DRIVER AIRBAG DESIGN TO MITIGATE NECK AND CHEST INJURIES FOR US-NCAP AND OPTIMIZATION METHODS WITH A DYNAMIC META MODEL

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ABSTRACT

The frontal airbag in a vehicle is considered supplemental to the safety belt restraint system and is important in lowering measured injury assessment values for Anthropomorphic Test Devices (ATD) during vehicle crash testing. The probability of neck and chest injuries is an important factor for a vehicle's performance rating under the United States-New Car Assessment Program (US-NCAP) protocol. A shorter lower tether was incorporated into the driver frontal airbag (DAB) to mitigate chest deformation injury, however higher neck injuries were observed with this change.

The purpose of this study is to identify the main factors influencing neck injury assessment values through the use of Design Of Experiments (DOE) techniques and find an optimum airbag design which mitigates neck and chest injury assessment values by using optimization techniques. Four different airbag designs were used in the first stage of the DOE, and one DAB design was chosen for the best performance in US-NCAP. Traditional meta model based optimization of the chosen DAB design followed.

The direct optimization method requires a great deal of computational resource, whereas meta model based optimization methods use comparatively little computational resource once there are sufficient sample data from the DOE. Dynamic meta model based optimization methods were introduced with combined CAE runs to reduce computing resource in this study. CAE runs were periodically sampled to update the meta model and provide improved accuracy. Two different optimization methods with dynamic meta models were demonstrated and compared with traditional meta model based optimization.

INTRODUCTION

Since the current US-NCAP rating protocol was introduced in 2006 [3], neck and chest deformation injuries became more important for both the frontal driver and passenger injury matrix than in the previous US-NCAP rating system. The seat belt restraint system is one of the main countermeasures for US-NCAP occupant injury performance, and a low level of Single Load Limiter (SLL) and Dynamic Locking Tongue (DLT) were successfully proven to lower chest deformation injury. The frontal airbag is considered a supplemental restraint to the safety belt restraint system and is still important in lowering measured injury assessment values for Anthropomorphic Test Devices (ATD).

The purpose of this study is to find an optimum asymmetric airbag design which mitigates neck and chest injuries assessment values. A sled CAE model was built, and validation work was performed using physical tests. The base lower tether of the DAB was replaced by a shorter lower tether to mitigate chest deformation injury. Four DAB designs, differing according to the location of an upper tether attachment on the front panel of the DAB, were built and used as design factors in the DOE study. The relationship between the upper tether design and neck injuries was investigated, and the DAB design was chosen through a DOE study and meta model based optimization. A new asymmetric DAB was incorporated into the sled CAE model for the next airbag tether optimization process.

Meta models have been frequently used in place of time-consuming detailed CAE models. Usually, multiple CAE iterations are done before an optimization, and then a meta model is built and used for evaluation in optimization. Many researchers employed a dynamic learning approach utilizing a meta model [1], [4], [10], [11].

In this study, an initial DAB design was chosen from the first DOE, and another DOE was performed, which was then used to fit the meta model that is used for the following optimization. Meta model based optimization methods were used with an Elliptical Basis Function network algorithm (EBF) to reduce computing resource required. These meta models represented a dynamic learning approach that was periodically updated considering results from CAE iterations. Two approaches were demonstrated for airbag tether optimization work to improve US-NCAP performance.

CAE MODELING AND VALIDATION

An occupant sled CAE model was built from a full vehicle structure model. Vehicle pulse, pitching and z-drop motion were extracted from barrier test results and validation work was performed.

Occupant sled CAE model

A sled CAE model, which has a rigid body-in-white (BIW), for use with prescribed motion was built. Some benefits of this approach are that it is easy to apply a vehicle pulse extracted from full-scale hardware tests, and this requires relatively lower computing resources than a full vehicle occupant model would. One weak point of this approach is that it is difficult to mimic instrument panel (I/P) intrusion. In most instances, a small amount of I/P intrusion was observed for full frontal rigid barrier loading conditions. Figure 1 shows an occupant sled model with belted driver ATD for US-NCAP.

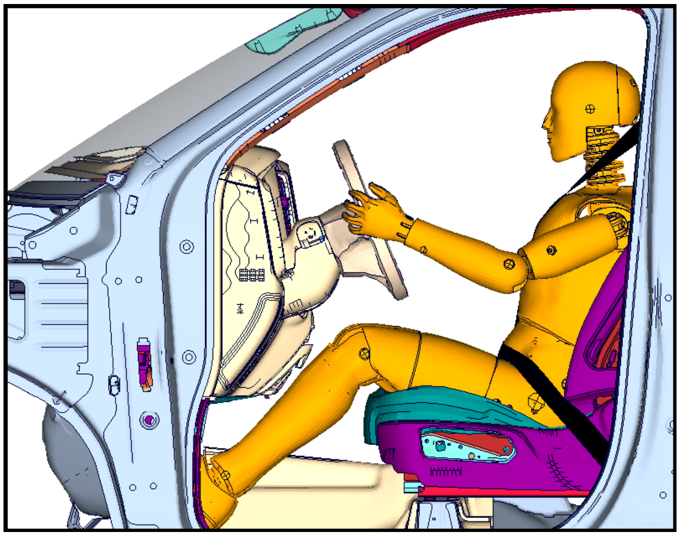


Figure 1. Occupant sled CAE model for frontal driver sides

Driver airbag model

Barrier tests were performed using an airbag design proposed by the airbag supplier. This airbag has an upper and a lower tether, and the tether length is 250mm for upper tether, and 220mm for lower tether. Typical tether length is 254mm (10”) with traditional methods, such as 5”-30ms criterion [8], with the proposed target time to fire (TTF). One of the benefits of these upper and lower tether designs is easily controllable cushion depth for a vehicle crash test which has large pitching and vehicle z-drop motion. Tethers stretch during airbag deployment, because of the internal pressure of the airbag and airbag fabric material properties, and the magnitude of stretch depends on the characteristics of the selected airbag cushion fabric material and the number of fabric layers. Fabric materials have orthotropic characteristics [6] and usually have three axis loading component data, for instance, warp, weft and 45°. This airbag supplier uses a tether design which has a 45° direction and one layer fabric tether. This tether design showed greater stretched tether length compared to a warp or weft direction tether design from another airbag supplier. Figure 2 shows statically deployed airbags. Figure 3 shows expected tether stretch from CAE results.

