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Sensitivity Analysis of Airbag Parameters on Driver's Head Injury in a Frontal Vehicle Crash by DOE Method

Esmail Dehghani[1], Vahid Rastegar[1], Javad Marzbanrad[1*]

[1] School of Automotive Engineering, Iran University of Science and Technology, Tehran, Iran

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ABSTRACT

In this study, the driver airbag geometry and internal pressure were considered as the main parameters to investigate the head injury severity in a frontal crash. The total energy absorption of an airbag was investigated in a drop test simulation and its rate was discussed by the depression distance parameter. On the other hand, the maximum deceleration of the impactor was determined to represent the airbag stiffness by a defined deceleration peak parameter. Thus, the depression distance and the deceleration peak were the objective functions for an isolated airbag under a lumped-mass impact simulation. Furthermore, an optimal matrix was generated using the design method of experiments (DOE) and yielded the airbag parameters as outputs. After the evaluation of the design parameters by the Taguchi method, the ANOVA method was used to predict the most effective parameters. Finally, a sled test with the 50% HYBRID III dummy and the defined airbag was simulated. An experimental crash was selected as the reference point to verify the simulation and to be used to compare the outcomes. Even though the objective function of depression distance showed contradictory effects to reduce the head injury severity, the results showed a %16.4 reduction in the driver head injury in a full-frontal crash.

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*Corresponding Author
Email Address: marzban@iust.ac.ir

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1. Introduction

In the automotive industry, occupant safety remains the most challenging design considerations. The severity of occupant injury from a crash is the result of combinations of many factors, but in component design approaches of vehicle, pre-crash and crash factors are to be investigated. One of the important factors is the optimal designs of restraint systems and mostly airbags [1].

Considering the conducted researches, the percentages of all crashes are as follows: (a) 65% front impacts, (b) 17.5% right-side impacts, (c) 13.5% left-side (driver-side) impacts, and (d) 3.5% rear-end impacts which the most fatalities are related to the frontal impacts. This issue can demonstrate the importance of the front impact. Thus, the safety of the passengers and pedestrians in all the above-mentioned accidents are two important issues that need to be evaluated. Furthermore, the most common cause of death is head injury and even among the occupants with the restraint system, the head is the most likely injured body part [2-4]. Head injuries are one of the main focus for regulations and NCAP and Head Injury Criterion (HIC) 36 is wildly used to in many researches [5].

Among all of the ergonomic parameters that influence the driver's safety in a crash, the interaction between the airbag and human body was studied by Iwamoto in a sudden frontal collision. They used a human body FE model (THUMS), which included three types of muscle activations to simulate sleeping, relaxed, and braced drivers, were predicted such as without muscle activation, with posture control, and with total control of posture and force. The results of their study showed that changing the driver's kinematics and alter injury outcomes are depended on muscle activations, and that relaxed drivers could endure more brain injury and neck injury than braced drivers [6].

Khalkhali used Taguchi and analysis of variance (ANOVA) methods to optimize airbag distance to dummy, trigger time, initial inflator gas temperature and tank pressure are considered as input parameters in a frontal crash [7].

Wang investigated on optimization of the effective parameters of the airbag by Design of Experiment (DOE) with the method of Latin Hypercube DOE. For the mathematical approaches, the radial basis function employed instead of the complex finite element model. Additionally, the result of optimization caused a reduction in the maximal acceleration of airborne vehicles and increased energy absorption [8].

Torbjörn assessed the experimental design (DOE) and optimization by factorial and fractional factorial designs. Further, the linear relationship between the experimental variables and the responses were considered by a polynomial function and the influence of variables were extracted by the full factorial design [9].

Xianguang used Non-dominated Sorting Genetic Algorithm II (NSGAII) to investigate effective parameters on the Occupant Restraint Systems (ORS) that are Head Injury Criteria (HIC) and chest displacement. This was done by considering the overall design requirements in the frontal impact crash of the Euro-NCAP. The major sensitive parameters on the HIC were inflator mass flow and strap length. The chest displacement was sensitive to the belt limiter load, trigger time, seat cushion stiffness, and webbing stiffness [10]. Yahaya

Potula et al investigated the effect of the curtain airbag on the head injury on the 1996 Dodge Neon model. It was shown that the curtain airbag has a significant effect on occupant injury and safety when the occupant is in Out-of-Position (OOP) conditions and in In-Position (IP) impact. Also, their investigation indicated that the depression distance of the airbag is significant during a side impact while the airbag was inflated at the time of impact [11].

In order to determine the optimum values of the airbag effective parameters in a frontal crash, an optimization method was practiced. First, the optimization parameters were designated with respect to the previous researches. Second, based on the design of the experiment, several conditions were simulated for a lump mass collision with the airbag. In addition, a sled test with the 50% Hybrid III dummy and the evaluated airbag was simulated in a frontal crash. The results are compared to the baseline and finally, a sensitivity analysis shows the effect of each parameter of the airbag on the outputs.

