Using a Parametric Method for Investigating Automotive Crashworthiness

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Abstract

Parametric design optimization is presented for the crashworthiness improvement of an automotive body. The thickness of principle internal parts of the automotive frontal crumple zone was employed as design variables for optimization. The objective was to improve automotive crashworthiness conditions according to the defined criterion during a full frontal impact. Using the Taguchi method, this study analyzed the optimum conditions for design objectives. The impact factors and their optimal levels were obtained by analyzing the experimental results. A full frontal impact was implemented for simulating crashworthiness in the nonlinear dynamic code, LS-DYNA.The controllable factors used in this study consisted of six internal parts of the vehicle's frontal structure in a condition that their thickness was the "design parameter". Interestingly, the optimum conditions for automotive crashworthiness occurred with 14% improvement in the performance criterion in comparison with the baseline design while several parts experienced mass reduction.

Keywords: Design optimization; Design of experiments; Automotive crashworthiness; Taguchi method

1. INTRODUCTION

Crashworthiness is defined as a measure of the vehicle's structural ability to plastically deform and yet maintain sufficient survival space for its occupants in crashes involving reasonable deceleration loads. Vehicle crashworthiness and occupant safety remain among the most important and challenging design considerations in the automotive industry.

Although still in its infancy, mathematical optimization techniques are increasingly being applied to the crashworthiness design of vehicles. Early crashworthiness studies of the mid 1980s were followed by response surface-based design optimization studies in the 1990s for occupant safety [1, 2], component-level optimization [3-5], airbag-related parameter identification [6] and for a full vehicle simulation [7-9].

Before determining an objective for the optimization of automotive crash worthiness conditions, it is better to briefly introduce types of regulations and rules in the field of passive safety which are related to designing and manufacturing the automotive body structure.

The first group includes mandatory rules (obligatory) which an automobile manufacturer is required to follow them in its products. For example, FMVSS in the United States and ECE R in the European Union.

The formation of these rules is in a way that only determines the minimum and does not make it possible to rate and compare the vehicles with each other in terms of safety. In addition, their formation date is related to previous years and no reforming trend can be observed in them.

Another group includes rules which are mainly optional although some of them are obligatory in a number of countries. The main aim is to formulate a legal framework for rating and comparing vehicles in terms of safety. NHTSA test in the United States and NCAP test in the European Union have been formulated accordingly. Moreover, this category is always being reformed; that is, by the progress of automotive industry and improvement of product safety, these rules get gradually stricter and, naturally, obtaining higher scores becomes more difficult.

Although both of these groups include a vast array of rules, they have a fundamental difference in the field of automotive passive safety.

The first group is based on static criteria (mainly, deformation) while the second one emphasizes dynamic criteria (like impact and deceleration).

Although it has been determined that deformation is not a suitable criteria for rating safety in automobiles and less deformation at the time of accidents does not absolutely mean more safety, still most academic studies focus on the optimization of this criterion.

Furthermore, considering the limitations and complexities of the simulations and analysis of dynamic responses in crash tests, few studies which have been published with regard to dynamic criteria are restricted to the research centers of a number of automotive companies.

What follows is an attempt to obtain a suitable criterion which can be selected as the optimization objective.

In NCAP and NHTSA standard frontal impact test, consideration is given to whether the original safety score should be adjusted to reflect occupant kinematic or sensitivity to acceleration changes, which might influence the protection of different-sized occupants in different seating positions.

The vehicle must have deformable, yet stiff, front structure with crumple zones for absorbing the crash kinetic energy resulting from frontal collisions by plastic deformation.The objective function, i.e. the dynamic criterion minimized in crashworthiness optimization, has been mostly related to occupant safety. For instance, the head injury criterion was used as an objective in [1]and [10] while the maximum knee force or a femur force-related was used for deriving the design optimization in [5]. The criteria related to other body parts were the rib deflection criterion or viscous criterion (rib cage), abdomen protection criterion (abdominal area) and pelvis performance criterion (pelvic area) [3]. The selection depends on the design criteria and crash type, e.g., side impact; full and partially offset frontal impact or roof crush. These evaluations consider the structural performance of a car by taking aspects like HIC into account. HIC is an abbreviation for Head Injury Criterion. The HIC value is the standardized maximum integral value of the head acceleration. The length of corresponding time interval is unlimited, a maximum of 36 ms and 15 ms for HIC, HIC_{36} and HIC_{15}, respectively. The HIC value is calculated using the following formula:

