Optimization of an Automobile Curtain Airbag using Design of Experiments

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ABSTRACT

A side collision of an automobile poses a higher risk of injury compared to those of a frontal collision. Therefore governments and insurance companies establish and implement new safety standards in order to ensure the safety of the occupants throughout the world. Most of the suggested standards aim to reduce the Head Injury Criterion (HIC). Widely used side airbag systems, including the curtain airbag, are known to be the most effective means to reduce HIC, but designing a curtain airbag is a very difficult task due to the non-linear characteristics of HIC and the airbag deployment mechanism. These difficulties cause an airbag engineer to choose design variables more cautiously and seek more effective design methods. This paper introduces the curtain airbag design procedure which uses current optimization methods in order to reduce the HIC risks of the occupants. First of all, it defines various elements of the curtain airbag as design variables, performs a computer-based analysis based on the Analysis of Variance (ANOVA) technique, and then selects and defines design variables important to the head injury criterion. These defined variables and the Orthogonal Array (OA) test to reduce the head injury criterion were used. The Response Surface Method (RSM) was used as an approximation method. The results were reviewed and compared in order to find a design solution to minimize the head injury criterion. These test results will give effective design methods for curtain airbag engineers.

INTRODUCTION

A side collision of an automobile imposes a higher death rate compared to a frontal collision because an automobile does not have enough space to absorb the impact energy. Throughout the world, government agencies and private sectors are using various automobile safety standards, such as the New Car Assessment Programs (NCAP) to protect occupants from a side collision. The common objective of those safety standards and NCAP standards is to reduce the occupants' injuries, especially a head injury. In the case of a frontal collision, the structure of a car is designed to be deformed enough to absorb the collision impact energy, and it consequently provides protection to the occupants. However, in the case of a side collision, due to the structural limitation, it is impossible to install such a protective mechanism. Therefore curtain airbags are widely adopted as a protective means for the occupants.

The noticeable benefits of a curtain airbag system include the easiness of installing/activating in a narrow space and the very short deflation time. However, designing a curtain airbag system is a difficult task because of the many non-linear characteristics of related variables, including the head injury criterion and the variety of possible collision situations. In the past, researchers accomplished various studies for the curtain airbag system. Zhang and his colleagues designed an airbag system and also the kind of inflator needed to improve the curtain airbag inflation speed and in order to reduce the head injury criterion.(1) Foneseka and his colleagues performed sensitivity analysis on design parameters such as the thorax/pelvis airbag systems and the thickness of car door structures, in order to reduce the occupants injuries in a side collision.(2) Jeon and his team researched the injury patterns of dummies and their dependence on airbag design parameters.(3) Marklund and his colleagues used elements that have an influence on airbag inflation as the design parameters and applied them in order to achieve an optimum airbag design to minimize occupants' injuries.(4-6) There is a research suggesting that in the case of a side impact, generally chest and abdomen related injury parameters, such as chest compression are the most important factors to body injuries.

In existing assessment methods, the performance of an airbag is regarded satisfactory if the head injury criterion does not exceed a certain level. However, some research suggested that more attention should be given to the head injury criterion in the airbag design stage because of the newly amended United States New Car Assessment Program (U.S. NCAP) regards the level of the head injury criterion as an important factor of assessment.(9) It means that head injuries are the most influential factors on the injury distribution chart in case of death during an accident. Whereas chest and back injuries are the influential factors on the injury distribution chart in case of serious injuries during an accident.

Previous studies have identified important elements that pose an important influence on the performance of an airbag. These are Mass Flow Rate (MFR), Time to Fire (TTF), Vent Hole Area (VHA), Material Density (MD), Tether Length (TL).(10-13) Especially one study performed sensitivity analysis on these design parameters and identified MFR, TTF, and VHA as the most important design parameters.(13)

One benefit of using the Orthogonal Array (OA) table is that engineers can obtain non-continuous design values instead of continuous design values which is difficult to use in a real manufacturing stage just like an optimum design.(15-16) Moreover using orthogonal arrays in a discrete space helps engineers to obtain design results with a limited number of analysis trials because they can use fractional replication for the combination of design parameters.(12)

One of the simplest test plan strategy is known as the One-Way Table. This test table can be used when only one factor is used while multiple levels are used.(14) This table is most widely used when the rest of the influential factors, that influence the characteristics values are examined. Only one influential factor remains to be examined for its influence under a given condition. The one-way table is most commonly used if the number of levels are between 3 to 5, and the number of repetition is between 3 to 10.(17) Setting the number of levels to 3 and ±20% is done because the level of design parameters can be selected appropriately according to a given condition. Also normal design changes are limited and the design parameter values are choosen from several values.

