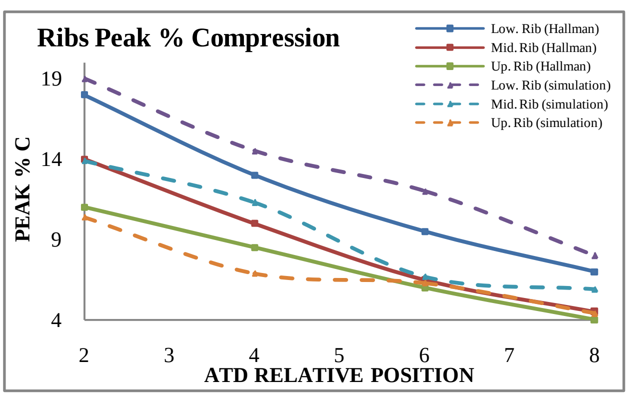


Figure 9 : Comparison of ATD ribs maximum % compression against results by Hallman et al

c) Airbag Model Validation

A generic vehicle interior is modeled as shown in Figure 10. The vehicle model is a partial model of the Ford Taurus FE model. The vehicle's side-panels and cushion seats are selected to be included in this study because these parts are of great importance in influencing the occupant placement and the path of the deploying airbag.

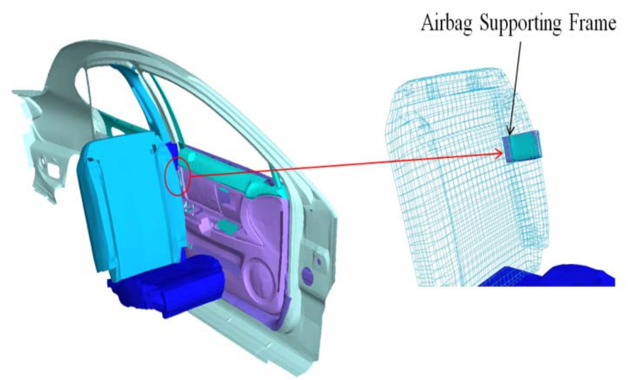


Figure 10 : Partial Ford Taurus interior showing seat mounted side-impact airbag

Once the vehicle interior is successfully modeled and constrained properly, a torso-only side airbag (SAB) is mounted onto the back seat as shown in Figure 10. The airbag supporting frame is constrained to the back seat. The position of the supporting frame with respect to the back cushion is important to ensure proper airbag inflation. Figure 11 shows the SAB frame-by-frame deployment. It can be seen that the side airbag reaches fully deployed state in between 20ms to 35ms and extends outward to provide protection to the torso body region.

With the SAB positioning and the vehicle interior defined, the ATD is incorporated into the model in accordance to the TWG test procedures as shown in Figure 12. The surface contacts used between the ATD (multi-body), vehicle interior (FE) and SAB (FE) are *Contact.* (MB_FE) for multi-body to FE surfaces and *Contact.* (FE_FE) for FE to FE surfaces.

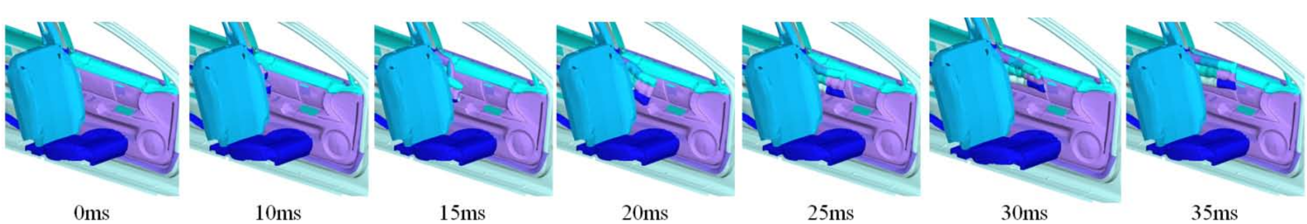


Figure 11 : SAB frame-by-frame deployment process

Figure 12 : OOP test configurations. (a) 3yo dummy rearward facing; (b) 6yo dummy forward facing; (c) small female inboard facing

d) Parametric Study using Design-of-Experiment

The full factorial design is conducted to investigate the joint effect of the three factors on the injury criteria denoted as the output responses. This design also provides the relevant information such as interactions between factors. Once the factor's interaction is determined to be significant, design optimization may be conducted but it is not within the scope of this study to optimize the airbag design. Subsequently, a set of parametric equations can be obtained through the factorial's regression analysis to predictto occupant's injury levels. The DoE used is a single-replicate 2^3 factorial design, the 3 factors of interests are airbag mass flow rate, allowable inflated depth and fabric permeability. The design matrix for a 2^k factorial experiment can be seen in Table 2. The "+" and "-" geometric coding represents the high and low levels of the factors. The high and low factors used are quantitative values and because the factors are of only two levels, therefore, the response must be assumed to be linear over the range of the selected factor range.