Asymmetric or smiley DAB designs, which have a shorter lower tether than the upper tether are frequently used in order to mitigate chest deformation injury assessment values. Asymmetric or smiley DAB designs were considered for this work to improve US-NCAP performance for the next DOE study.

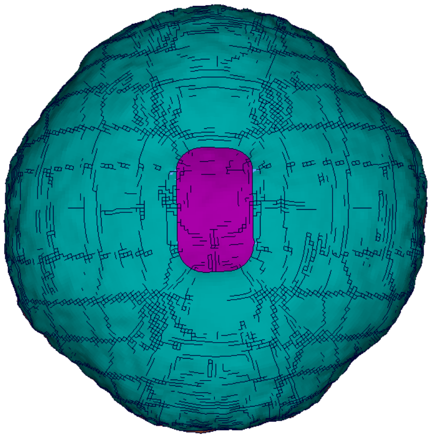


Figure 2.Static deployment of baseline airbag

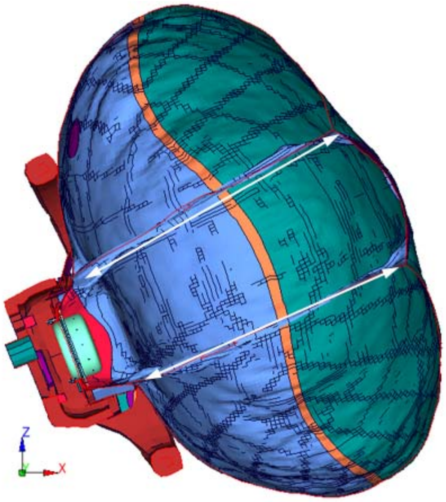


Figure 3. Tether stretch during deployment

Barrier test and validation work
It is important to verify the sled CAE model for subsequent optimization work. Validation work was performed with a belted 50th ATD in the 56kph full frontal loading condition, considering available data from a full-scale vehicle test. Figure A-1 and figure A-2 show the comparison between barrier test and the validated CAE model.

DOE STUDY

Asymmetric or smiley DAB designs, which have a shorter lower tether than the upper tether are frequently used in order to mitigate chest deformation injury assessment values. Airbag supplier proposed a smiley DAB for other vehicle program in past times and this asymmetric or smiley DAB design had been tried to mitigate chest deformation injury matrix, but these smiley DAB designs didn't lower chest deformation injury matrix significantly. It was hypothized that the attachment location on front panel of DAB for lower shorter tether was not appropriate, therefore smiley DAB had not lowered the chest deformation injury. Figure 4 shows proposed smiley (asymmetric) DAB by airbag supplier for other vehicle program in past time. Figure 5 shows interaction between smiley DAB and ATD from sled test, and figure 6 shows ATD's chest displacement transducer contact area on front panel of smiley DAB, it suggests that tether attachment location for lower tether didn't match to ATD's chest displacement transducer contact area in previous work. The neck injuries were changed with smiley DAB, but it was not clear upper or shorter tether changed the neck injuries.

Asymmetric or smiley DAB designs were considered for this work again. DOE technique [12] was used to identify the significant design factors on neck injuries.

A parameter CAE study was performed to find the recommended location for the lower tether attachment on the front panel of the airbag, which can lead to decrease chest deformation injury assessment values. Several new asymmetric airbag designs were proposed and used as design variables for the DOE study to identify the effect of upper tether location (design) on neck injuries. The main design factors, affecting injuries assessment values, especially neck injuries assessment values, were identified in this DOE study. Additionally, meta model based optimization was performed with these DOE sample data, and an asymmetric airbag design was chosen for subsequent airbag tether optimization work.

Figure 4. Smiley (asymmetric) DAB which was proposed by supplier

Figure 5. Interaction between asymmetric DAB and ATD chest

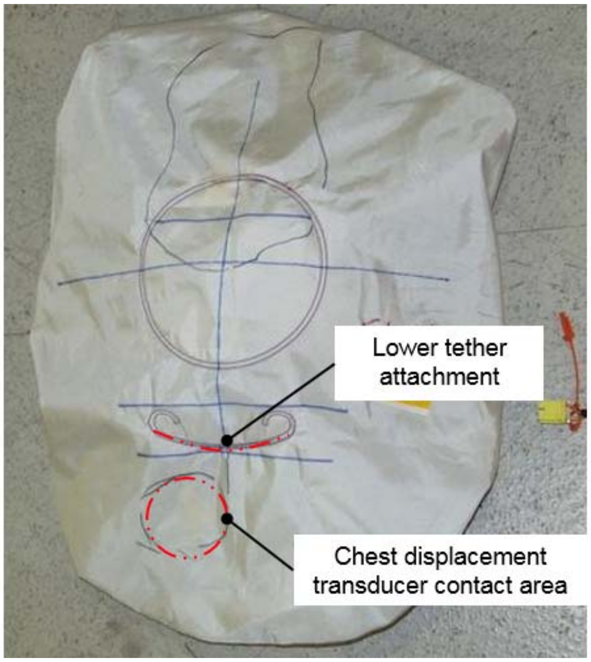


Figure 6. Lower tether attachment vs. chest potentiometer contact area with asymmetric DAB

New asymmetric airbag model

The results of several barrier tests showed higher neck and chest deformation injury assessment values than expected given the pulse severity. Therefore, the performance of the proposed occupant restraint systems resulted in a 4 star US-NCAP rating score. The motivation of this study was to find a better airbag design with the goal of improving US-NCAP performance rating without changing other restraint system components, such as the seat belt system.