In statistics, the response surface methodology (RSM) explores the relationships between several explanatory variables and one or more response variables. The method was introduced by Box and Wilson in 1951, and it has been studied by many other researchers recently.(17) This method is mainly used to optimize the approximation function.

In the case of analysis of occupants injuries, the response surface methodology can be a great tool to estimate HIC, an objective function, more effectively and easily.(12) In this research, PIAnO(Process Integration Automation and Optimization),(18) a commercially-sold statistical application, for optimization was used.

In this research, 4 new design parameters (gas temperature, cushion thickness, elasticity constant, and fabric leakage) and 4 already-studied design parameters (MFR, TTF, VHA, MD)were used. They were combined to perform variance analysis to analyze their influences, find/choose the most influential design parameters, and use them to design a curtain airbag that minimized the head injury criterion. In this analysis, the impact speed is set to 55 km following the side collision speed used in the Korea New Car Assessment Program (KNCAP). And this test is conducted to simulate a vehicle crash in a SLED condition. In order to construct an optimal design methodology, the orthogonal array, the one-way table and the response surface method were applied in order. Moreover, the results of each test were checked through a verification test and the optimal curtain airbag design methods to reduce head injury were introduced. The results of this research is expected to be a meaningful tool in designing the curtain airbag to protect occupants during a side crash.

Safety Standards for Side Impact

Safety Standards and Safety Level Assessment

There are two major safety standards concerning occupants' safety in a vehicle crash: automobile safety standards and new car assessment programs. Side crash safety standards include the Vehicle Safety Standard Act (article 104, Korea), FMVSS (214, U.S.), UN Regulation (95, European Union).(19) Generally, the test conditions are not severe or extreme, but if a test automobile does not satisfy the regulations, legal actions, such as a forced recall is done.

Generally new car assessment programs impose more severe test conditions compared to normal automobile safety standards, but they do not have legal binding power. Most of the automobile safety agencies have adopted a star rating system to provide safety information to the customers. There are many new car assessment programs concerning a side collisions which include KNCAP (Korea), US NCAP (U.S.), Euro NCAP (Europe), JNCAP (Japan), etc.

Side Crash Safety Test Methods

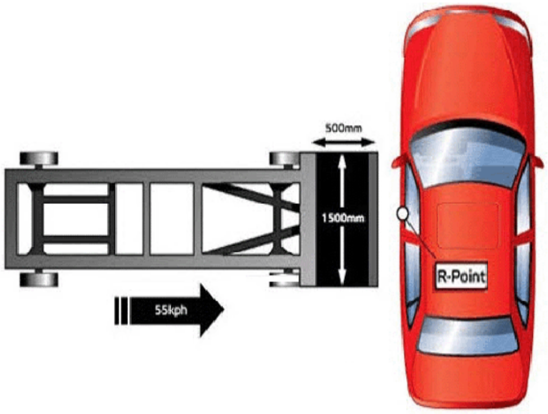

Figure 1. Side Crash Test Methods

Figure 1 shows the side crash assessment method of KNCAP. In this assessment test, a side crash mobile wall crashes into a test vehicle driver's side at 55±1 km/h perpendicular to the direction of the vehicle. Injury values such as head injury, chest injury, abdomen injury, and pelvis injury are measured. More specifically, injury values are categorized into the head injury criterion (HIC), chest compression, viscous criterion, total abdominal force and pubic symphysis force. In terms of HIC, a vehicle should have 1,000 points or lower to pass the test, and to achieve the most credit, it should have 650 points or lower.

