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Sensitivity analysis and optimization for occupant safety in automotive frontal crash test

Abstract

Nowadays, safety is a competitive advantage for automotive products and therefore receives considerable attention by automotive research centers. In this paper, a frontal crash test of sedan product of an under development platform is simulated and occupant head injuries are investigated based on ECE R94 regulation. First, an initial evaluation of the crash behavior of the sedan car is carried out and then airbag, dummy and seat belt are added to the model to study occupant head injuries under crash test. In this study, peak head acceleration and head injury criteria (HIC36) are considered as two output parameters based on ECE R94 regulation. Considering these two output parameters, sensitivity analysis and optimization are performed using Taguchi and analysis of variance (ANOVA) methods. In this way, airbag distance to dummy, trigger time, initial inflator gas temperature and tank pressure are considered as input parameters. Obtained results show that in all computer experiments designed by Taguchi responses values satisfy the requirements of ECE R94. Two different out-of-position conditions are considered by reducing the distance between dummy and airbag relative to the optimum design obtained by Taguchi. The worst case of design and its response values are also predicted using Taguchi. Finally, re-evaluating finite element analyses are performed based on the optimum and the worst cases. The results of these simulations show the validity of approach of this paper.

Keywords

Frontal crash simulation; Head injury criterion; Optimization; Sensitivity analysis; ANOVA; Taguchi

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1 INTRODUCTION

Nowadays, safety is one of the most important attributes that affects the market of automotive products. Hence, many researches have been carried out by automakers to improve the safety of their products. To provide more occupant protection, safety regulations developed for automobiles are getting stricter day by day. Vehicle safety in European Union countries is regulated mainly by international standards and regulation devised by the European Union (EU) and the United Nations Economic Commission for Europe (UN-ECE). The ECE regulations are also used in many other countries like Asian countries. ECE R94 is one of the well-known regulations which is used for frontal crash evaluation test (United Nations Economic Commission for Europe, 1998).

Actual crash testing according to the safety regulations is so expensive and time-consuming. Therefore, to evaluate the crash behavior of automobiles, before performing actual tests, computer experiments usually are carried out. According to the results of such simulations, the initial designs can be modified. There are exist previous research works in the field of automotive impact simulation. 1997 Honda Accord full and 50% offset front impact, side impact and two car impact were simulated by Cheng et al. (2001). The results demonstrated that the simulated model is compatible with these types of crash tests. Qi et al. (2006) performed front impact simulation for a commercial vehicle. They showed that by modifying material and structure of automotive front box energy absorbing capacity was improved. Deng et al. (2013) studied occupant head injuries in the car side impact test. They modeled a Dodge Neon with dummy, airbag and seat belt in LSDYNA software. After that, Deng et al. (2014) assessed human head injuries in a side impact that quantify the tensile pressures and maximum strain profiles. The crashworthiness of side doors and B pillar in a Pole Side Impact Test is evaluated by Lilehkoohi et al. (2014). The results represented that to increase the amount of absorbed energy, the part which has more influence on the

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crashworthiness of the vehicle should be taken into greater consideration. Li et al. (2015) quantitatively estimated occupant injuries in automotive crash events. They used occupant injury criteria based directly on dummy responses and compared to those based solely on vehicle responses. Shojaeefard et al. (2015) examined the validity of the extent of four different simplified models of body-in-white (BIW) from different points of views. Beik et al. (2016) assessed the effectiveness of tapering S-rails in the automotive application using finite element method. They showed the reinforcing and tapering S-rails both could improve the energy absorption and specific energy absorption in static and dynamic loading conditions. A methodological approach which uses global deformation characteristics to simplify finite element vehicle models and crash barriers is presented by Schäffer et al. (2017). Safari et al. (2017) simulated a full frontal impact, side-impact and roof crush for a Dodge Neon vehicle to assess the structural crashworthiness. They showed that Advanced High Strength Steel (AHSS) materials, due to their excellent properties, have considerable potential for assessing a vehicle's crash safety performance.

It is obvious that there are many factors affecting car safety and therefore investigating effects of each parameter separately, need so many experiences and is not actually possible. In this way, for a more precise study of different parameters and their effects, a sensitivity analysis can be used. In this regard, different approaches such as Taguchi and analysis of variance (ANOVA) are available (Shojaeefard et al., 2016; Khalkhali et al., 2017a). Using these techniques one may observe the effect of design parameters on desired or required outputs. Deng et al. (2013) used Taguchi and ANOVA methods for sensitivity analysis of two criteria including peak head acceleration and the HIC36.