$$\mathrm{HIC} = \sup_{t_2,t_1}\left\{\left(\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a\,dt\right)^{2.5}(t_2-t_1)\right\}$$

$$a = \sqrt{a_x^2 + a_y^2 + a_z^2}$$

With the resultant deceleration of the head a in units of acceleration of gravity ($g = 9.81 m/s^2$). t_1 and t_2 are the moments during an impact for which the HIC value is the maximum value. The measured times are to be specified in seconds. The HIC(d) or Performance Criterion value is the weighted standardized maximum internal value of the deceleration and is calculated through the HIC_{36} value.

The HIC(d) value is calculated with the following formula:

$$HIC(d) = 0.75446 HIC_{36} + 166.4$$

It is obvious that the measured values of the dummy's head resultant deceleration and the resultant deceleration of the vehicle's structure are in a direct relationship, meaning that the reduction of one results in the reduction of another. Because of the limitations in crash simulation and dummy positioning in academic studies, the resultant deceleration value of the vehicle's structure was used instead of the dummy's head resultant deceleration and the objective was to minimize the relevant performance criterion (HIC(d))in order to improve the crashworthiness of the vehicle. Note that, this safety criterion is convenient but not conventional; its application was only because of its simplicity and availability and it was solely used for in demonstrating the methodology.

2. TAGUCHI METHOD

The Taguchi method [11] has been generally adopted to optimize the design parameters [12-19] because this systematic approach can significantly minimize the overall testing time and cost. Using orthogonal array specially designed for the Taguchi method, the optimum experimental conditions can be easily determined.

This study considered six controllable factors (Figure 3) with each factor having five levels. Therefore, an L_{25} (5^6) orthogonal array was chosen and the experimental conditions depending on the orthogonal array are listed in Table 1 where n is the number of repetitions under the same experimental conditions and Y represents the result of measurement, i.e. Y is the maximum resultant deceleration of the vehicle center of gravity.

Accordingly, an analysis of the signal to noise (S/N) ratio was needed for evaluating the experimental results. Three types of S/N ratio analysis are usually applicable: (1) the lower, the better (LB), (2) nominal is the best (NB) and (3) the higher, the better (HB). Because the aim of this study was to minimize the performance criterion, the S/N ratio with LB characteristics was required, which is given by:

$$\frac{S}{N_s} = -10\log_{10}\frac{1}{n}\left(\sum_{i=1}^{n} Y_i^2\right) \qquad (1)$$

Where n is the number of repetitions under the same experimental conditions and Y represents the result of measurement, i.e. Y is the performance criterion.

The analysis of mean (ANOM) statistical approach was adopted here in order to construct the optimal conditions. Initially, the mean of the S/N ratio of each controllable factor at a certain level must be calculated. For example, $(M)_{factor=I}^{level=i}$, the mean of the S/N ratio of factor Iat level i, was given by

$$(M)_{factor=I}^{level=i} = \frac{1}{n_{Ii}}\sum_{j=1}^{n_{Ii}}\left[\left(\frac{S}{N}\right)_{factor=I}^{level=i}\right]_j \qquad (2)$$

In Eq. (2), n_{Ii} represents the number of appearances of factor I at level i and $\left[\left(\frac{S}{N}\right)_{factor=I}^{level=i}\right]_j$ is the S/N ratio of factor I at level I; its appearance sequence in Table 1 is the jth. By the same measure, the mean of the S/N ratios of other factors can be determined at a certain level. Thereby, the S/N response table and figure were obtained and the optimal conditions were established. Finally, the crash simulations were carried out under these optimal conditions. In addition to ANOM, the analysis of variance (ANOVA) statistical method was also used for analyzing the influence of each controllable factor on the process of simulation. The percentage contribution of each factor, ρ_F was given by:

$$\rho_F = \frac{SS_F - (DOF_F V_{Er})}{SS_T} \times 100 \qquad (3)$$

In Eq. (3), DOF_F represents the degree of freedom for each factor, obtained by subtracting one from the number of the level of each factor (L). The total sum of squares, SS_T was given by:

$$SS_T = \sum_{j=1}^{m}\left(\sum_{i=1}^{n} Y_i^2\right) - mn\overline{(Y_T)}^2 \qquad (4)$$