Head Injury Criterion (HIC)

Body injury criterion is adopted in order to assess the occupant protection performance of a vehicle. The injury criterion is a physical measurement (acceleration/deceleration, impact load, changes in shape) of the human body which occurred due to the collision. HIC is the most widely used parameter in body injury assessment, and it can be calculated using the acceleration history values as shown below:

$$\text{HIC} = \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a\,dt\right]^{2.5} (t_2 - t_1) \quad (1)$$

Curtain Airbag System

Components and Activation Principles

Generally an airbag system consists of airbag modules, impact sensors, and a control unit. The airbag module includes an inflator (an inflation device for operation gas), an airbag cover, and a cushion. Impact sensors measure acceleration/deceleration of the vehicle, and they are installed in both sides of the vehicle, or in both door sides of the vehicle in the case of curtain airbags. They detect the deceleration of the vehicle when a side impact occurs and send a signal to the inflator to activate the curtain airbag.

Before inflation After inflation

Figure 2. Curtain Airbag

Finite Element Model Used for Simulation

The European side impact dummy, EUROSID II (Euro Side Impact Dummy), was used for the body analysis. This dummy model was developed to be used in side impact tests by TNO, a Dutch company, to compete with FTSS's existing modeling dummies. Side crashes were simulated following SLED test conditions to simulate the side impact of a vehicle, and collision speed was set to 55 km/h. This Finite Element Model for side impact consists of the SLED test and the dummy, specially designed for side impact. The dummy was seated wearing a seat belt on the driver's seat. In this simulation, LS-DYNA was used for finite element modeling.

Figure 3. Finite Element Module (Initial)

Figure 4. Finite Element Module (90ms)

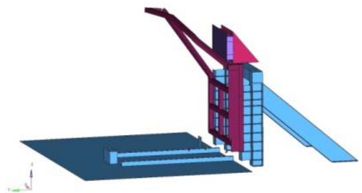

Figure 5. Finite Element Module (SLED)

Curtain Airbag Design Optimization

Design Formulation

This research defined new design parameters of the already widely identified major design parameters from previous researches for optimum design of the curtain airbag. The newly defined design parameters include fabric leakage, cushion thickness, gas temperature, and fabric elasticity constant. These 4 design parameters are used upon on 4 other previously known design parameters. These 8 parameters assumed to have ±20% of variation in reference to the reference value (100%).

Table 1. Design Parameters and Levels

	80%	100%	120%
MFR	0.0008	0.001	0.0012
TTF	6.4	8	9.6
VHA	141.28	176.6	211.92
MD	7.20E-07	9.00E-07	1.08E-06
Leakage	0.8	1	1.2
Thickness	0.248	0.31	0.372
Gas Temp	0.8	1	1.2
Elasticity Constant	0.2548	0.3186	0.3832

The objective function in this research is a minimization of HIC occurance, and the optimum design is fomulated as below:

Minimize HIC(b_1,b_2, b_3, b_4, b_5, b_6, b_7, b_8) (2)

$0.0008 \le b_1 \le 0.0012$ (2.a)

$6.4 \le b_2 \le 9.6$ (2.b)

$141.28 \le b_3 \le 211.92$ (2.c)

$7.20E\text{-}07 \le b_4 \le 1.08E\text{-}06$ (2.d)

$0.8 \le b_5 \le 1.2$ (2.e)

$0.248 \le b_6 \le 0.372$ (2.f)

$0.8 \le b_7 \le 1.2$ (2.g)

$0.2548 \le b_8 \le 0.3832$ (2.h)

Optimum Design Method and Procedure

Using the full fractorial experment technique with 8 design parameters in level 3 requires a total of 6,561 tests. However, with the help of an orthogonal array, one can find a valid solution with only 36 tests (L_{36}). An orthogonal array table is formed for the defined design parameters, and Analysis of Variance is performed to find influential design parameters. The orthogonal array table, the one-way table and the response surface method are all applied in order.