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2. Methodology

This research was divided into two parts. The first part was dedicated to the analysis of an isolated airbag in a drop test simulation and the other one was the sled test simulation. The outcomes from the first part were the inputs for the second part. T Two methods, Control Volume (CV) and Particle Method (PM) are commonly used to model the driver's airbag. In this research, the PM method was chosen to achieve more realistic and accurate results. The main purpose of the investigation on the airbag was to optimize the effective parameters of the driver airbag on the injury criteria and to reduce the HIC. In the following sections, the airbag impact modeling, optimization parameters, DOE, Sled test simulation, Taguchi method, and ANOVA are represented respectively.

2.1. Lumped Mass Modeling and Simulation

To investigate the airbag parameters, a rigid impactor hit different pre-designed airbags from a 450(mm) distance with the initial velocity of 15.56(m/s) based on FMVSS 208 frontal impact. The mentioned initial distance between the impactor and the airbag was used to minimize the effect of unfolded fabric on the depression of the airbag and deceleration of the lumped mass and also to make sure that the airbag would be fully deployed before any collision.

The airbags general shapes were similar to the conventional driver airbags as represented in Figure 1. The simulations were performed in a free-fall situation. Each airbag was fully developed in less than 30(ms) to minimize the effect of inflating conditions.

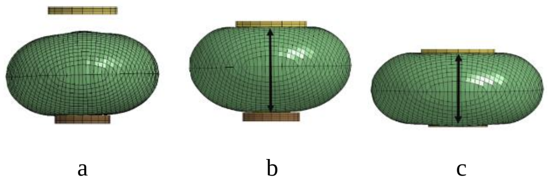
a b c

Figure 1: Simulation of the lumped mass and the airbag during the impact: (a) Inflated airbag before the impact, (b) maximum deployment, (c) depression of the airbag during the contact.

Table 1 shows the fabric properties of a typical airbag [10], gas properties and initial conditions that used to simulate the unfolding process of the airbag.

Table 1: Driver airbag properties

Description	**Value**
Density (Kg/m^3)	850
Young's modulus (Gpa)	0.427
Shear module (Gpa)	0.1
Poisson's ratio	0.35
Number of particles	100,000
Initial pressure (GPa)	1.013e-4
Universal molar gas constant (KJ/Kmol k)	8.314
Initial temperature (K)	295

3. Optimization Parameters

In this section, each and all the objective functions and design parameters, which are used in the drop test simulation of the airbag are introduced.

3.1. Design parameters

During the accident, the airbag is one of the most important factors that influence the reduction of injury severity. Head acceleration and the HIC have a direct correlation with the airbag geometry. In addition, the airbag's geometry is dependent on its diameter. On the other hand, the maximum inflation of the airbag depends on the strap length. The internal pressure of the airbag is directly related to the mass flow rate, airbag volume at the time of impact, and the diameter of vents. These four factors are selected as the design parameters and defined in Table 2. More explanation is given in the DOE section.

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Table 2: Design parameters of the airbag

Factors	Parameters
A	Dimeter of the airbag (mm)
B	Strap length (mm)
C	Vent diameter (mm)
D	Inflator mass flow

3.1.1. Depression distance

By the time of collision between the driver's head and the airbag, the airbag should be fully deployed to prevent extra injury to the head and neck. Besides, the driver's head might contact to internal instrumental devices like the steering wheel or dashboard if the volume of the airbag does not reach to an appropriate value. Therefore, the depression of the airbag has an important effect on the acceleration and rebound of the head.

Considering this and the results from the drop test into account, a depression distance parameter is introduced. When an impactor hits the airbag, the kinetic energy will be absorbed by the airbag. However, the faster this happens there will be a lower chance of collision of the human body to the interior parts of the vehicle. The depression distance is the traveling distance of the dummy's head into the airbag from the outer fabric at the time of impact until the head velocity becomes zero. As a fact, the airbag is considered collapsed if this distance is equal to the strap length. If the airbag fails, the head will hit the interior parts and the damage could be fatal. The depression distance is shown by a two-head arrow in Figure 1 and was selected as an objective function [11].

3.1.2. Deceleration peak

As the driver collides the airbag, several restraint systems will be causing the head deceleration. The airbag acts as one of these restraint systems and the reaction force on the head causes the deceleration. The deceleration peak was represented in this study to define the maximum force exerted on the driver's head, which was one of the parameters affecting the head injury criterion. The HIC was calculated by the resultant acceleration of the head *a(t)* that was measured at its center of gravity. It is represented as the units of acceleration (9.81 m/s^2) during the time interval of 36(ms), which is known as HIC$_{36}$:

$$HIC = max\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5} (t_2 - t_1) \tag{1}$$

$$a(t) = \left(a_x^2 + a_y^2 + a_z^2\right)^{1/2}$$

4. Design of Experiments

The design of experiments is a technique of defining and investigating all possible conditions in an experiment involving multiple factors. This technique is relevant to the full factorial design. Table 3 shows the four factors used in the analysis of DOE and each design parameter has three levels which donate by -1, 0 and 1 (minimum, mean, maximum respectively).