Where $\overline{Y_T} = \sum_{j=1}^{m}(\sum_{i=1}^{n} Y_i)_j/(mn$, m represents the number of experiments carried out in this study and n represents the number of repetitions under the same experimental conditions. The factorial sum of squares, SS_F was given by:

$$SS_F = \frac{mn}{L}\sum_{k=1}^{L}\left(\overline{Y}_k^F - \overline{Y}_T\right)^2 \qquad (5)$$

Where $\overline{Y}_k^F$ is the average value of the measurement results of a certain factor at the *k*th level. Additionally, the variance of error V_{Er} was given by:

$$V_{Er} = \frac{SS_T - \sum_{F=A}^{D} SS_F}{m(n-1)} \qquad (6)$$

3. FULL FRONTAL CRASH OPTIMIZATION

The crash worthiness simulation contained approximately 30000 elements of a National Highway Transportation and Safety Association (NHTSA) automotive (Figure 1) undergoing a full frontal impact into a rigid 90-degree fixed barrier with the speed of 30 MPH. The automotive crash model is shown in Figure 2 for the un-deformed and deformed (time=80 ms) states.

According to Figure 2, only the frontal parts of the automotive body structure or "frontal crumple zone" were affected and deformed during the full frontal impact. Crumple zones in the automotive body structure work by managing crash energy and absorbing it within the inner and outer parts of the vehicle in the relevant zones, rather than being directly transmitted to the occupants, while also preventing intrusion into or deformation of the passenger cabin. This better protects car occupants against injury, which is achieved by the controlled weakening of sacrificial parts of the car, while strengthening and increasing the rigidity of the

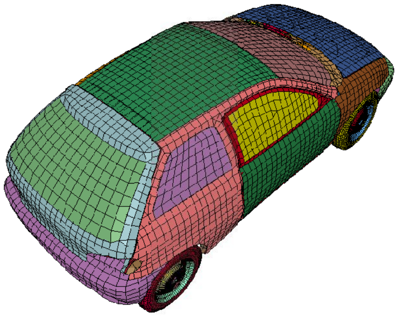

Fig. 1. Simulation model of National HighwayTransportation and Safety Association (NHTSA)

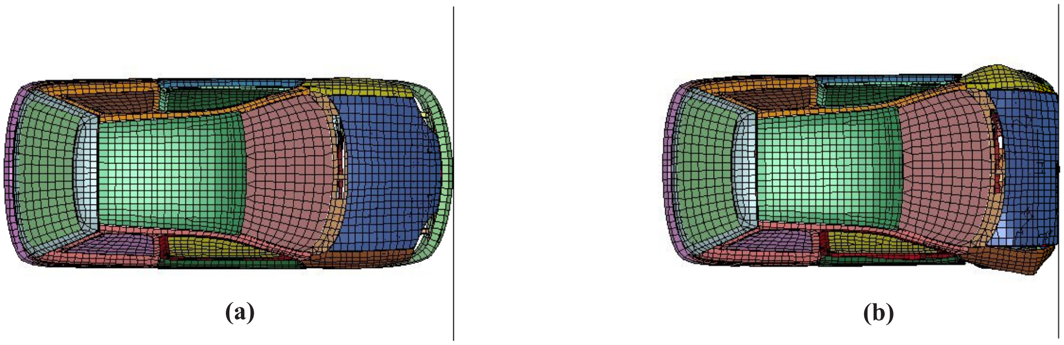
(a) (b)

Fig. 2. Crash model of the vehicle (Top View); (a) Undeformed, (b) Deformed (80 ms)

mid part of the car structure and turning the passenger cabin into a 'safety cell'.

When a vehicle and all its contents are travelling at speed, they have inertia, meaning that they want to continue forward at that direction and speed (Newton's first law of motion). In the event of a sudden deceleration of a vehicle due to an impact, unrestrained vehicle contents continue forwards at their previous speed due to inertia, and impact the vehicle interior due to gravity with a force equivalent to many times of their normal weight. The main purpose of crumple zones' optimization is to slow down the collision, to absorb energy and to reduce the speed difference between the vehicle and its occupants.