Table 2 : 2^3 Design matrix

Run	Factor: A (Mass Flow Rate)	Factor: B (Allowable Depth)	Factor: C (Fabric Permeability)	Labels	Responses
1	-	-	-	(1)	
2	+	-	-	a	
3	-	+	-	b	
4	+	+	-	ab	
5	-	-	+	c	
6	+	-	+	ac	
7	-	+	+	bc	
8	+	+	+	abc	

The high and low levels of each factors are determined using the Heidelberg stationary model in which the model is subjected to various level of parameters and the coefficient of determinant is used to indicate the linearity of the injury level. To avoid repetitive R2figures, only the R^2 for injury levels based on increasing mass flow rate are shown. The R^2 for the peak VC and rib % compression, as shown in Figure 13 and Figure14 ,are all above 0.80.

The R^2 tabulation for all three factors can be seen in Table 3. It is shown that the R^2 for factors A, B and C are good with factor B peak VC yielded the lowest R^2. It can be concluded from this linearity test, represented by R^2, that the data are linearly distributed and it can be safely assumed that further studies on injuries to the thoracic body region are approximately linear over the range of high/low factor levels.

By performing DoE, a regression model or the fitted model can be determined to estimate occupant's injury from the governing factors. The generalized regression model for this design is represented as:

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x_1 + \hat{\beta}_2 x_2 + \hat{\beta}_3 x_3 + \hat{\beta}_{12} x_1 x_2 + \hat{\beta}_{13} x_1 x_3 + \hat{\beta}_{23} x_2 x_3 + \hat{\beta}_{123} x_1 x_2 x_3 \quad (14)$$

Where the coded x_1, x_2,x_3 represent factors A, B and C respectively and x_1x_2, x_1x_3, x_2x_3 and $x_1x_2x_3$ represent the interaction between factors.

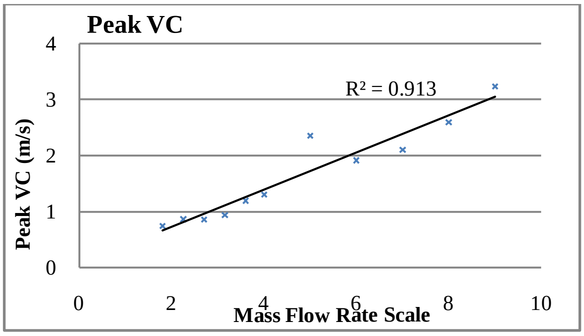


Figure 13 : R-square for peak VC based on increasing mass flow rate

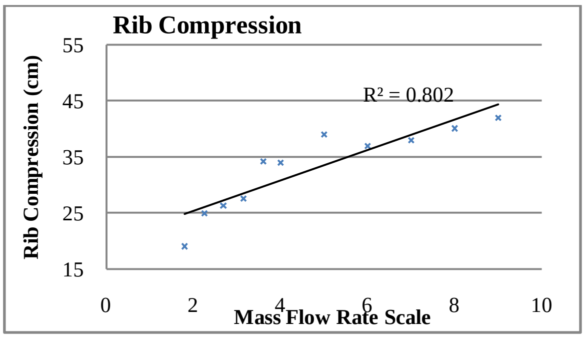


Figure 14 : R-square for rib % compression based on increasing mass flow rate

Table 3 : R^2 for all three factors determined by Heidelberg stationary simulation

Factors	Injury Parameters	R^2 Coefficient
Mass Flow Rate Scale (Factor A)	Peak VC	0.91
	Rib % Compression	0.80
Strap Length (Factor B)	Peak VC	0.67
	Rib % Compression	0.60
Fabric Permeability (Factor C)	Peak VC	0.75
	Rib % Compression	0.77

e) *Injury Criteria*

The injury criteria mainly describe the effect of dynamic forces acting on a particular body region. A threshold limit is assigned to each injury criteria and the occupant is considered severely injured if the injury values exceed the injury limit. The threshold injury limits can be referred to the dummy Injury Reference Values (IARV) for OOP occupants as shown in Table 4. The occupant injury caused by deploying airbag is monitored in three body regions, namely, the head, neck and thorax.