Table 3: Varying parameters and their levels considered for the finite element simulations

Factors	Min (level −1)	Mean (level 0)	Max (level 1)
A	520	660	710
B	188	228	268
C	20	30	40
D	0.6	1	1.4

The strap length is the maximum allowable height of the airbag and is limited by two straps on each side of the airbag.

The diameter of the airbag shows the unfolded airbag volume with respect to the inlet and outlet mass flow rates and strap length, the final pressure can be defined.

The vent diameter represents the output mass flow rate form the airbag. In this study, two vents were considered to maintain the symmetry of the model on both sides of the inflator.

The inflator mass flow is the main parameter to evaluate the airbag pressure in each state. It fully depends on the inflator function, but a commonly used mass flow chart described in several papers are used in this study [10, 13].

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Factor (D) represents the differentiation ratio from the mean value.

5. Taguchi Methods

The Taguchi method is an analytical method widely used in the design of engineering products and processes. This method is most effective when applied to experiments with multiple factors. Additionally, it is proposed for improving the quality of products and processes where the efficiency depends on many factors.

The logarithmic transformation of the results in terms of S/N ratios allows the prediction of improvement in performance from the analysis. The S/N ratio expresses the scatter around a target value. There are three levels for analysis: the larger is better, the nominal is the best, or smaller is better. In this study, “the smaller is better” was used as shown in equation 2, because the purpose of this study was to minimize the head deceleration peak and the depression distance. The S/N ratio can be expressed as the following equation [14]:

$$\eta = -10\, log_{10}(\frac{1}{n}\sum_{i=1}^{n} y_i^2) \tag{2}$$

Where y_i is the value of the responses at the i^{th} experiment of the deceleration peak or the depression distance. n is the number of test simulations, and η is the S/N ratio.

6. Analysis Of Variance (ANOVA)

The analysis of variance (ANOVA) is a standard statistical technique that is used to provide a measure of confidence in all the factors in the test design. In the analysis, many quantities such as sums of squares (*SS*), mean square (*MS*), F-value, and percent of contribution can be computed as depended on the following equations. SS_T is the total sum of squared deviations from the total mean S/N ratio (η_n) can be shown as follows [16]:

$$SS_T = SS_d + SS_e \tag{3}$$

$$SS_T = \sum_{i=1}^{n_i} (\eta_i - \eta_n)^2 \tag{4}$$

where n_i is the number of experiments of orthogonal array and η_i is the mean S/N ratio for the i^{th} experiment. In ANOVA there is an important relationship to calculate the distribution percentage $P(\%)$ and can be computed as below:

$$P(\%) = \frac{SS_d}{SS_T} * 100 \tag{5}$$

where SS_d is the sum of squared deviations and SS_e is the sum of squared error.

In this study, the ANOVA was utilized to analyze the effects of dimeter of airbag, strap length, vent, and mass flow rate. While the orthogonal array L81 was used in the design of the experiment of this study, any function could be expressed by a linear function regarded as a proportionality. The linear function can be derived by [15, 17]:

$$\{Y\} = \{X\}\{\beta\} \tag{6}$$

where $\{X\}$ listed in factors of Table 3 and is the parameter matrix corresponding to the chose orthogonal array (OA) and $\{Y\}$ is the response of lumped mass in 81 states of experiments.$\{\beta\}$ is known as the coefficient of influences.

Hence, the matrix {Y} and {X} data was extracted from the finite element method by using the DOE, the main purpose is to obtain the coefficient of $\{\beta\}$. The following equations were used to obtain this coefficient:

$$\{Y\} = \begin{Bmatrix} y_1 \\ y_2 \\ \vdots \\ . \\ y_{81} \end{Bmatrix} \qquad \{X\} = \begin{Bmatrix} 1 & \dots & 1 \\ \vdots & \vdots & \vdots \\ -1 & \dots & -1 \end{Bmatrix} \qquad \{\beta\} = \begin{Bmatrix} \beta_0 \\ \vdots \\ . \\ \beta_D \end{Bmatrix} \tag{7}$$

The least-squares estimators for β are the solution to the normal equations. To determine this coefficient following equation can be applied:

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$$\beta = (X^TX)^{-1}(X^TY) \tag{8}$$

The coefficient of influences includes the parameter β_0, which is a statistical average of the DOE outputs, and other coefficients β_A, β_B, β_C, and β_D are related to the diameter of the airbag, the length of the strap, the vents, and mass flow rate, respectively.

Table 4 is summarized the results of the simulations that are the maximum deceleration and the maximum depression of the airbag. Considering tables 2 and 3, there are 4 parameters in which every single parameter has 3 levels. Taking this and Multilevel Factorial Design into accounts, the total of the orthogonal array would be 81 designs. Eventually, all L81 had been designed and the results had been used in Taguchi and Factorial methods.

Additionally, the S/N ratio was calculated and specified for each extracted result. The full results of this table are given in the appendix A.