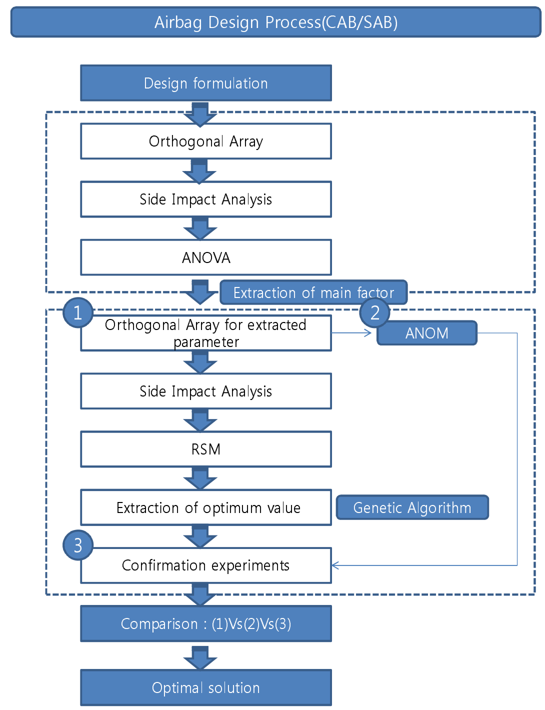

Figure 6. Optimum Design Method and Procedure

Results of Optimal Design

A design solution was found using the level 2 orthogonal array table for the 8 selected design parameters. Orthogonal array table, $L_{36}(3^8)$, was chosen and used, and the results are shown in Table 2. In the $L_{36}(3^8)$ orthogonal array table, the optimal result was found in the 30th test and HIC was 78. For the reader's reference, HIC was 255 in the validation test result while using the basic model.

Table 2. Orthogonal Array Table(L_{36})

Based on Table 2, the influence of 8 design parameters on HIC was analysed using ANOVA. As

	x1	x2	x3	x4	x5	x6	x7	x8	HIC
1	7.20E-07	0.8	0.248	0.0008	0.0064	141.28	0.8	0.25488	122
2	7.20E-07	0.8	0.248	0.0008	0.008	176.6	1	0.3186	88
3	7.20E-07	0.8	0.31	0.0012	0.0064	176.6	1.2	0.38232	201
4	7.20E-07	0.8	0.372	0.001	0.0064	211.92	1	0.38232	105
5	7.20E-07	1	0.31	0.0012	0.0096	141.28	1	0.25488	143
6	7.20E-07	1	0.372	0.001	0.0064	141.28	1.2	0.3186	148
7	7.20E-07	1	0.372	0.0008	0.0096	176.6	0.8	0.38232	108
8	7.20E-07	1	0.248	0.0012	0.0096	211.92	0.8	0.3186	111
9	7.20E-07	1.2	0.248	0.001	0.0096	176.6	1.2	0.25488	129
10	7.20E-07	1.2	0.31	0.001	0.008	141.28	0.8	0.38232	89
11	7.20E-07	1.2	0.372	0.0012	0.008	211.92	1	0.3186	157
12	7.20E-07	1.2	0.31	0.0008	0.008	211.92	1.2	0.25488	107
13	9.00E-07	0.8	0.372	0.001	0.0096	141.28	0.8	0.3186	88
14	9.00E-07	0.8	0.372	0.0012	0.0096	176.6	1	0.25488	149
15	9.00E-07	0.8	0.248	0.0008	0.0096	141.28	1.2	0.38232	112
16	9.00E-07	0.8	0.31	0.0012	0.0064	211.92	0.8	0.3186	86
17	9.00E-07	1	0.372	0.0008	0.008	211.92	0.8	0.25488	121
18	9.00E-07	1	0.31	0.001	0.008	176.6	1	0.3186	115
19	9.00E-07	1	0.31	0.001	0.0096	211.92	1.2	0.38232	142
20	9.00E-07	1	0.248	0.0012	0.008	141.28	1.2	0.25488	168
21	9.00E-07	1.2	0.248	0.0012	0.008	176.6	0.8	0.38232	113
22	9.00E-07	1.2	0.248	0.001	0.0064	211.92	1	0.25488	91
23	9.00E-07	1.2	0.372	0.0008	0.0064	176.6	1.2	0.3186	108
24	9.00E-07	1.2	0.31	0.0008	0.0064	141.28	1	0.38232	93
25	1.08E-06	0.8	0.248	0.001	0.008	211.92	0.8	0.38232	85
26	1.08E-06	0.8	0.372	0.001	0.008	176.6	1.2	0.25488	145
27	1.08E-06	0.8	0.31	0.0008	0.0096	211.92	1	0.25488	89
28	1.08E-06	0.8	0.31	0.0012	0.008	141.28	1.2	0.3186	202
29	1.08E-06	1	0.372	0.0008	0.008	141.28	1	0.38232	87
30	1.08E-06	1	0.31	0.001	0.0064	176.6	0.8	0.25488	78
31	1.08E-06	1	0.248	0.0008	0.0064	211.92	1.2	0.3186	99
32	1.08E-06	1	0.248	0.0012	0.0064	176.6	1	0.38232	128
33	1.08E-06	1.2	0.372	0.0012	0.0096	211.92	1.2	0.38232	179
34	1.08E-06	1.2	0.372	0.0012	0.0064	141.28	0.8	0.25488	103
35	1.08E-06	1.2	0.248	0.001	0.0096	141.28	1	0.3186	111
36	1.08E-06	1.2	0.31	0.0008	0.0096	176.6	0.8	0.3186	112