The head injury criteria (HIC) value is a measurement standard for measuring the injury to the head. The HIC_{36} threshold used for this study is 570. TWG predicts that the neck injuries will be the most important injury ratings for OOP test from deploying airbag. Based on TWG frontal airbag data, the cause of fatalities among children is the rupture of the connecting tissues at the occipital condoyle [7]. In order to properly predict the neck injury, two models of neck injuries can be utilized, namely, the N_{ij} index value or imposing limits threshold on neck forces and bending moments. The first model, the N_{ij} value, is used based on the linear combination of neck loads and moments. A N_{ij} value of above 1 indicates 30% risk of AIS 3+ injury to the cervical spine [13]. The second approach is to impose a limit threshold to the neck loadings. The lower neck forces were selected as the primary loadings to the neck. Recent research suggested that measuring the upper neck forces may not be adequate in determining the neck injuries due to the fact that OOP occupants' back may be exposed to the deploying side airbags [7]. The complete neck loadings can be found in NHTSA final ruling for neck injury criteria [14].

According to IIHS injury measurements, rib deflection equal to or less than 34mm is the border between good and acceptable rating [15]. Based on Viano injury curves for smaller size females, a 34mm deflection rating corresponds to 21-27% of severe thoracic injury [16]. An average rib deflection for SID-IIs of above 50mm is susceptible to an 80% chance of rib fracture.

The suggested rib deflection rate of 8.20m/s by IIHS marks the border between good and acceptable rating [15]. A deflection rate of 8.20m/s also correlates to an approximately 5% risk of AIS 4 thoracic injury. Based on research by Mertz et al, the lateral rib deflection rate is the same to the frontal deflection [17].

Table 4 : ATD Injury Reference Value (IARV) for OOP Occupants

Body Region	Injury Parameters	Hybrid III 3-yo	Hybrid III 6-yo	SID-II
Head	HIC, 15ms window	570	723	779
Upper Neck	N_{ij}	1.0	1.0	1.0
N_{ij} Intercepts Values	Tension Force (N)	2120	2800	3880
	Compression Force (N)	2120	2800	3880
	Flexion Moment (N.m)	68	93	155
	Extension Moment (N.m)	27	37	61
Lower Neck Forces	Tension Force (N)	1130	1490	2070
	Compression Force (N)	1380	1820	2520
Thorax	Deflection (mm)	36	40	34
	Deflection rate (m/s)	8.0	8.5	8.2

IV. Results and Discussions

A parametric study was conducted to investigate the OOP occupant injuries from a deploying side airbag. Three airbag governing factors such as fabric permeability (factor C), inlet jet mass flow rate (factor B) and maximum allowable airbag depth (factor A) were analyzed and considered. As discussed in the methodology section, the airbag aggressively test was conducted on three scenario, namely, TWG 3.3.3.2, TWG 3.3.3.5 and TWG 3.3.3.6 OOP test configurations.

a) TWG 3.3.3.6 – Small Female Inboard Facing

The kinematics for SID-IIs simulation can be seen in Figure 15. The kinematics shown is simulation with A, B and C factors set at high level. It can be seen that the ATD is positioned inboard facing with arm stretched outward. The pelvic region was aligned to contact the door trim panel. The ATD first thoracic rib was aligned with the top edge of the airbag module to allow maximum contact force between the airbag and the thoracic region. The injury levelmeasured were injuries to the thorax body regions such as the lower, middle and upper rib deflection as well as the thorax deflection rate.