Chest deformation can be lowered by removing pressure on the ATD chest, whereas chest acceleration injury can be lowered by using the ride down effect offered by the restraint systems [8]. One countermeasure to lower chest deformation is an asymmetric DAB design, which has a quite shorter lower tether length than upper tether length. A shorter lower tether length, 100mm, was incorporated into the baseline airbag by replacing the lower tether only. The internal airbag pressure may be high enough to tear this 45° angle fabric tether, so a warp or weft fabric direction tether with two or three layers of material was recommended. Proper location of the lower tether attachment on the front panel of the airbag was achieved by performing a parameter study. Figure 7 and figure 8 show the interaction between the airbag and ATD chest for the baseline DAB and asymmetric DAB, respectively.

The parameter study with 100mm lower tether length showed that chest deformation was significantly lowered, but neck assessment values, such as, Nij were increased contrarily. It was assumed that upper tether length and the location of the upper attachment on the front panel of the airbag might play a role in neck performance. Therefore, four different DAB designs were built by changing the location of the upper tether attachment on the front panel of the airbag with 250mm upper tether length. Figure 9 shows the proposed asymmetric DAB configurations, which were used as design variables in the DOE study (DAB #1, DAB #2, DAB #3, DAB #4).

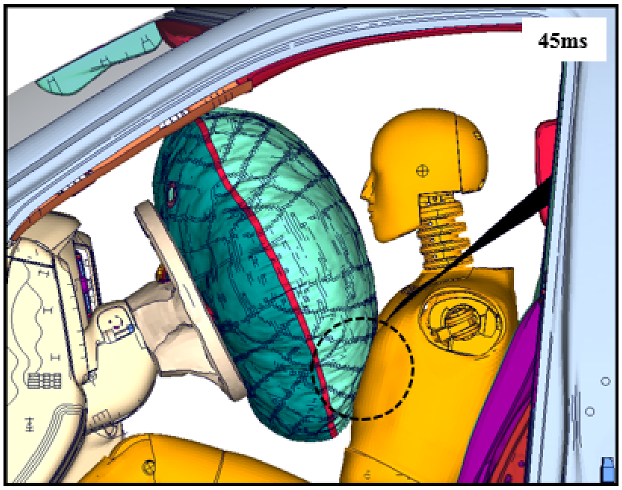


Figure 7. Interaction between baseline DAB and ATD chest

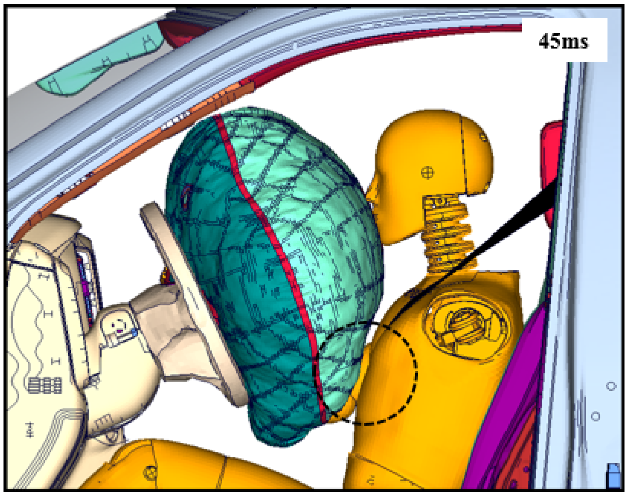


Figure 8. Interaction between asymmetric DAB and ATD chest

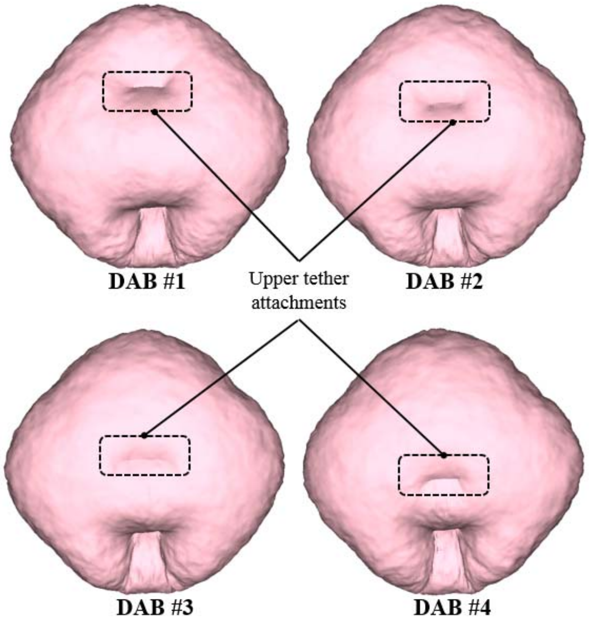


Figure 9. Asymmetric DAB, which were used as design variable in DOE

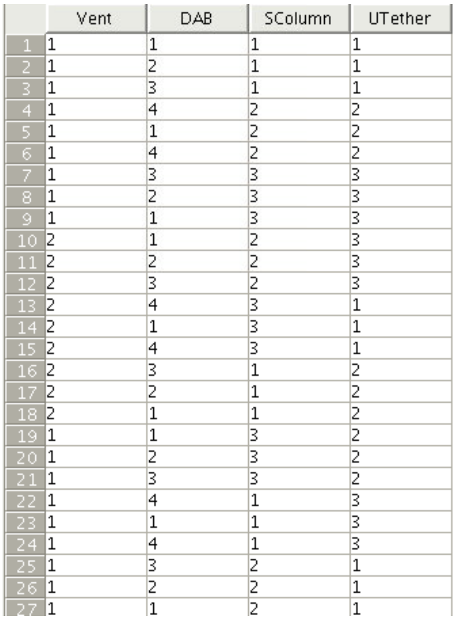
Design variables and DOE matrix

The purpose of this DOE work is to identify the main factors contributing to neck assessment values and to find the best DAB design through meta model based optimization. Four discrete design variables were defined. Vent size was one of the variables, because airbag internal pressure has a strong relationship with ATD measured assessment values. The variable name 'DAB' in the study represents different DAB designs according to the location of upper tether attachment. Upper tether length was also considered as one of the design variables in order to find the relationship between neck performance and upper tether length. An L27 orthogonal matrix was used for DOE sampling. Table-1 shows the variables and Table-2 shows the L27 orthogonal DOE matrix. A polynomial-base meta model [5] was built with L27 DOE sample data.