Table 4: The Taguchi L81 orthogonal array, simulations results, and S/N ratio

Factors					**Peak deceleration (G's)**	**S/N ratio of deceleration**	**Depression distance (mm)**	**S/N ratio of depression**
#	A	B	C	D				
1	-1	-1	-1	-1	163.411	-44.266	120.683	-41.633
2	-1	-1	-1	0	189.829	-45.567	126.575	-42.047
3	-1	-1	-1	1	212.785	-46.559	114.707	-41.192
4	-1	-1	0	-1	154.832	-43.797	144.497	-43.197
5	-1	-1	0	0	181.212	-45.164	141.905	-43.04
6	-1	-1	0	1	205.802	-46.269	127.262	-42.094
7	-1	-1	1	-1	145.648	-43.266	165.221	-44.361
8	-1	-1	1	0	171.431	-44.682	152.179	-43.647
9	-1	-1	1	1	163.411	-44.266	135.014	-42.607
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.

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7. Sled Test Simulation

This test is one of the FMVSS-208 procedures to investigate various parameters on passenger behavior and injury severity in a frontal crash. In this study, a sled test is simulated by means of a one-quarter vehicle model, 50% dummy with the three-point belt system, and the desired airbags. A reference baseline is designed based on the experimental data from Prasad investigation on the Hybrid III in a sled test [18]. Figure 2 shows a typical view of the sled test simulation in the baseline design. The excitation is applied to point O with respect to the crash pulse defined in Figure 3. An equivalent Half-sine crash pulse was evaluated and to find the excitation of the system, it was integrated twice by considering the initial condition.

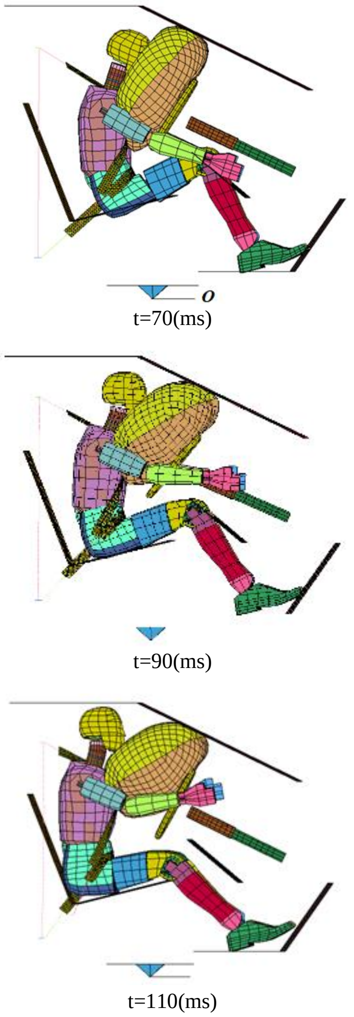

Fig. 2: Sled test simulation in three different states to visualize the driver behavior in the frontal crash form time 70(ms) to 110(ms)

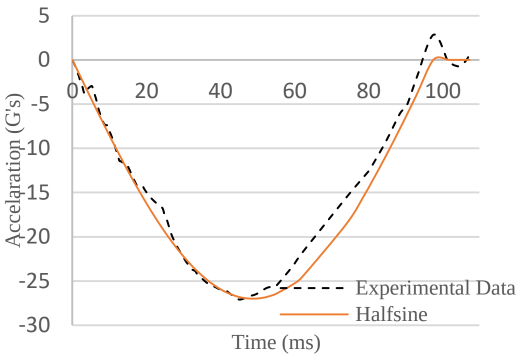

Fig. 3: Crash pulse and equivalent Half-sine pulse

The simulation and experimental results of the head deceleration are shown in Figure 4, which illustrates good conformity between the outcomes. As a result, head maximum deceleration is 64.07 (g) and the evaluated HIC_{36} is 733.6.

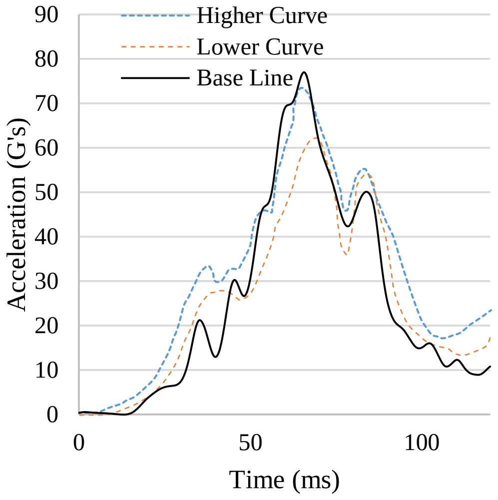

Fig 4: The Experimental and the simulation outputs comparison based on a vehicle sled test[16]

8. Results and Discussion

In the analysis of data, the average values of S/N ratio for the peak deceleration and maximum depression of the airbag were computed -46.86(dB) and -44.71(dB) respectively. Similarly, the mean values of the peak deceleration and maximum depression of lumped mass were computed 141.1(G's) and 175.32(mm) that Fig 6 exhibits the mean values. Figure 5 illustrates the effect of factors