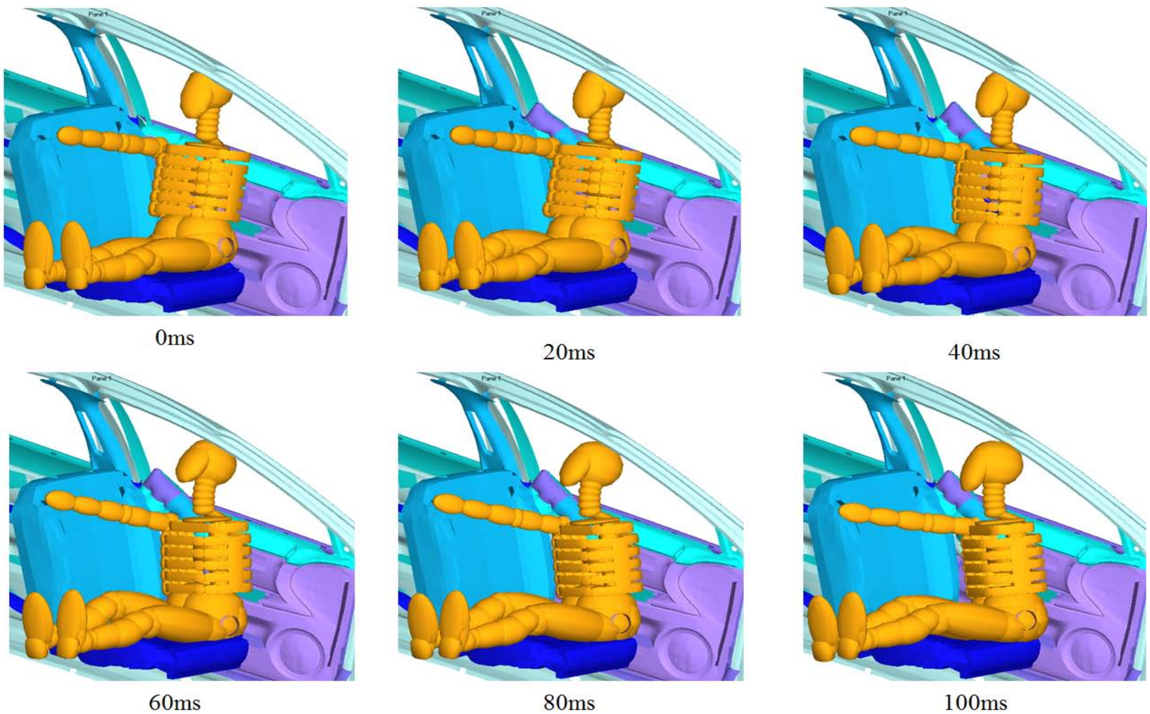


Figure 15 : Simulated kinematics for SID-IIs with factor levels A, B and C set at high

Table 5 : SID-IIs DoE Injuries Responses at Different Factors Levels

Run Order	Factors			Labels	Responses				
					Rib Lateral Deflections (mm)				Thorax Deflection Rate (m/s)
	A	B	C		Low	Mid	Up	Peak Rib Deflection (mm)	
1	-	-	-	(1)	21.12	16.65	14.48	21.12	7.07
2	+	-	-	a	29.90	24.43	25.10	29.90	6.72
3	-	+	-	b	9.60	12.51	10.86	12.51	4.44
4	+	+	-	ab	7.67	9.48	12.97	12.97	4.44
5	-	-	+	c	13.78	11.38	0.76	13.78	3.82
6	+	-	+	ac	59.14	39.76	31.63	59.14	7.00
7	-	+	+	bc	20.52	18.27	14.59	20.52	6.90
8	+	+	+	abc	17.98	12.35	19.18	19.18	7.20

Table 6 : SID-IIs Simulation DoE Parametric Equation

DoE Responses	DoE Regression Model Equation
Lower Rib Deflection	$23.40 + 0.76A - 0.21B - 2238.89C - 0.023AB + 472.94AC + 57.3626BC - 10.22ABC$
Middle Rib Deflection	$16.05 + 1.58A - 0.060B - 1503.69C - 0.040AB + 391.25AC + 42.66BC - 8.59ABC$
Upper Rib Deflection	$13.32 + 1.83A - 0.057B - 2550.94C - 0.031AB + 357.38AC + 57.57BC - 6.50ABC$
Peak Rib Deflection	$22.26 + 1.58A - 0.20B - 2279.73C - 0.030AB + 677.71AC + 62.28BC - 14.03ABC$
Thorax Deflection Rate	$8.18 - 0.064A - 0.075B - 635.22C + 0.0013AB + 62.98AC + 17.51BC - 1.18ABC$

To complete the DoE design matrix, 8 simulations were performed as shown in Table 5. Table 6 represents the complete injuries responses at different combination of levels. It is shown that the rib deflection is above the IARV values for simulations #6. 5 out of 8 simulations also yielded at least one response is 80% or above the suggested IARV threshold. The regression model equations seen in Table 6 are calculated using Equation 14. These parametric equations can be used to generate model graphs that present a prediction model of OOP injury level based on any combinations of factors. Table 6 is a complete regression model that can be used to predict OOP SID-II injury risks from deploying airbag.