In short, a passenger whose body is decelerated more slowly due to the crumple zone over longer time survives much more often than a passenger whose body indirectly impacts a hard, undamaged car body which has come to a halt nearly instantaneously. The importance of this issue is clearly reflected in a safety criterion like HIC.

Based on the automotive simulation designed in *Politecnico di Milano* and represented by NHTSA as the standard CAE model for academic crash investigations, a group of parts consisting of six internal parts of the vehicle's foreheads structures were selected as design parameters (Figure 3). These parameters were the principle parts of the crumple zone on the automotive frontal sides. Figure 4 illustrates the locations of design parameters within a transparent automotive body.

The next step was to define design variables according to design parameters for optimization. Design parameters were the function of material property, shape and thickness. Since shape optimization usually results in the whole model revision and material selection was out of the scope of this study, thickness was selected as the design variable.

Therefore, this study focused on thickness optimization in order to improve automotive crash worthiness. Thickness of parameters with the change domain of 5% and 10% was considered as the design variable, according to which the optimization levels were arranged as shown in Table 2.

Therefore, an L_{25} (5^6) orthogonal array was chosen and the experimental conditions (Table 3) were

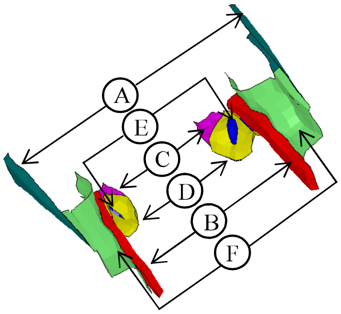

Fig. 3. Structural components selected as design parameters

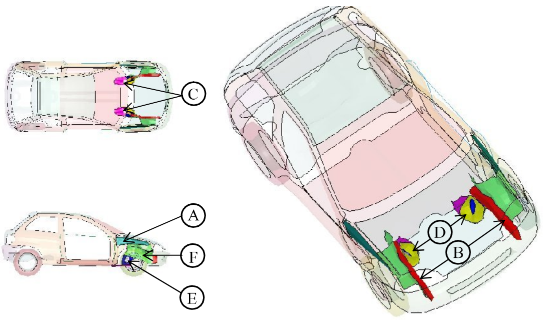

Fig. 4. Locations of design parameters within a transparent automotive body

Table 1. Test Conditions

	Factor A	Factor B	Factor C	Factor D	Factor E	Factor F
test 1	level 1	level 1	level 1	level 1	level 1	level 1
test 2	level 1	level 2	level 2	level 2	level 2	level 2
test 3	level 1	level 3	level 3	level 3	level 3	level 3
test 4	level 1	level 4	level 4	level 4	level 4	level 4
test 5	level 1	level 5	level 5	level 5	level 5	level 5
test 6	level 2	level 1	level 2	level 3	level 4	level 5
test 7	level 2	level 2	level 3	level 4	level 5	level 1
test 8	level 2	level 3	level 4	level 5	level 1	level 2
test 9	level 2	level 4	level 5	level 1	level 2	level 3
test 10	level 2	level 5	level 1	level 2	level 3	level 4
test 11	level 3	level 1	level 3	level 5	level 2	level 4
test 12	level 3	level 2	level 4	level 1	level 3	level 5
test 13	level 3	level 3	level 5	level 2	level 4	level 1
test 14	level 3	level 4	level 1	level 3	level 5	level 2
test 15	level 3	level 5	level 2	level 4	level 1	level 3
test 16	level 4	level 1	level 4	level 2	level 5	level 3
test 17	level 4	level 2	level 5	level 3	level 1	level 4
test 18	level 4	level 3	level 1	level 4	level 2	level 5
test 19	level 4	level 4	level 2	level 5	level 3	level 1
test 20	level 4	level 5	level 3	level 1	level 4	level 2
test 21	level 5	level 1	level 5	level 4	level 3	level 2
test 22	level 5	level 2	level 1	level 5	level 4	level 3
test 23	level 5	level 3	level 2	level 1	level 5	level 4
test 24	level 5	level 4	level 3	level 2	level 1	level 5
test 25	level 5	level 5	level 4	level 3	level 2	level 1