Table 1. Loading condition and design variables of DOE matrix

Loading condition and DOE matrix		
Matrix		L27 Orthogonal matrix
Loading condition	Speed	56kphFF US-NCAP
	Occupant	Driver 50th
	Belt condition	Belted
Design variables	Vent (2 x ϕmm)	35, 40
	DAB (UT attch location)	1, 2, 3, 4
	S/Column load (kN)	2.0, 3.0, 4.0
	Upper tether length (mm)	150, 200, 250

Table 2. L27 orthogonal DOE matrix



	Vent	DAB	SColumn	UTether
1	1	1	1	1
2	1	2	1	1
3	1	3	1	1
4	1	4	2	2
5	1	1	2	2
6	1	4	2	2
7	1	3	3	3
8	1	2	3	3
9	1	1	3	3
10	2	1	2	3
11	2	2	2	3
12	2	3	2	3
13	2	4	3	1
14	2	1	3	1
15	2	4	3	1
16	2	3	1	2
17	2	2	1	2
18	2	1	1	2
19	1	1	3	2
20	1	2	3	2
21	1	3	3	2
22	1	4	1	3
23	1	1	1	3
24	1	4	1	3
25	1	3	2	1
26	1	2	2	1
27	1	1	2	1

Sensitivity analysis and main design factors

The US-NCAP rating score consists of probability of head (Phead), neck (Pneck), chest (Pchest), and femur injuries (Pfemur) for the frontal impact loading conditions, and all of these four injury components are combined as "joint probability of injury (Pjoint)" [3]. Figure 10 shows that barrier test results suggest the following.

- The probability of neck injuries is the most important factor on NCAP
- The second most influential factor is the probability of chest injury

Neck assessment values, such as Nij [3], are calculated from upper neck moment and axial force. Figure A-1 and figure A-2 (in the Appendix) show that neck tension flexion moment (Ntf) is the major factor influencing the probability of neck injury for this specific vehicle. Figure 11 and figure 12 show that the main factors for Ntf are upper tether length (UTether) and the location of the upper tether attachment on the front panel of the airbag (DAB). Also, neck tension force was highly dependent on the location of the upper tether attachment, whereas neck flexion moment was highly dependent on the upper tether's length. Main effect plots suggests that DAB #4 design showed the best performance.

There were interaction effects between upper tether length (UTether) and the location of the upper tether attachment (DAB) on head, neck tension force, and neck flexion moment values. This suggests that a conventional DOE approach using a first order polynomial response surface model (RSM) would not work well to identify the best design configuration. Figure 13 shows interaction plots for head, neck tension force and neck flexion moment.

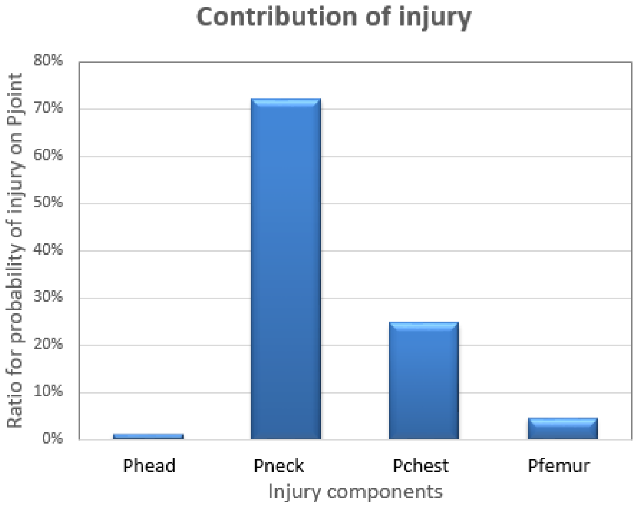


Figure 10. Comparisons for probability of injury on NCAP rating score (Pjoint)