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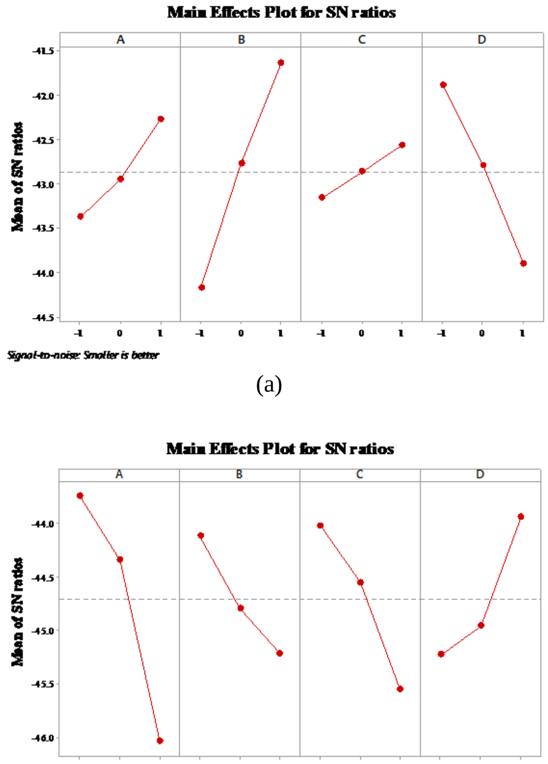
on S/N ratio for the two parameters. Figure **5** (a) shows the factor B, which is the strap of the airbag, has a significant influence on the peak deceleration. Additionally, Figure 5 (b) shows that factor A, which is the diameter of the airbags, has a weighty effect on the depression of the airbag among other factors.

Analysis of the effect of each factor (A, B, C, and D) on the peak deceleration and the maximum depression of the airbags was performed by Taguchi and ANOVA method. Table 5 is the mean response tables of the S/N ratio and Figure 5 exhibits the graphic forms of S/N ratio. Table 6 is the mean of factors and Figure 6 demonstrates the graphic forms of mean values as well.



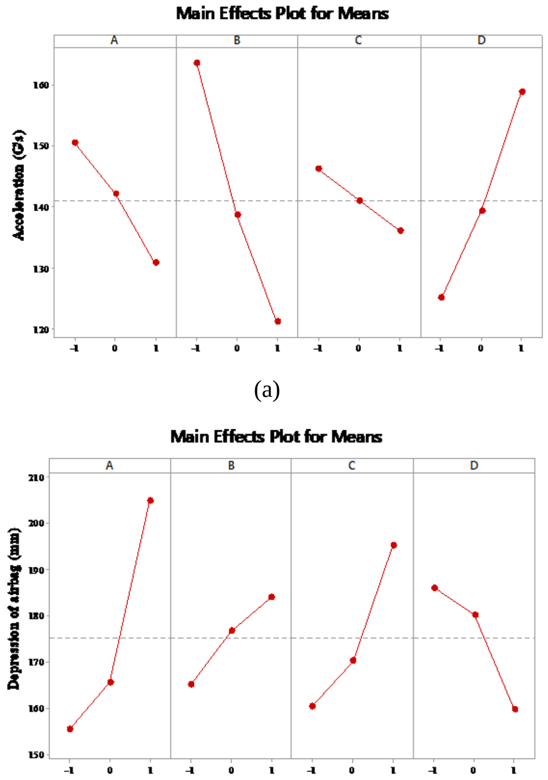
(a)

(b)

Figure 5: Effect of parameters on average S/N ratio: (a) the peak deceleration; (b) the maximum depression distance

Given the results of mean values, which are indicated in Table 6, the best design parameters for the deceleration peak were A-1 (the dimeter of airbag = 560 mm), B-1 (the strap length = 188 mm), C-1 (the vent diameter = 20 mm), D1 (the inflator mass flow= 1.4). Furthermore, the best design parameters for the depression of airbag are A1 (the dimeter of airbag = 760 mm), B1 (the strap length = 268 mm), C1 (the vent diameter = 40 mm), D-1 (the inflator mass flow= 0.6).

Therefore, to find the optimal parameters of the airbag by considering two functions of the peak deceleration and the depression of the airbag were done by optimization method.



(a)

(b)

Fig 6: Mean response graph-variation: (a) the acceleration with different process parameters. The strap (B) has the largest influence on the mean response. (b) The depression of the airbag with different process parameters. The diameter of the airbag (A) has the largest influence on the mean response.

The coefficient of influences of the various factors was calculated by using equation (5) The parameters $\{\beta\}$ for the deceleration of the lumped mass and the depression of the airbag are listed in Table 5. The results of the ANOVA of the parameters are shown in Table 7.