In this paper, firstly the full model of the passenger car is discretized in the HyperMesh software using appropriate elements. For frontal impact simulation, the model is then imported into Pam-Crash software. All test conditions are considered according to ECE R94 regulation. After an initial evaluation, Hybrid III dummy, seat belt, and airbag are added to FE model to evaluate driver head injury in the frontal impact. Using such model, optimization and sensitivity analysis are then performed. In this analysis, four input parameters and two output parameters are considered. Airbag distance to dummy, trigger time, initial inflator gas temperature and tank pressure are considered as input parameters. Peak head acceleration and the HIC36 are also considered as output parameters. Finally, finite element re-evaluation simulation is carried out based on the optimum and the worst design obtained by Taguchi method.

2 FRONT IMPACT FINITE ELEMENT SIMULATION

In this paper frontal impact of NP01 full vehicle model which is the main product of NP0 is simulated using Pam-Crash software. NP0 is an automotive national platform which is under development in Iran University of Science and Technology. Body in white (BIW) and the full vehicle CAD model of NP01 is shown in Figure 1.

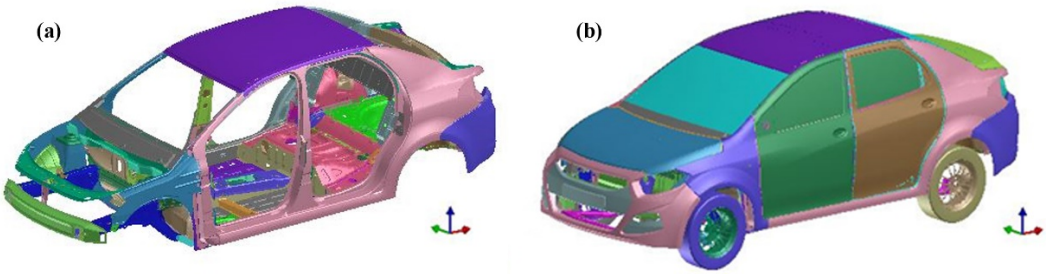

Figure 1: *NP01 CAD model: a) Body in white (BIW); b) full vehicle model*

All systems and components of the full model are meshed first in HyperMesh software and then imported in PAM-Crash. Parts in the vehicle model connected with CWELD elements as spot weld. The CWELD element is a well-known 1D element used widely for simulate the spot weld connections in the finite element method. The CWELD element fulfills the main requirements that it can connect non congruent meshes as well as congruent and the weld area is considered (Eppler and Schatz, 2007). Finite element model of NP01 is shown in Figure 2(a). Elements quality metrics are represented in Table 1. Details of the FE model are represented in Table 2. According to this table, the model consists of 3114 spot weld connections. Location of the spot welds is depicted in Figure 2(b).

Table 1: *Elements quality metrics*

kind of quality	failed
Skew	0.03%
Aspect	0.2%
jacobian	2.9%
warpage	3.9%

Table 2: *Details of NP01 finite element model*

Number of parts	246
Number of nodes	472770
Number of shells	430869
Rigid body connections	37
Spot weld connections	3114
Tied connections	91
Rigid bodies	1

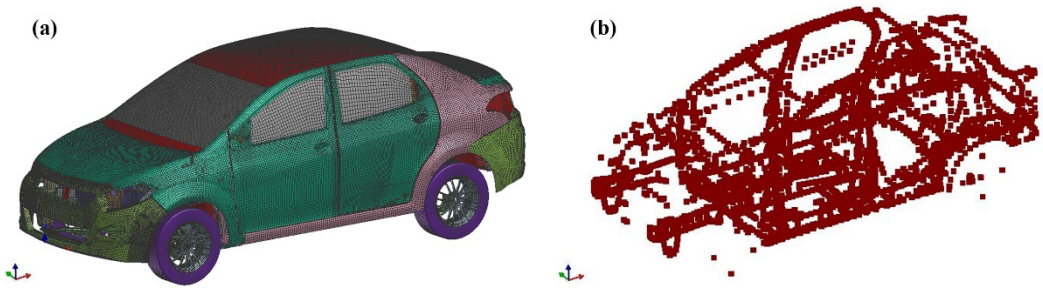

Figure 2: *a) NP01 full vehicle finite element model; b) Location of the spot welds on the NP01 BIW*

All test conditions are considered according to ECE R94 regulation. According to this regulation, test automotive velocity is considered equal to 56 km/h. The stable and deformable barrier is placed in front of the automotive with 40% offset (see Figure 3). The rigid part of barrier is fixed in three coordination. The friction coefficient between the components of the structure at impact and the friction coefficient between the structures and the barrier are considered of 0.1 and 0.3, respectively. Finite element model of the barrier includes three different parts: two front parts of the barrier are deformable made of null material and rear part of the barrier is considered rigid.