a result of the analysis, the magnitude of the influence of the design parameters were estimated: gas temperature (27 %), MFR (25%), cursion thickness (6%) and TTF (5%).

Table 3. Variance Analysis Results

Design variables	Effect
b1	5.21%
b2	4.73%
b3	6.56%
b4	25.79%
b5	5.23%
b6	4.43%
b7	27.44%
b8	0.21%
interaction	20.39%
TOTAL	100.00%

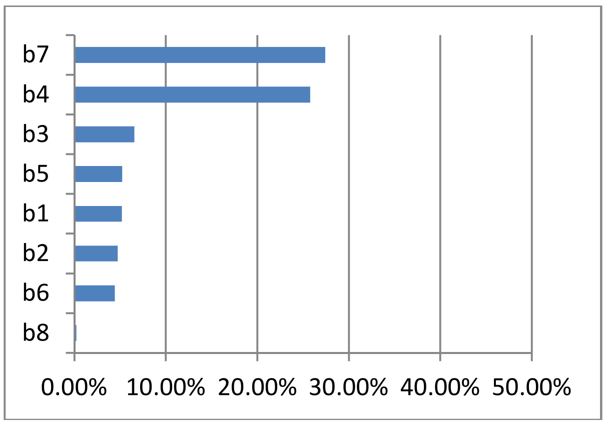

Figure 7. Variance Analysis Results

After completing ANOVA analysis, the 4 most influential design parameters were found, and a design solution was found using the $L_{18}(3^4)$ level 3 orthogonal array table. This is shown in Table 4.

Table 4. Orthogonal Array Table (L_{18})

	TTF	MFR	Temp.	Thick.	HIC
1	0.0064	0.0008	0.8	0.248	121
2	0.0064	0.0008	1	0.372	83
3	0.0064	0.001	0.8	0.372	87
4	0.0064	0.001	1.2	0.31	146
5	0.0064	0.0012	1.2	0.248	177
6	0.0064	0.0012	1	0.31	145
7	0.008	0.001	1.2	0.248	142
8	0.008	0.001	1	0.31	110
9	0.008	0.0012	1	0.248	140
10	0.008	0.0012	0.8	0.372	108
11	0.008	0.0008	0.8	0.31	118
12	0.008	0.0008	1.2	0.372	105
13	0.0096	0.0008	1	0.248	91
14	0.0096	0.0008	1.2	0.31	108
15	0.0096	0.0012	1.2	0.372	194
16	0.0096	0.0012	0.8	0.31	108
17	0.0096	0.001	1	0.372	112
18	0.0096	0.001	0.8	0.248	89

The optimal result was found in the second test condition of the $L_{18}(3^4)$ OA table, and it was HIC of 82. Optimal results were extracted from Table 4, added to a one-way table, and the design parameter solution was calculated and shown in Table 5. The optimal design parameter levels were level 3(TTF), level 1(MFR), level 1(gas temperature) and level 3(cushion thickness). More specifically, parameter values were 0.0096(TTF), 0.0008(MFR), 0.8(gas temperature) and 0.372 (cushion thickness). HIC was found to be 108 in the validation test. The results produced in the one-way table were worse than the results produced from the orthogonal array table because the interaction between the design parameters were not taken into consideration when the orthogonal array table method was used.