Table 3. Test Conditions

	Factor A	Factor B	Factor C	Factor D	Factor E	Factor F
test 1	0.810	1.246/1.257	1.440	1.343	1.280	0.734
test 2	0.810	1.316/1.327	1.520	1.418	1.351	0.775
test 3	0.810	1.385/1.397	1.600	1.492	1.422	0.816
test 4	0.810	1.454/1.467	1.680	1.567	1.493	0.857
test 5	0.810	1.523/1.537	1.760	1.641	1.564	0.898
test 6	0.855	1.246/1.257	1.520	1.492	1.493	0.898
test 7	0.855	1.316/1.327	1.600	1.567	1.564	0.734
test 8	0.855	1.385/1.397	1.680	1.641	1.280	0.775
test 9	0.855	1.454/1.467	1.760	1.343	1.351	0.816
test 10	0.855	1.523/1.537	1.440	1.418	1.422	0.857
test 11	0.900	1.246/1.257	1.600	1.641	1.351	0.857
test 12	0.900	1.316/1.327	1.680	1.343	1.422	0.898
test 13	0.900	1.385/1.397	1.760	1.418	1.493	0.734
test 14	0.900	1.454/1.467	1.440	1.492	1.564	0.775
test 15	0.900	1.523/1.537	1.520	1.567	1.280	0.816
test 16	0.945	1.246/1.257	1.680	1.418	1.564	0.816
test 17	0.945	1.316/1.327	1.760	1.492	1.280	0.857
test 18	0.945	1.385/1.397	1.440	1.567	1.351	0.898
test 19	0.945	1.454/1.467	1.520	1.641	1.422	0.734
test 20	0.945	1.523/1.537	1.600	1.343	1.493	0.775
test 21	0.990	1.246/1.257	1.760	1.567	1.422	0.775
test 22	0.990	1.316/1.327	1.440	1.641	1.493	0.816
test 23	0.990	1.385/1.397	1.520	1.343	1.564	0.857
test 24	0.990	1.454/1.467	1.600	1.418	1.280	0.898
test 25	0.990	1.523/1.537	1.680	1.492	1.351	0.734

obtained by combining Table 1 and Table 2.

The resultant automotive deceleration versus time curve for the baseline crash model is shown in Figure 5. By substituting the value of HIC_{36} into Performance Criterion, HIC(d)=1.787 was calculated for the baseline model.

It can be observed that, during a full frontal impact, the model suffered an immerse impulse instantly after the impact; then, this impulse dropped down at about 40 ms.

4. RESULTS AND DISCUSSION

The performance criterion of each vehicle body structure prepared in tests 1-25 was then measured as shown in previous section and its value is presented in Table 4. Substituting the number of experimental repetitions and results of the measurement (i.e. the maximum deceleration) into Eq. (1), the S/N ratio of each test condition was determined (Table 5). The boldface in Table 4 refers to the maximum value of S/N ratio among the 25 tests. Subsequently, the values of the S/N ratio were substituted into Eq. (2) and the mean of the S/N ratios of a certain factor, $(M)_{level}^{factor}$, was obtained (Table 5). In Table 5, the boldface refers to the maximum value of the mean of the S/N ratios of a certain factor among five levels, and thus it indicates the optimum conditions for the vehicle crash modelin order to minimize the performance criterion and improve automotive crashworthiness.

According to Table 5, the optimum conditions of automotive structural components are as following. (1) Parameter A thickness 0.810 mm; (2) Parameter B thickness (Left/Right)1.246/1.257 mm; (3) Parameter

Table 2. Controllable factors and their levels

Factor	Level 1 initial thickness with 10% decrease	Level 2 initial thickness with 5% decrease	Level 3 initial thickness	Level 4 initial thickness with 5% increase	Level 5 initial thickness with 10% increase
A	0.810	0.855	0.900	0.945	0.990
B(Left/Right)*	1.246/1.257	1.316/1.327	1.385/1.397	1.454/1.467	1.523/1.537
C	1.440	1.520	1.600	1.680	1.760
D	1.343	1.418	1.492	1.567	1.641
E	1.280	1.351	1.422	1.493	1.564
F	0.734	0.775	0.816	0.857	0.898

*Note that, all factors, except B, are symmetrical; thus, the left and right parts have equal thickness