To avoid repetitive graph, only the DoE model graphs for selected injury level for SID-IIs simulation are shown. Figure 16 and Figure 17 represent the fitted model for SID-II peak rib deflection and Figure 18 and Figure 19 shows the fitted model for SID-II thorax deflection rate.

The fitted model as shown in Figure 16 and Figure 17 is a good tool to measure the SID-II's peak rib deflection. It is shown that the maximum rib deflection can be obtained by using a high mass flow rate, low strap length and low fabric permeability. Similarly, Figure 17 suggest that the lowest rib deflection can be obtained by utilizing combination of high fabric permeability, high strap length and the combination of any level of mass flow rate.

The thorax deflection rate as shown in fitted models Figure 18 and Figure 19 can be interpreted in two scenarios. The thoraxdeflection rate values are generally high with high mass flow rate, high strap length and low fabric permeability or low strap length, high fabric permeability and any level of mass flow rate. The blue region as seen in Figure 19 suggests that the lowest deflection rate can be achieved with the combination of low fabric permeability, low strap length and mass flow rate.

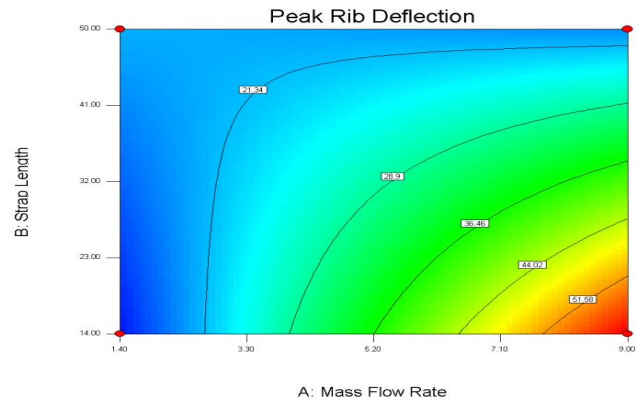


Figure 16 : Peak Rib Deflection DoE Model Graph with C Level: Low

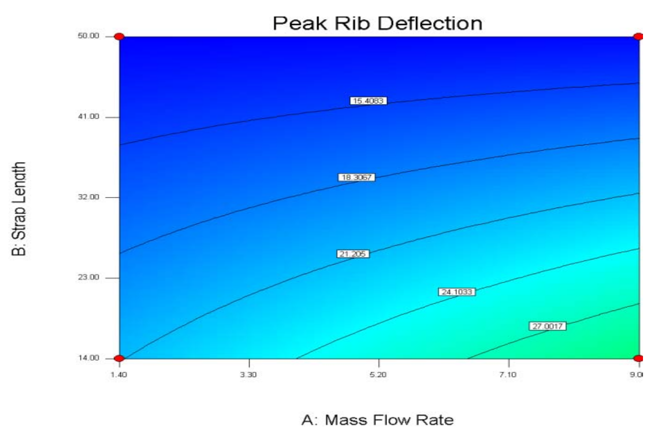


Figure 17 : Peak Rib Deflection DoE Model Graph with C Level: High

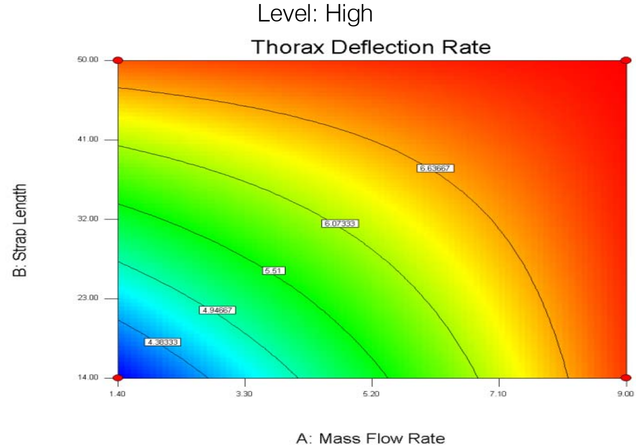