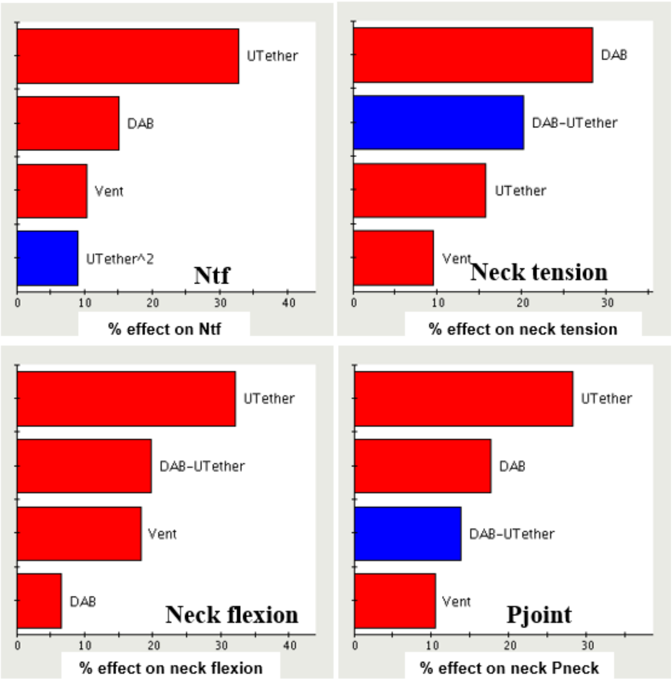


Figure 11. Pareto graph for neck assessment values and Pjoint

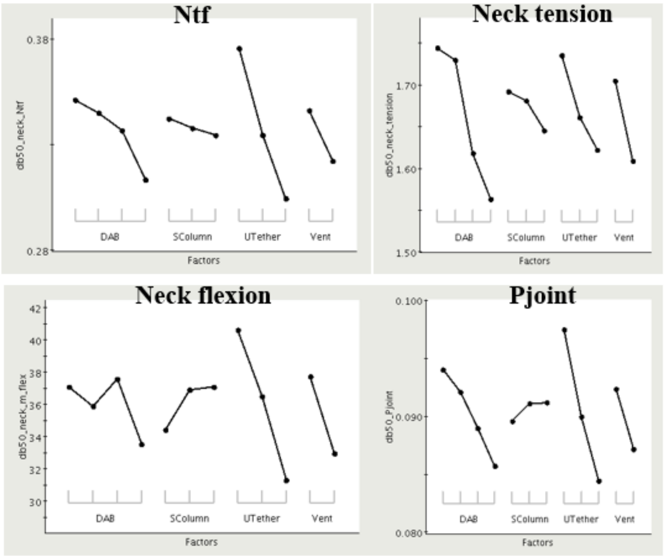


Figure 12. Main effect plots for neck assessment values and Pjoint

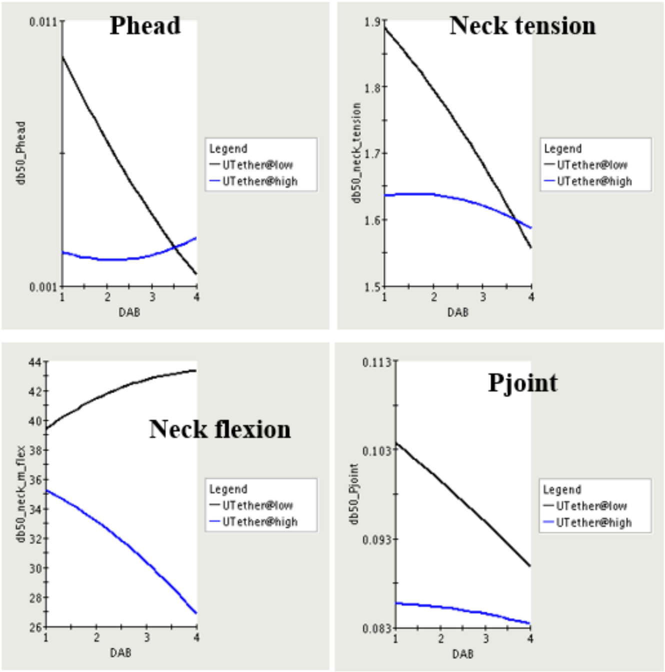
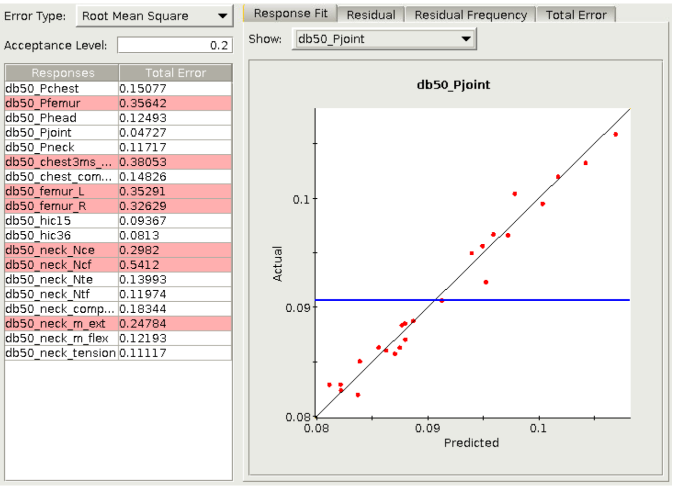


Figure 13. Interaction plots for Phead, neck tension force, neck flexion moment and Pjoint

Optimization by polynomial meta model

A polynomial 3rd order meta model was built with L27 DOE sample data. A Root Mean Square Error (RMSE) was used with leave-one-out cross validation analysis. Figure 14 shows errors are less than 15% for neck and chest deformation performance, but error for femur injury matrix is high, 36%, because there was not significant contact loading by knee-bolster, the femur loads were mainly caused by floor interaction to feet. A Genetic Algorithm (GA), such as NSGA-II algorithm [2], [5] was used for meta model based optimization [13], because occupant analyses have non-linearity. The predicted joint probability of injury (Pjoint) is

0.0823 based on meta model based optimization, and the corresponding confirmation CAE run showed 0.0820 of Pjoint. Table-3 shows the injury comparison between baseline DAB and the new asymmetric DAB design. Figure 15 shows a bar chart comparison of US-NCAP performance.