Table 4. Results of the measurement and the S/N ratio of each test condition

	Factors						Y_i	S/N
	A	B	C	D	E	F		
test 1	0.810	1.246/1.257	1.440	1.343	1.280	0.734	**1.567**	**-3.8623**
test 2	0.810	1.316/1.327	1.520	1.418	1.351	0.775	1.738	-4.8010
test 3	0.810	1.385/1.397	1.600	1.492	1.422	0.816	1.672	-4.4647
test 4	0.810	1.454/1.467	1.680	1.567	1.493	0.857	1.733	-4.7760
test 5	0.810	1.523/1.537	1.760	1.641	1.564	0.898	1.841	-5.3011
test 6	0.855	1.246/1.257	1.520	1.492	1.493	0.898	1.646	-4.3286
test 7	0.855	1.316/1.327	1.600	1.567	1.564	0.734	1.659	-4.3969
test 8	0.855	1.385/1.397	1.680	1.641	1.280	0.775	1.653	-4.3655
test 9	0.855	1.454/1.467	1.760	1.343	1.351	0.816	1.771	-4.9644
test 10	0.855	1.523/1.537	1.440	1.418	1.422	0.857	1.759	-4.9053
test 11	0.900	1.246/1.257	1.600	1.641	1.351	0.857	1.666	-4.4335
test 12	0.900	1.316/1.327	1.680	1.343	1.422	0.898	1.872	-5.4461
test 13	0.900	1.385/1.397	1.760	1.418	1.493	0.734	1.629	-4.2384
test 14	0.900	1.454/1.467	1.440	1.492	1.564	0.775	1.695	-4.5834
test 15	0.900	1.523/1.537	1.520	1.567	1.280	0.816	1.798	-5.0958
test 16	0.945	1.246/1.257	1.680	1.418	1.564	0.816	1.668	-4.4439
test 17	0.945	1.316/1.327	1.760	1.492	1.280	0.857	1.761	-4.9152
test 18	0.945	1.385/1.397	1.440	1.567	1.351	0.898	1.870	-5.4368
test 19	0.945	1.454/1.467	1.520	1.641	1.422	0.734	1.664	-4.4231
test 20	0.945	1.523/1.537	1.600	1.343	1.493	0.775	1.796	-5.0861
test 21	0.990	1.246/1.257	1.760	1.567	1.422	0.775	1.565	-3.8903
test 22	0.990	1.316/1.327	1.440	1.641	1.493	0.816	1.727	-4.7458
test 23	0.990	1.385/1.397	1.520	1.343	1.564	0.857	1.770	-4.9595
test 24	0.990	1.454/1.467	1.600	1.418	1.280	0.898	1.819	-5.1957
test 25	0.990	1.523/1.537	1.680	1.492	1.351	0.734	1.766	-4.9398

C thickness1.440 mm; (4) Parameter D thickness 1.492 mm; (5) Parameter E thickness 1.422 mm; and (6)Parameter F thickness 0.734mm.

The confirmation test was carried out according to the aforementioned optimum conditions and the Performance Criterion, HIC(d) = 1.540 for optimum model is calculated (Figure 6).

The results show the 14% reduction of the performance criterion.

Under the optimum condition the thickness of four parameters was lower than their thickness in the base design and two other parameters remain in their base level without any change. These results are pretty exciting; owing to the fact that the smaller thickness sometimes corresponds to better automotive crash worthiness and of course it would result in mass reduction.

Initially, Y_K^F (the average value of the measurement results of acertain factor in the *k*th level) was obtained from Y_i in Table 3 which is listed in Table 5.

Table 5. The mean of the S/N ratios of a certain factor

Factor/Level	$\left[\left(\frac{\mathbf{S}}{\mathbf{N}}\right)^{\mathbf{Level}}_{\mathbf{factor}}\right]$	$\left[(\mathbf{M})^{\mathbf{Level}}_{\mathbf{factor}}\right]$
A/1	**-4.5810**	-4.5810
A/2	-4.5921	
A/3	-4.7594	
A/4	-4.8610	
A/5	-4.7464	
B/1	**-4.1317**	-4.1317
B/2	-4.8610	
B/3	-4.6930	
B/4	.-4.7887	
B/5	-5.0656	
C/1	**-4.6467**	-4.6467
C/2	-4.7216	
C/3	-4.7156	
C/4	-4.7943	
C/5	-4.6619	
D/1	-4.8037	
D/2	-4.7171	
D/3	**-4.6463**	-4.6463
D/4	-4.7192	
D/5	-4.6538	
E/1	-4.6271	
E/2	-4.9151	
E/3	**-4.6259**	-4.6259
E/4	-4.6350	
E/5	-4.7370	
F/1	**-4.3121**	-4.3121
F/2	-4.5453	
F/3	-4.7429	
F/4	-4.7979	
F/5	-5.1419	

By substituting Y_K^F and $Y_T = 1.722$ into Eq. (5), the factorial sum of squares, SSF was calculated individually for each factor and these are listed in Table 6. Using Eq. (4), the total sumof squares, SS_T, was determined. By inserting SSF and SST=0.5875 in Eq. (6), the variance of error, V_{Er}, was obtained.