Figure 18 : Thorax Deflection Rate DoE Model Graph with C Level: Low

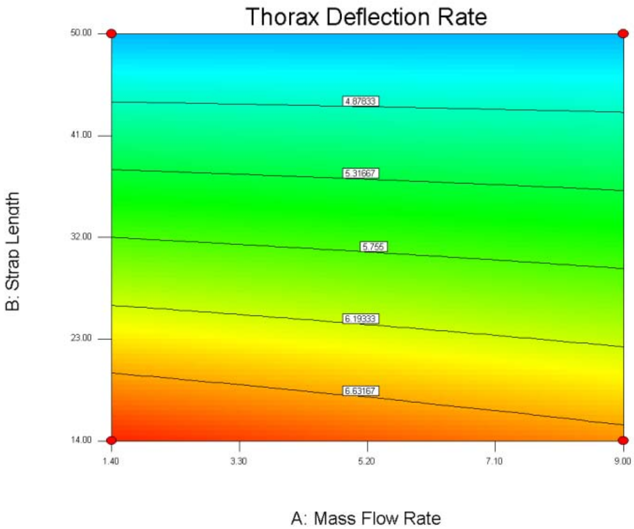


Figure 19 : Thorax Deflection Rate DoE Model Graph with C Level: High

b) TWG 3.3.3.2 – 3-year old Dummy Rearward Facing

In order to fully present the findings of injuries caused by deploying airbag on Hybrid III 3-Year Old, the ATD was positioned in accordance to TWG recommendation. According the TWG recommendation, the ATD was positioned kneeling and facing backwards along the outer-line of the bottom cushion. The sternum must be placed as close as possible to the leading edge of the back cushion and in contact with the back seat. Finally, the head must be in between the back cushion and the vehicle side trim to allow maximum contact. The ATD injury ratings of interest are the Neck N_{ij}, neck vertical loading values, rib deflection and rib deflection rate. The kinematics of the ATD at all factors set to high can be seen in Figure 20.

It can be seen in the kinematic figures that the placement of the ATD completely blocked the path of the deploying airbag. As such, the airbag needed much longer time to reach fully deployed state. It is shown in 60 – 80ms that the airbag compressed the rib in order to reach full deployment. Table 7 shows the DoE tabulation of the simulation results.

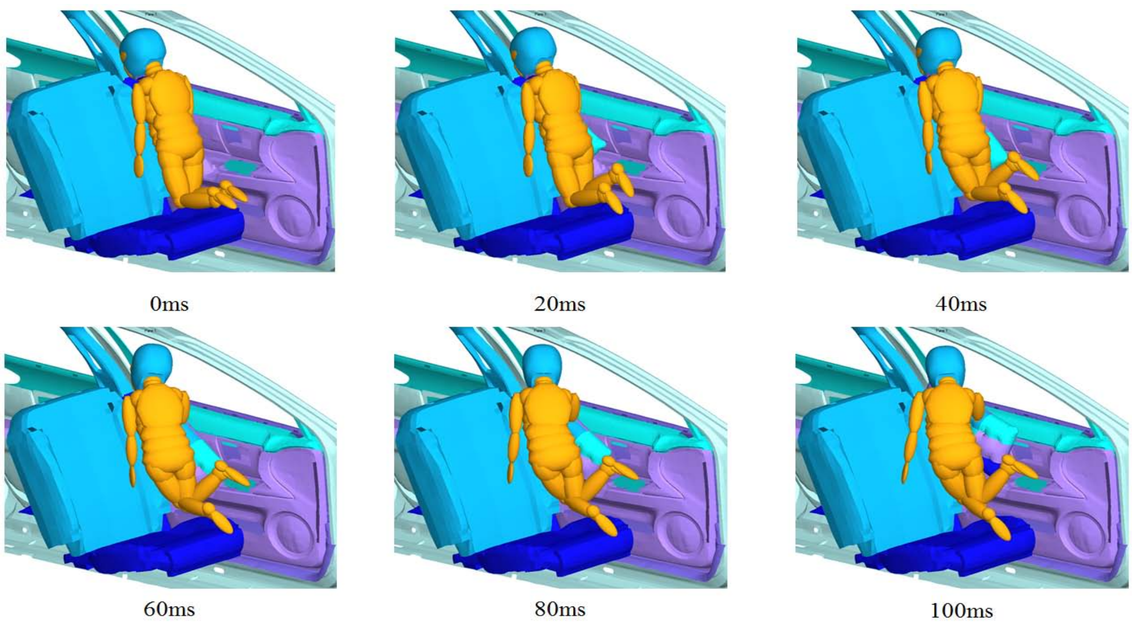


Figure 20 : Simulated kinematics for Hybrid III 3yo with factor levels A, B and C set at high

Table 7 : Hybrid III 3-Year Old DoE Injuries Responses at Different Factors Levels