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Table 5: Deceleration peak and maximum depression of the airbag responses from the finite element simulations for the coefficients of influences

Deceleration peak					
Coefficient	$\boldsymbol{\beta_0}$	$\boldsymbol{\beta_A}$	$\boldsymbol{\beta_B}$	$\boldsymbol{\beta_C}$	$\boldsymbol{\beta_D}$
Values	141.09	-9.77	-21.14	-5.03	16.85
Depression distance					
Coefficient	$\boldsymbol{\beta_0}$	$\boldsymbol{\beta_A}$	$\boldsymbol{\beta_B}$	$\boldsymbol{\beta_C}$	$\boldsymbol{\beta_D}$
Values	175.32	24.66	9.40	17.37	16.85

Table 6: Response mean values table (Bold font represents the highest values)

Deceleration peak				
Factors	**A**	**B**	**C**	**D**
Level -1	**150.338**	**163.442**	**146.148**	125.082
Level 0	142.147	138.672	141.035	139.413
Level 1	130.791	121.163	136.093	**158.780**
Mean value for all	141.09			
Depression distance				
Factors	A	B	C	D
Level -1	155.503	165.218	160.482	**185.982**
Level 0	165.640	176.730	170.268	180.216
Level 1	**204.831**	**184.026**	**195.223**	159.776
Mean value for all	175.32			

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This statistical analysis is based on the 95% confidence limit for all intervals and a 5% significance level. As it was mentioned, the significance of control factors in ANOVA was determined by comparing the F-values and contribution of each factor. According to Table 7, the contribution of the diameter of the airbag, the strap length, the vent diameter, and the mass flow rate were 10.23%, 47.89%, 2.68%, and 30.35% that affected the acceleration of the lumped mass, respectively.

Table 7: Results of ANOVA for lumped mass deceleration peak

Source	DF	Sum of squares	Contribution	Mean of square	F-Value	P-Value
A	2	5203.4	10.23%	2601.7	402.15	0.000
B	2	24368.4	**47.89%**	**12184.2**	**1883.33**	**0.000**
C	2	1364.9	2.68%	682.4	105.48	0.000
D	2	15444.2	30.35%	7722.1	1193.62	0.000
A*B	4	1936.2	3.81%	484.0	74.82	0.000
A*D	4	743.9	1.46%	186.0	28.75	0.000
B*D	4	1434.5	2.82%	358.6	55.43	0.000
Error	60	388.2	0.76%			
Total	80	50883.6	100.00%			

Regarding the depression distance, according to Table 8, the contribution of the diameter of the airbag, the strap length, the vent diameter, and the mass flow rate were 33.99%, 4.5%, 16.07%, and 9.5% respectively. The depression of airbag had two interaction factors that included the interaction between the diameter of the airbag and the strap length (A*B), the interaction between the diameter of the airbag and the mass flow rate (A*D), and strap length and the mass flow rate (B*D) that contributed 3.27%, 23.68%, and 2.39% respectively. The results of the deceleration illustrated that three factors B, D and A in deceleration peak had the amounts of F-Value are 402.15, 1883.33 and 1193.62 respectively. In addition, A, C, and A*C had the F-Value of 154.51, 73.06 and 53.81 in depression distance of the airbag. These factors had the most significant effect on the outcomes.

Besides these individual factors, there is another factor in the analysis which had similarly significant criteria for analyzing called interaction. The interaction factor is the effect of two parameters or more on the results.

The deceleration of the lumped mass had two interaction factors. These were the interaction between the dimeter of airbag and tether (A*B) as well as the interaction between the dimeter of airbag and mass flow rate (A*D) that contributed 3.81% and 1.46% respectively

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Table 8: Results of ANOVA for Depression of the airbag

Source	DF	Sum of squares	Contribution	Mean of square	F-Value	P-Value
A	2	36647	**33.99%**	**18323.5**	**154.51**	**0.000**
B	2	4856	4.50%	2427.8	20.47	0.000
C	2	17329	16.07%	8664.7	73.06	0.000
D	2	10240	9.50%	5119.8	43.17	0.000
A*B	4	3523	3.27%	880.8	7.43	0.000
A*C	4	25526	23.68%	6381.5	53.81	0.000
B*D	4	2581	2.39%	645.4	5.44	0.001
Error	60	7116	6.60%			
Total	80	107818	100.00%			

9. Optimization

To optimize the design parameters following relation can be used:

$$\begin{cases} Minimize: \quad Acc(X_j), Dep(X_j) \\ \qquad X_j^L \leq X_j \leq X_j^H \end{cases} \tag{9}$$

where $Acc(X_j)$ represents the deceleration of the lumped mass and $Dep(X_j)$ is the depression of the airbag. X_j is the design variable parameter. X_j^L is the lower bound and X_j^H is the upper bound of design variables (the j index indicates the variables). The design variable parameters included the diameter of the airbag, the strap length, the vent diameter, and the mass flow rate.

Table 9 and Fig 7 show the optimal results. As shown in Table 9, the comparison between the base and optimal results showed the head deceleration reduction of 13.4% The head injury criteria had been reduced to 612.9 which is a 16.4% drop. The results showed that the parameters of the airbag had related directly to the deceleration peak and injury of the driver's head.