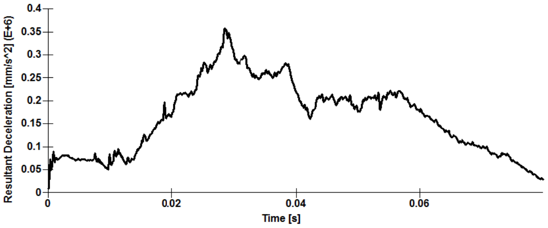

Fig. 5. Resultant deceleration versus time for the baseline design

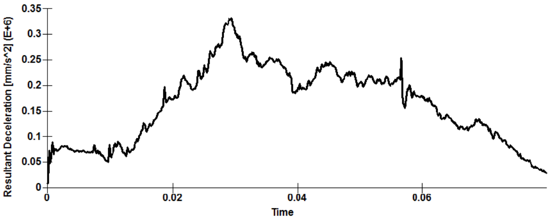

Fig. 6. Resultant deceleration versus time for the optimum condition design

Table 6. The average value of the measurement results of a certain factor in the kth level

	$\bar{Y}_K^A$	$\bar{Y}_K^B$	$\bar{Y}_K^C$	$\bar{Y}_K^D$	$\bar{Y}_K^E$	$\bar{Y}_K^F$
Level 1	1.698	1.610	1.712	1.743	1.708	1.645
Level 2	1.698	1.751	1.723	1.723	1.762	1.689
Level 3	1.732	1.719	1.722	1.708	1.706	1.738
Level 4	1.752	1.736	1.738	1.725	1.706	1.738
Level 5	1.729	1.792	1.713	1.710	1.727	1.810

Table 7. The factorial sum of squares and the percentage of contribution of each factor

Factor	SS_F	ρ_F (%)
A	0.0331	5.6283
B	0.2765	47.0718
C	0.0068	1.1553
D	0.0119	2.0268
E	0.0351	5.9678
F	0.2241	38.1500

Finally, by the substitution of SSF, SST, V_{Er}, and DOF_F=4 in the Eq. (3), the percentage contribution of each factor, ρ_F, was sequentially determined; and these values are presented in Table 7 .

According to their magnitudes, the rank order of the contribution percentage of each factor is as follows: (1) Parameter B (47.07%), (2) Parameter F (38.15%), (3) Parameter E (5.97%), (4) Parameter A (5.63%), (5) Parameter D (2.03%), and (6) Parameter C (1.16%).

Parameters B and F are the most influential factors on the deceleration of automotive body structure, among the six controllable factors.

5. CONCLUSION

This paper described the parametric optimization of a full vehicle model considering crashworthiness design criteria. Almost 14% improvement in the Performance Criterion was achieved by this method. Also, this approach resulted in the mass reduction of several parts and significantly minimized the overall testing time and cost. Moreover, the contribution percentage of each controllable factor was determined by the analysis of variance (ANOVA).

Future work will focus on further improvement of automotive crashworthiness and additional parameters such as material selection will be considered for structural parts in order to reduce weight and increase energy absorption.

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Nomenclature

L	Number of the level of each factor
n	The number of repetitions under the same experimental conditions
HIC	Head Injury Criterion
ANOM	The analysis of mean
ANOVA	The analysis of variance
$(M)_{level}^{factor}$	The mean of the S/N ratio of factor I in level i
ρ_F	The percentage contribution of each factor
DOF_F	The degree of freedom for each factor
SS_T	Total sum of squares
SS_F	Factorial sum of squares
$\overline{Y}_T$	The number of experiments carried out in this study
$\overline{Y}_k^F$	The average value of the measurement results of a certain factor in the kth level
V_{Er}	The variance of error