Table 5. One-way Table

	TTF	MFR	Temp.	Thick.
Level 1	126	104	105	126
Level 2	120	114	113	122
Level 3	117	145	145	114

After completing the above mentioned procedues, the reponse surface method was applied to calculate HIC using the 3rd order formula (cubic). The results of the calcuation are shown in Table 6. Candidate points were selected from Table 2 (results of the orthogonal array table) to produce the reponse surface method. After applying the response surface method for HIC calculation, optimal design parameters were found to be 0.0064(TTF), 0.0008(MFR), 1(gas temperature) and 0.372(cushion thickness) while HIC was 84. Validation tests were performed by combining the above mentioned design parameters, and HIC was found to be 213.

Table 6. Response Surface Method

	Lower	Initial	Optimal	Upper

TTF	6.40E-03	8.00E-03	6.40E-03	9.60E-03
MFR	8.00E-04	1.00E-03	8.00E-04	1.20E-03
Temp.	8.00E-01	1.00E+00	1.00E+00	1.2E+00
Thick.	2.48E-01	3.10E-01	3.72E-01	3.72E-01
HIC			84	

HIC values, calculated from $L_{36}(3^8)$ and $L_{18}(3^4)$ orthogonal array tables, one-way table, and response surface method, were tested through the validation test, and the final results were found as shown in Table 7.

Table 7 Final Results

	TTF	MFR	Temp.	Thick.	HIC
O.A.(L_{36})	0.0064	0.001	0.8	0.31	78
O.A.(L_{18})	0.0064	0.0008	1	0.372	83
O.W.T.	0.0096	0.0008	0.8	0.372	108
R.S.M.	0.0064	0.0008	1	0.372	84

As a result, optimal HIC(78) was obtained from the orthogonal array table while the design parameters were 0.0064(TTF), 0.001 (MFR), 0.8 (gas temperature) and 0.31 (cushion thickness). It means that HIC is reduced by more than 69.4 % compared to the initial reference HIC, which is 255. The optimal solution found from the reponse surface method was HIC(84), but after examining it through a validation test using design parameters, it produced the worst HIC(213).

Conclusions

In this research, the optimal design of the curtain airbag to provide safety to the occupants in a vehicle was conducted. Generally, due to the nonlinear characteristics of the airbag, head injury criterion and a variety of crash conditions, designing a curtain airbag is a difficult task. Therefore, a literary search of previous researches have been carried out to define important design parameters.

In this research, newly found design parameters were adopted upon already identified important design parameters, used in the curtain airbag design. A design solution was produced by the use of 8 design parameters, 4 of them were newly adopted, and an orthogonal array with 3 levels. Furthermore, ANOVA analysis was carried out along with orthogonal array table method to find the most important design parameters concerning HIC. The orthogonal array table, the one-way table, the response surface method were all applied in order, and the results produced from each method were tested and validated through impact simulation.

As a result, optimal HIC(78) was obtained from the orthogonal array table $L_{36}(3^8)$ while design parameters were 0.0064(TTF), 0.001(MFR), 0.8(gas temperature) and 0.31(cushion thickness). It means that HIC was reduced by more than 69.4 % compared to the initial reference HIC, which was 255. Generally the results obtained from the response surface method is supposed to be better. However, the optimal solution found from the response surface method was HIC(84), but after examining it through a validation test using design the parameters, it turned out to produce the worst HIC of 213. This unmatch was caused by the difference between continuity condition of the response surface method and the nonlinear characteristcs of the real values produced from the validation test.

Acknowledgements

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