Error Type: Root Mean Square

Acceptance Level: 0.2

Responses	Total Error
db50_Pchest	0.15077
db50_Pfemur	0.35642
db50_Phead	0.12493
db50_Pjoint	0.04727
db50_Pneck	0.11717
db50_chest3ms_...	0.38053
db50_chest_com...	0.14826
db50_femur_L	0.35291
db50_femur_R	0.32629
db50_hic15	0.09367
db50_hic36	0.0813
db50_neck_Nce	0.2982
db50_neck_Ncf	0.5412
db50_neck_Nte	0.13993
db50_neck_Ntf	0.11974
db50_neck_comp...	0.18344
db50_neck_m_ext	0.24784
db50_neck_m_flex	0.12193
db50_neck_tension	0.11117

Show: db50_Pjoint

Figure 14. Error analysis for polynomial 3rd order meta model

Table 3. Injury comparison between baseline DAB and asymmetric DAB

56kph FF US-NCAP		
	Base DAB	Asymmetric DAB
DAB	Std.	DAB #4
Upper tether length	250 mm	246 mm
Lower tether length	218 mm	100 mm
Vent	2 x ϕ 35 mm	2 x ϕ 40 mm
S/Column	2.0 kN	3.8 kN
Phead	0.0010	0.0010
Pneck	0.0690	0.0660
Pchest	0.0240	0.0120
Pfemur	0.0040	0.0040
Pjoint	0.0960	0.0820

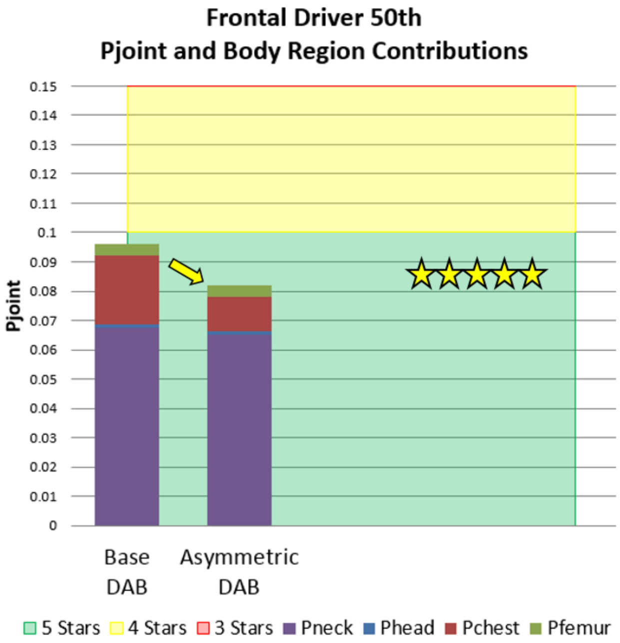


Figure 15. Bar chart comparison of US-NCAP performance

DYNAMIC META MODEL BASED OPTIMIZATION

Optimization was performed again with the goal of optimizing an upper and a lower tether length with new asymmetric airbag design, which was chosen from the DOE study section. Meta model based optimization was chosen with consideration of high computational cost. Traditionally, a meta model is built over the design space, and it is used in optimization. A dynamic learning approach was proposed with artificial neural network algorithms for time consuming water resource simulation models [10]. A Dynamic Kriging method was demonstrated to improve the accuracy of the meta model by dynamically selecting the optimal set of the basis function of the universal Kriging meta model [1], [11]. An adaptive meta model using a neural network algorithm was demonstrated. The meta model was initially built with the Latin Hypercube sampling method. Sequential designs using an adaptive error-based sampler were used to train the meta model [4].

In this study, meta model based optimization was combined with the dynamically trained meta model. Two approaches were compared and demonstrated.

Design variables and sampling method

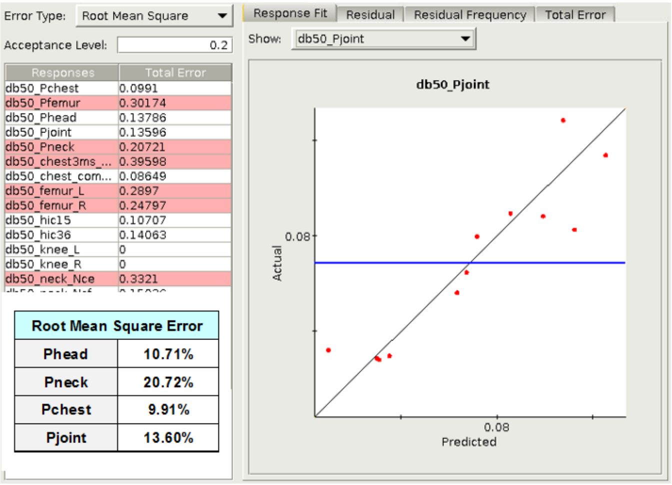
Two continuous variables for the length of an upper and a lower tether were defined as design variables, and two discrete design variables for vent size and steering column collapse load were defined. Optimal Latin Hypercube [5] was used as the sampling method. The sampling number is twelve (3 times of the number of design variables). Table-4 shows the loading condition and continuous and discrete design variables.

Table 4. Loading condition and design variables for DOE sampling run

Loading condition and DOE matrix			
Matrix		Optimal Latin Hypercube 12	
Loading condition	Speed	56kphFF US-NCAP	
	Occupant	Driver 50th	
	Belt condition	Belted	
Design variables	Vent (2 x ϕmm)	30, 35, 40	
	S/Column load (kN)	2.0, 2.5, 3.0, 3.5, 4.0	
	Upper tether length (mm)	200 <	< 300
	Lower tether length (mm)	75 <	< 125

Meta model

Radial Basis Function network (RBF) is a kind of neural network algorithm which can be trained [9]. Mak, et al proposed the Elliptical Basis Function network (EBF) by replacing the base function of RBF and compared it to the original RBF [7]. In this study, EBF meta model was used after a comparison of accuracy between RBF and EBF with same sample data. Figure 16 shows the error analysis for an EBF meta model with 12 CAE data samples. The target of RMSE is less than 20%, but the error for Pneck is high, 20.72%, and exceeding 20% at initial EBF meta model output.