Run Order	Factors			Labels	Responses				
	A	B	C		N_{ij}	Thorax Deflection (mm)	Thorax Deflection Rate (m/s)	Lower Neck Tension (+Fz)	Lower Neck Compression (-Fz)
1	-	-	-	(1)	0.19	3.0	1.27	123	178
2	+	-	-	a	0.57	12.5	5.33	152	549
3	-	+	-	b	0.20	5.6	2.12	119	160

4	+	+	-	ab	0.60	15.2	4.79	121	613
5	-	-	+	c	0.20	3.2	1.37	134	161
6	+	-	+	ac	0.57	18.9	6.55	197	609
7	-	+	+	bc	0.21	4.9	1.66	94	168
8	+	+	+	abc	0.60	15.7	5.19	107	578

The DoE results shown in Table 7 suggested that the thorax deflection rate for simulation number 6 is 80% that of the IARV threshold. Other responses are well below IARV threshold. These results suggest that the Hybrid III 3-year old for this particular configuration do not risk injuries from deploying airbag. Based on the ATD's kinematic responses, the airbag mainly contacted the front sternum of the ATD instead of the side thorax, this explains the low thorax deflection values. Similarly, the regression model obtained from DoE analysis can be used to predict the Hybrid-III 3-Year Old injuries risks from deploying airbag in the case of OOP.

Table 8 : Hybrid III 3-Year Old Simulation DoE Parametric Equation

DoE Responses	DoE Regression Model Equation
Rib Deflection	$0.25 + 1.24A + 0.072B - 95.03C + 0.00037AB + 107.16AC + 0.058BC - 1.83ABC$
Thorax Deflection Rate	$0.32 + 0.62A + 0.024B - 36.24C - 0.0056AB + 13.03AC - 1.92BC$
N_{ij}	$0.12 + 0.049A + 0.00018B + 1.18C - 0.000073AB - 0.13AC$
Neck Peak Tension	$110.29 + 6.54A + 0.25B + 3107.75C - 0.14AB + 296.05AC$
Neck Peak Compression	$122.53 + 44.62A - 0.92B - 4950.29C + 0.30AB + 1627.19AC + 130.85BC - 43.86ABC$

c) TWG 3.3.3.2 – 6-year old Dummy Forward Facing

The OOP test objective for the Hybrid III 6yo is to measure the injuries to the neck. The ATD's pelvis and thorax is positioned close to the leading edge of the back seat and the booster block. The left arm is positioned to rest of the side panel. The ATD's torso is placed directly in the path of the deploying airbag.

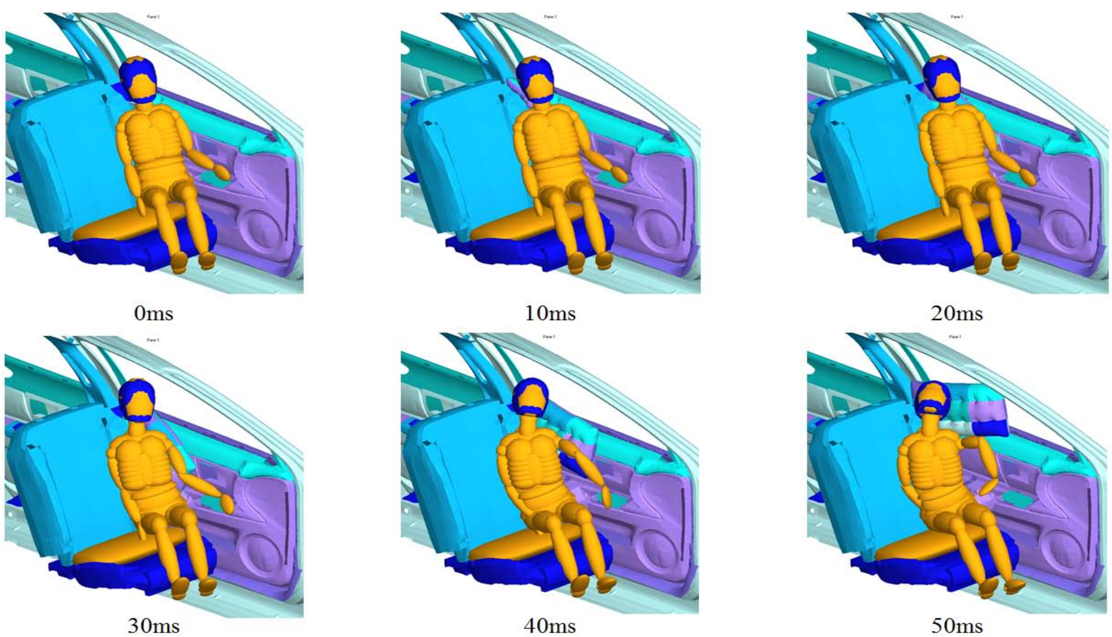


Figure 21 : Simulated kinematics for Hybrid III 6yo with factor levels A, B and C set at high