Table 9: Comparison of baseline and optimum

	X_1	X_2	X_3	X_4	Deceleration (G's)	HIC_{36}
Base Line	1	1	-1	0	76.988	733.6
Optimum	-1	1	-0.13	-1	66.752	612.9
Variation					13.4 %	16.45%

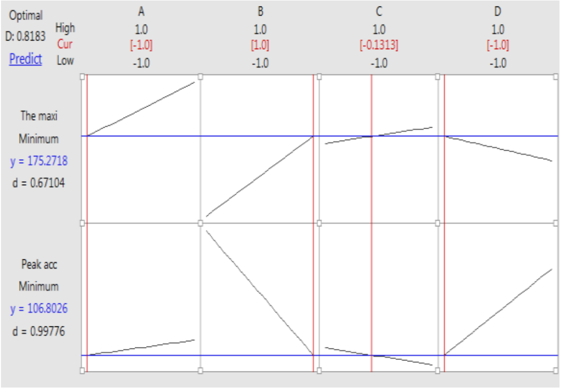

Fig 7: Obtained a set of optimum design parameters

Fig 8 shows a comparison of the results of the baseline and optimal head acceleration curves.

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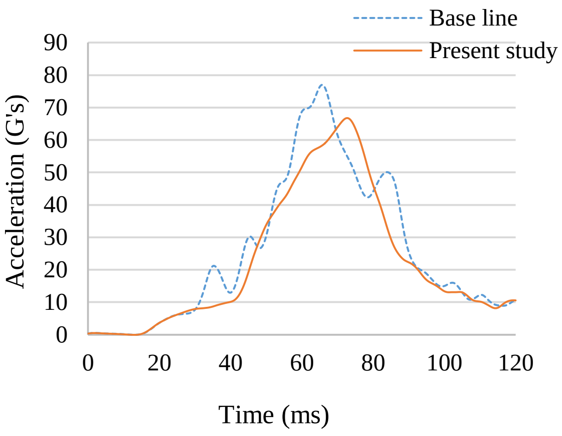

Fig 8: Comparison of the baseline and optimum of head acceleration

10. Conclusion

The airbag geometry and performance affect the occupant injury in a crash. The purpose of this study was to investigate the influence of the effective parameters of the driver airbag on the driver head injury in a frontal crash and to determine the optimum values of these parameters (the airbag diameter(A), the strap length(B), the vent diameter(C), and the mass flow rate(D)).

By using the Taguchi method, the S/N ratio and the coefficient of influences were calculated which showed the strap length (B) and the diameter of the airbag (A) had more influence on the deceleration of the driver's head and the depression distance of the airbag respectively. Furthermore, ANOVA performed to examine the influence of individual and interaction factors parameters on the quality characteristic. Therefore, the following specifics were concluded:

1. Factor B, factor D, and factor A have 47.89%, 30.35%, and 10.23%, respectively, which have also significant effects on the acceleration of impactor.

2. Factor A, factor A*C, and factor C have 33.99%, 23.68%, and 16.07% respectively, which have also a significant effect on the depression of the airbag.
3. Two combinations of $A_{-1}B_{-1}C_{-1}D_{1}$ and $A_{1}B_{1}C_{1}D_{-1}$ have a significant effect on the deceleration peak and the depression of the airbag, respectively.

In addition, the optimal responses were extracted by using an optimization method shown in Table 9.

As a result, the airbag optimal parameters were inserted into the sled-test model. Meanwhile, a sled-test frontal crash based on FMVSS-208 was simulated and the results were verified with an experimental test. The experimental test conditions were selected as the baseline in this study. By comparing the optimal and baseline results, the deceleration of the driver's head decreased by 13.4% and HIC by 16.45%.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Appendix A