Error Type: Root Mean Square

Acceptance Level: 0.2

Show: db50_Pjoint

Responses	Total Error
db50_Pchest	0.0991
db50_Pfemur	0.30174
db50_Phead	0.13786
db50_Pjoint	0.13596
db50_Pneck	0.20721
db50_chest3ms_...	0.39598
db50_chest_com...	0.08649
db50_femur_L	0.2897
db50_femur_R	0.24797
db50_hic15	0.10707
db50_hic36	0.14063
db50_knee_L	0
db50_knee_R	0
db50_neck_Nce	0.3321

Root Mean Square Error	
Phead	10.71%
Pneck	20.72%
Pchest	9.91%
Pjoint	13.60%

Figure 16. Error analysis for EBF Meta model with 12 CAE sample data

Optimization by dynamic meta model

The NSGA-II (Non-Dominated Sorting Genetic Algorithm) [2], [5] was used with the EBF meta model. The size of population = 12, the number of generations = 10, crossover probability = 0.9, crossover distribution index = 10, mutation distribution index =20. Two optimization methods were demonstrated. Method #1; perform optimization with meta model only; confirmation CAE run with optimized design, and update samples and meta model. Loop this process nine times. Method #2; 75% of populations were evaluated with the meta model and 25% of populations were evaluated by CAE runs, updating samples and meta model for each generation in order to get improved accuracy. Figure 17 shows work flow of optimization method #1, and Figure 18 shows work flow of optimization method #2.

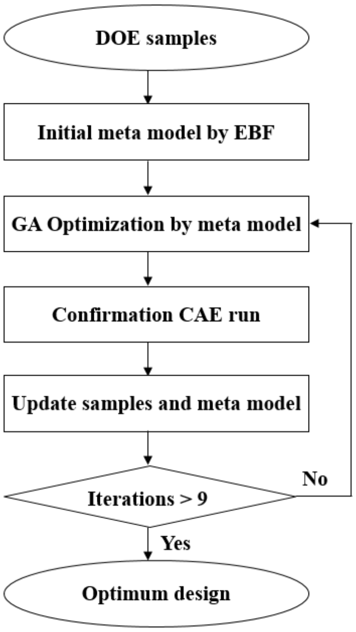


Figure 17. Work flow of optimization method #1

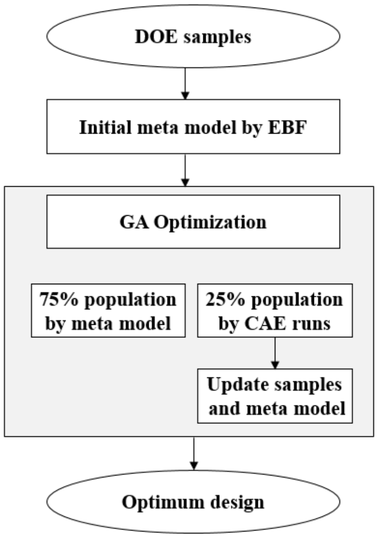


Figure 18. Work flow of optimization method #2

RESULTS

The accuracy of the EBF meta model was improved for both method #1 and method #2. Joint probability of injury was successfully lowered for both optimization methods. The accuracy of the meta model was better for method #2 with more sample data than method #1. The predicted joint probability of injury (Pjoint) by meta model is 0.0765 from method #2, and the corresponding confirmation CAE run showed Pjoint of 0.0770. Table-5 shows the comparison for the accuracy of the meta model between initial meta model and final meta models from method #1 and method #2. Table-6 shows the optimized design configuration and probability of injuries comparison, and figure 19 shows bar chart comparison of US-NCAP performance.

Table 5. Comparison of meta model accuracy: RMSE with leave-one-out cross validation

Root Mean Square Error			
Probability of injuries	Initial 12 samples	Method #1 12 + additional 8 samples	Method #2 12 + additional 28 samples
Phead	10.71%	9.11%	7.93%
Pneck	20.72%	13.73%	10.79%
Pchest	9.91%	7.98%	7.74%
Pjoint	13.60%	10.35%	7.76%

Table 6. Optimized design variable with dynamic meta model method

56kph FF US-NCAP				
	Base DAB	Asymmetric DAB	Optimization method #1	Optimization method #2
DAB	Std.	DAB #4	DAB #4	DAB #4
Upper tether length	250mm	246 mm	290 mm	296 mm
Lower tether length	218mm	100 mm	125 mm	78 mm
Vent	2 x ϕ 35 mm	2 x ϕ 40 mm	2 x ϕ 40 mm	2 x ϕ 40 mm
S/Column	2.0 kN	3.8 kN	2.5 kN	2.0 kN
Phead	0.0010	0.0010	0.0004	0.0005
Pneck	0.0690	0.0660	0.0631	0.0637
Pchest	0.0240	0.0120	0.0134	0.0093
Pfemur	0.0040	0.0040	0.0044	0.0045
Pjoint	0.0960	0.0820	0.0800	0.0770