Table 9 : Hybrid III 6-Year Old DoE Injuries Responses at Different Factors Levels

Run Order	Factors			Labels	Responses		
	A	B	C		N_{ij}	Lower Neck Tension (+Fz)	Lower Neck Compression (-Fz)
1	-	-	-	(1)	0.16	114	295
2	+	-	-	a	0.33	315	440

3	-	+	-	b	0.20	139	229
4	+	+	-	ab	0.55	669	708
5	-	-	+	c	0.15	119	300
6	+	-	+	ac	0.33	301	431
7	-	+	+	bc	0.19	154	289
8	+	+	+	abc	0.62	729	688

Table 10 : Hybrid III 6-Year Old Simulation DoE Parametric Equation

DoE Responses	DoE Regression Model Equation
N_{ij}	$0.13 + 0.0091A + 0.000011B - 1.83C + 0.00079AB + 0.59AC$
Neck Peak Tension	$105.83 + 6.73A - 1.60B - 2083.33C + 1.32AB + 116.67BC$
Neck Peak Compression	$288.04 + 5.85A - 2.61B + 4115.79C + 1.10AB - 618.42AC$

The complete DoE run matrix can be seen in Table 9. All the injury values are below the suggested IARV. The simulation kinematics in Figure 21 shows that the ATD's neck experienced large amount of rotation and compression to the occipital condoyle over a short period of time. It can also be seen that the neck is the only body region experienced large forces and deformation compared to the thorax body region. Besides that, it can be seen that the left arm may have sustain serious injuries. The IARV do not have a guideline for measuring injuries to the extremities. As such, injury assessment cannot be done on extremities. The results show that 6 year old at this test configurations do not risk any injuries to the neck region from deploying airbags. Table 10 represents the regression model equations for selected injuries response. It can also be seen that the 3 factors interaction, ABC, is not significant in affecting the injuries response.

V. Results and Discussions

The purpose of this study was to develop a set of parametric equations to predict injuries from a deploying airbag using computer simulations. The prediction model was developed through the use of DoE regression model and model graphs. The simulations were conducted using MADYMO 7.4.2 and DoE results were evaluated using Design Expert 7. The selected three main influential factors that have major effect on OOP injuries were fabric permeability, airbag fully inflated depth and inflator mass flow rate. In order to accurately utilize the DoE factorial design, linear injury response between high and low factors have been verified using Heidelberg stationary.

The test scenarios selected for this study comprised of wide range of ATD in accordance to the recommendation by TWG. These scenarios were carefully selected to measure various injuries and to represent a whole spectrum of OOP occupants that are susceptible to deploying side airbags. DoE results from this study indicated that parametric equations were successfully obtained to determine the occupant injuries. The DoE results also suggested that two or higher interactions between factors governs the regression model. Therefore, it was conclusive that no single factor can be altered without affecting the injury response.

This study has shown that a set of equations can be generated using DoE's full factorial design. Full factorial design proved to be a useful statistical tool in evaluating the interactions between factors. Similarly, the injury prediction model was performed successfully by using the regression model. The results showed that the test configurations for SID-IIs had the highest injuries values that exceeded the IARV. This is mainly due to the seating position in which the thoracic body region was fully exposed to the deploying airbag. The low injury values for 3-year old and 6-year old suggest that the occupant was not susceptible to any risk of injury for these particular configurations. It is also important to conclude that the interest of this study is not to evaluate whether the injury level exceed certain injury threshold but rather to present systematic approach in developing a set of injury prediction model to evaluate injuries to OOP occupants from deploying airbag.

The methodology and mathematical models developed in this study can be utilized in the design stage of future airbags by using the prediction model to approximate injuries without the need to perform experimental testing. This study, however, did not verify the reliability of these set of equations on the recent model year vehicles. As such, further study needs to be conducted to verify this concept.Future works may also include optimizing the airbag model in reducing injuries to OOP occupants through the use of DoE's response surface methodology.

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