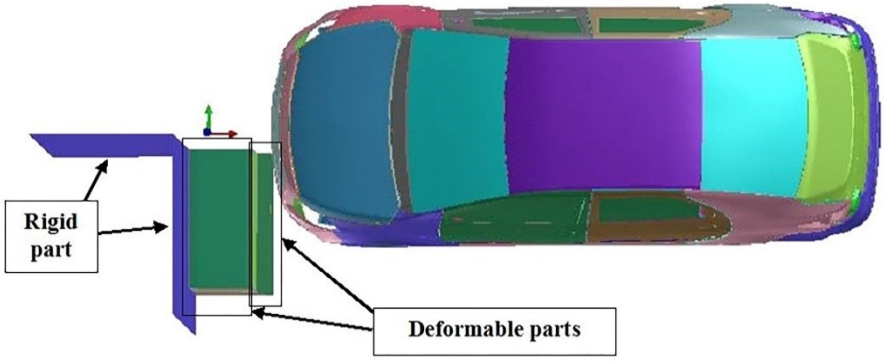

Figure 3: *Barrier's position according to ECE R94 regulation with 40% offset*

2.1 BIW constitutive materials

Three types of steel are used in NP01 body including mild steels, high strength steels (HSS) and advanced high-strength steels (AHSS). Mild steels which have low strength with high elongation capacity are used for closure parts where formability is more important than strength. HS steels which have high strength with low elongation capacity are used for the rails which are located around the passenger cabin. This is why low deformation is allowable in the automotive passenger cabin. AHSS steels which have high strength and high elongation capacity simultaneously have good energy absorbing capacity and are used for energy absorbing components like s-rails (mid rail), shot-guns (upper rail), bumper beam and crash boxes. The steel materials which are used in the NP01 with their location are shown in Figure 4.

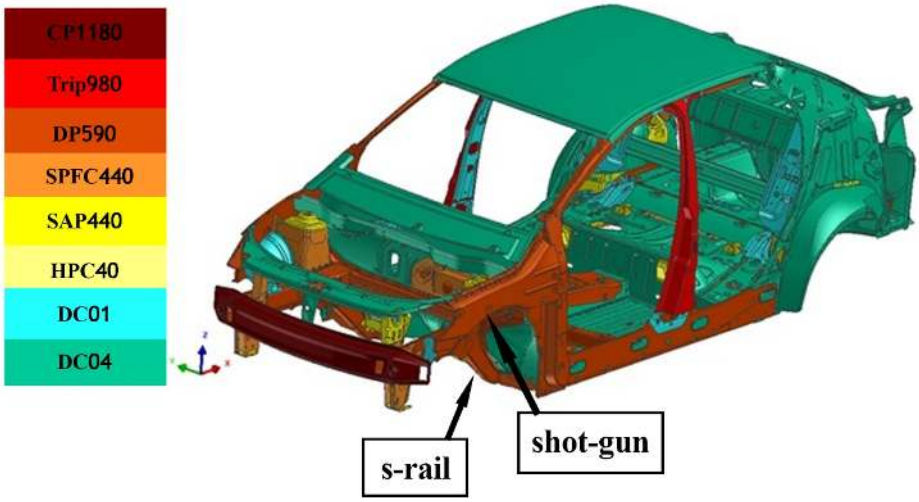

Figure 4: *Constitutive materials of NP01 BIW*

It is noteworthy that the crushing of automotive components occurs with high strain rate in a frontal impact. Therefore, constitutive materials behavior in different strain rates is needed for the simulation. Stress-strain graphs of the NP01 constitutive materials are shown in Figure 5 for different strain rates. For all steels, Young's module 210 GPa, density 7800 kg/m3 and Poisson's factor 0.3 are considered.