The Taguchi L81 orthogonal array, simulations results, and S/N ratio full data

Item#	A	B	C	D	The deceleration peak of lumped mass (G's)	S/N ratio of the deceleration peak mass	The maximum depression of the airbag	S/N ratio of the depression of the airbag
1	-1	-1	-1	-1	163.4	-44.3	120.7	-41.6
2	-1	-1	-1	0	189.8	-45.6	126.6	-42.0
3	-1	-1	-1	1	212.8	-46.6	114.7	-41.2
4	-1	-1	0	-1	154.8	-43.8	144.5	-43.2
5	-1	-1	0	0	181.2	-45.2	141.9	-43.0
6	-1	-1	0	1	205.8	-46.3	127.3	-42.1
7	-1	-1	1	-1	145.6	-43.3	165.2	-44.4
8	-1	-1	1	0	171.4	-44.7	152.2	-43.6
9	-1	-1	1	1	197.2	-45.9	135.0	-42.6
10	-1	0	-1	-1	132.0	-42.4	144.7	-43.2
11	-1	0	-1	0	154.4	-43.8	137.0	-42.7
12	-1	0	-1	1	181.0	-45.2	132.7	-42.5
13	-1	0	0	-1	124.9	-41.9	171.4	-44.7
14	-1	0	0	0	145.3	-43.2	153.5	-43.7
15	-1	0	0	1	171.3	-44.7	149.1	-43.5
16	-1	0	1	-1	119.5	-41.6	189.7	-45.6
17	-1	0	1	0	137.8	-42.8	162.0	-44.2
18	-1	0	1	1	162.7	-44.2	157.7	-44.0
19	-1	1	-1	-1	111.7	-41.0	166.7	-44.4
20	-1	1	-1	0	125.1	-41.9	149.7	-43.5
21	-1	1	-1	1	146.1	-43.3	161.7	-44.2
22	-1	1	0	-1	108.8	-40.7	189.5	-45.6
23	-1	1	0	0	120.4	-41.6	167.0	-44.5
24	-1	1	0	1	139.3	-42.9	178.4	-45.0
25	-1	1	1	-1	106.6	-40.6	201.5	-46.1
26	-1	1	1	0	116.5	-41.3	173.8	-44.8
27	-1	1	1	1	133.5	-42.5	184.3	-45.3
28	0	-1	-1	-1	145.5	-43.3	163.3	-44.3
29	0	-1	-1	0	169.1	-44.6	164.1	-44.3
30	0	-1	-1	1	195.2	-45.8	136.9	-42.7
31	0	-1	0	-1	140.6	-43.0	166.8	-44.4
32	0	-1	0	0	162.7	-44.2	165.2	-44.4
33	0	-1	0	1	188.8	-45.5	133.9	-42.5
34	0	-1	1	-1	136.1	-42.7	172.0	-44.7
35	0	-1	1	0	156.5	-43.9	165.1	-44.4
36	0	-1	1	1	182.2	-45.2	128.4	-42.2
37	0	0	-1	-1	127.0	-42.1	175.0	-44.9
38	0	0	-1	0	142.4	-43.1	184.9	-45.3
39	0	0	-1	1	165.2	-44.4	157.5	-43.9
40	0	0	0	-1	124.0	-41.9	174.6	-44.8
41	0	0	0	0	137.6	-42.8	180.0	-45.1
42	0	0	0	1	158.7	-44.0	152.8	-43.7
43	0	0	1	-1	121.0	-41.7	172.6	-44.7
44	0	0	1	0	133.0	-42.5	169.4	-44.6
45	0	0	1	1	152.3	-43.7	141.9	-43.0
46	0	1	-1	-1	116.3	-41.3	182.5	-45.2
47	0	1	-1	0	124.5	-41.9	189.1	-45.5
48	0	1	-1	1	138.9	-42.9	182.8	-45.2
49	0	1	0	-1	113.5	-41.1	178.7	-45.0
50	0	1	0	0	120.6	-41.6	176.0	-44.9
51	0	1	0	1	133.4	-42.5	175.1	-44.9
52	0	1	1	-1	109.6	-40.8	170.9	-44.7
53	0	1	1	0	115.9	-41.3	155.5	-43.8

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54	0	1	1	1	127.2	-42.1	157.4	-43.9
55	1	-1	-1	-1	130.9	-42.3	191.6	-45.6
56	1	-1	-1	0	148.6	-43.4	172.1	-44.7
57	1	-1	-1	1	173.0	-44.8	136.4	-42.7
58	1	-1	0	-1	127.7	-42.1	216.8	-46.7
59	1	-1	0	0	143.5	-43.1	194.4	-45.8
60	1	-1	0	1	166.5	-44.4	149.6	-43.5
61	1	-1	1	-1	124.9	-41.9	298.8	-49.5
62	1	-1	1	0	138.8	-42.8	269.0	-48.6
63	1	-1	1	1	160.2	-44.1	208.4	-46.4
64	1	0	-1	-1	119.3	-41.5	176.7	-44.9
65	1	0	-1	0	128.9	-42.2	187.0	-45.4
66	1	0	-1	1	145.5	-43.3	154.2	-43.8
67	1	0	0	-1	117.7	-41.4	197.6	-45.9
68	1	0	0	0	125.9	-42.0	202.8	-46.1
69	1	0	0	1	140.6	-43.0	163.1	-44.3
70	1	0	1	-1	116.4	-41.3	281.3	-49.0
71	1	0	1	0	123.4	-41.8	277.2	-48.9
72	1	0	1	1	136.2	-42.7	225.2	-47.0
73	1	1	-1	-1	113.8	-41.1	165.7	-44.4
74	1	1	-1	0	118.3	-41.5	190.3	-45.6
75	1	1	-1	1	127.1	-42.1	168.5	-44.5
76	1	1	0	-1	113.1	-41.1	180.9	-45.1
77	1	1	0	0	116.9	-41.4	196.1	-45.8
78	1	1	0	1	124.3	-41.9	170.3	-44.6
79	1	1	1	-1	112.4	-41.0	261.6	-48.4
80	1	1	1	0	115.6	-41.3	263.9	-48.4
81	1	1	1	1	122.0	-41.7	230.9	-47.3

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