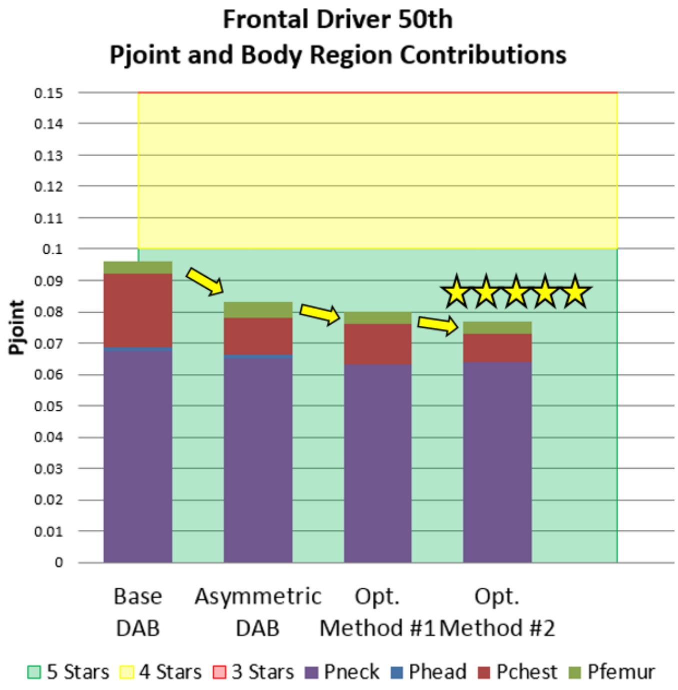


Figure 19. Bar chart comparison of US-NCAP performance

SUMMARY AND CONCLUSIONS

In this paper, an asymmetric airbag design was proposed with the goal of mitigating chest deformation and improving US-NCAP performance. The DOE technique was used to identify the main design factors for neck assessment values, and meta model optimization was performed to choose the location of an upper tether attachment on the front panel of the DAB. The DOE study shows; axial neck tension force was highly dependent on the location of upper tether attachment on the front panel of the DAB, whereas neck flexion moment was highly dependent on an upper tether's length. Meta model based optimization was performed to optimize tether length again, because a DOE study suggested that tether length has a role in neck flexion injuries. An initial EBF meta model was built with 12 data samples, and used for the evaluations. During the optimization, sample data and meta models were updated. Two methods using dynamic meta model were demonstrated, showed the accuracy of meta models were improved, and successfully found solutions. Method #2 shows better performance than method #1 with more sample data. For the future work, this asymmetric or smiley DAB needs to be verified for other loading conditions, for example, 40kph full frontal unbelted 5^{th} and 50^{th}. And low risk deployment performance also needs to be confirmed by actual hardware tests. There were arguments about performance with this asymmetric or smiley DAB in field condition, because the steering wheel can be rotated at real world field conditions and can show different performance.

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APPENDICES

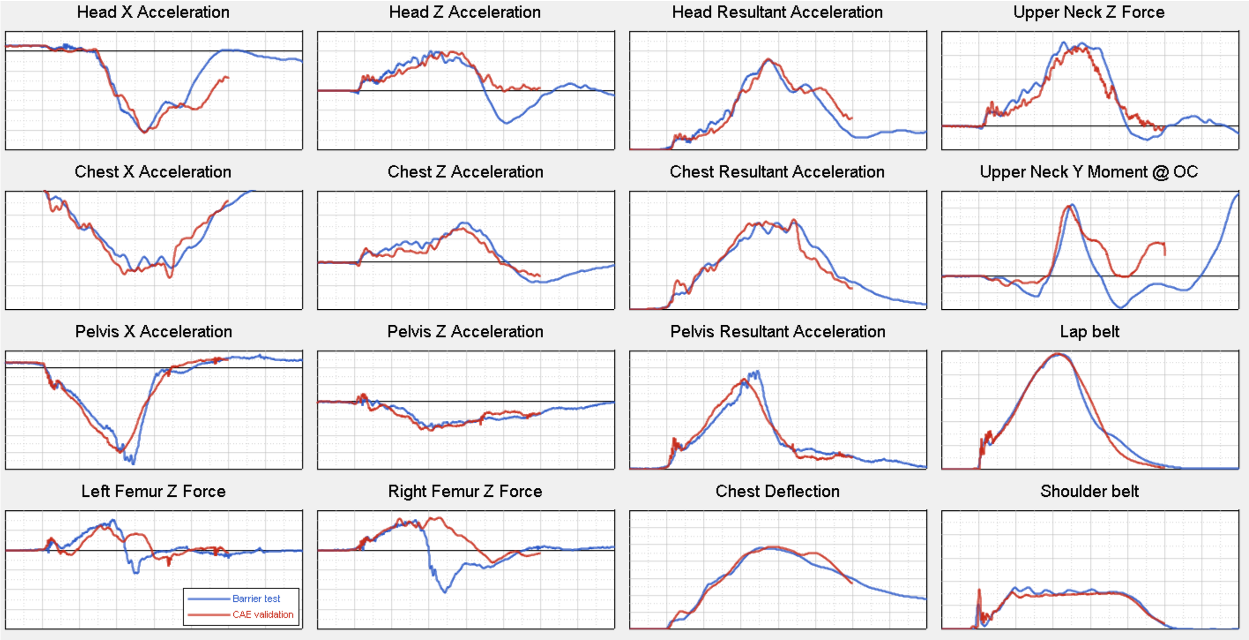

Figure A-1. Comparison between barrier test and validated CAE model for US-NCAP (blue: test, red: CAE)

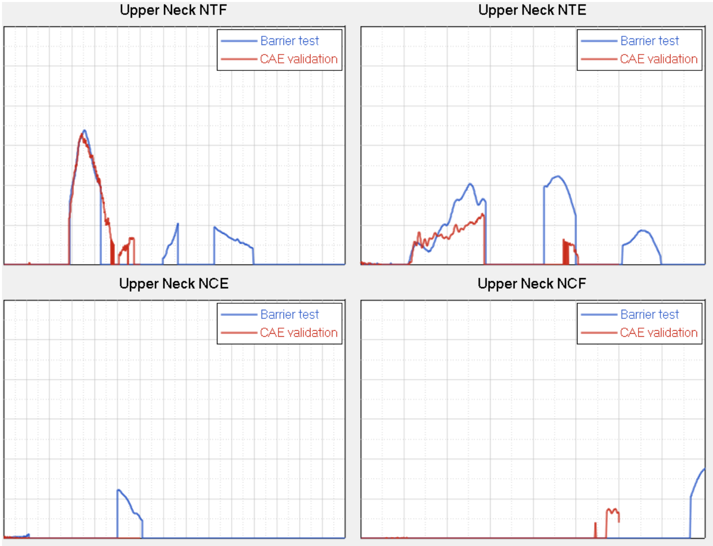

Figure A-2. Comparison between barrier test and validated CAE model for US-NCAP (blue: test, red: CAE)