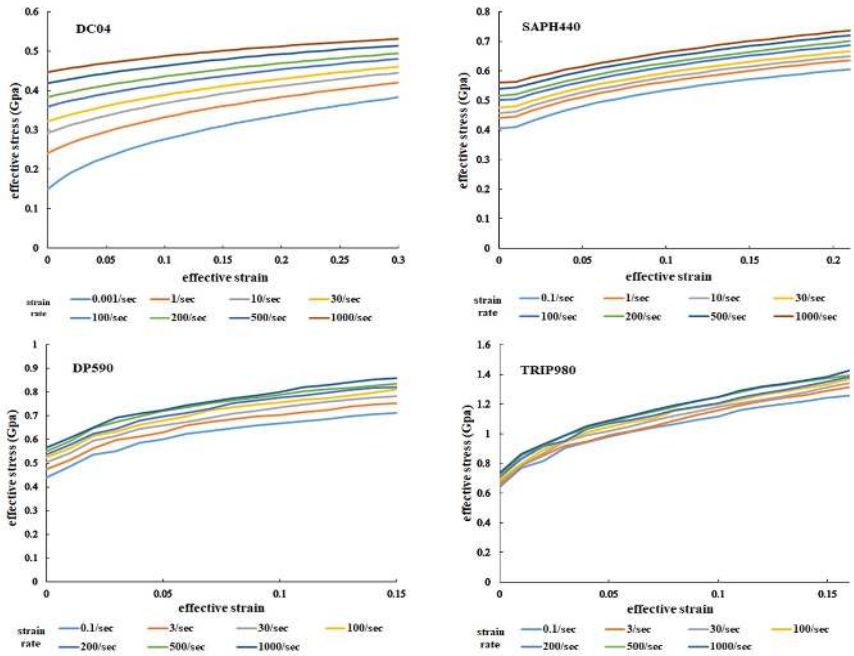

Figure 5: *Stress-strain graph of NP01 BIW constitutive materials including different strain rates (Pesco, 2017)*

After developing the finite element model, initial simulation of NP01 crash behavior is carried out according to the ECE R94. Penetration of the firewall to the cabin (see Figure 6(a)) and deflection of the hinge pillar (lower A-pillar) are then evaluated to ensure minimal deformations in the cabin zone. Values of deformations in the firewall and the hinge pillar is represented in Table 3. Location of point 1 and 2 that their deflection is reported in Table 3 are shown in Figure 6(b). This is why that in automotive body design for crashworthiness, cabin zone deformations are considered as a criterion and must be minimum (see Figure 7). Results of this evaluation show that the body deformations are in the range of the target book and the system design specification (SDS) of NP01 product. The allowed deformation in the firewall and the hinge pillar is represented in Table 3.

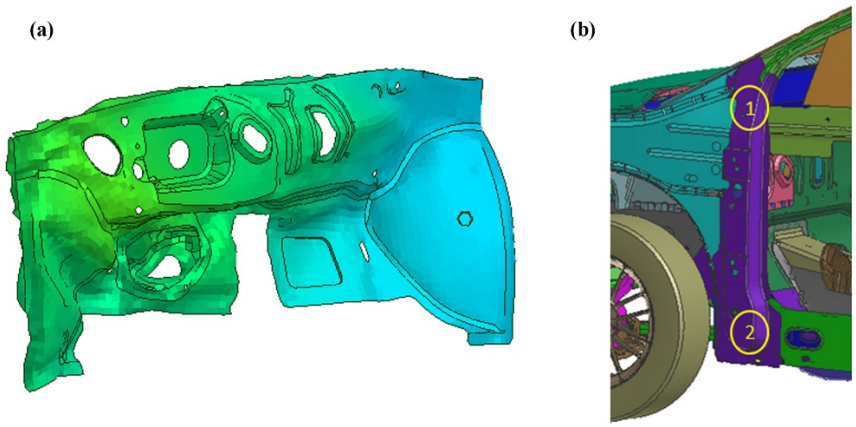

Figure 6: *a) Firewall deflection contour after crash test simulation and b) Locations of the point 1 and 2 on the hinge pillar which are used for calculating the deflection of the hinge pillar*

Table 3: *Deflection of body structure on A-pillar and firewall after crash test*

position	Structural Deformation (mm)	Allowed Deformation on the Target Book (mm)
Point1 of A-pillar	210	≤200-250
point2 of A-pillar	220	≤200-250
firewall	410	≤380-420

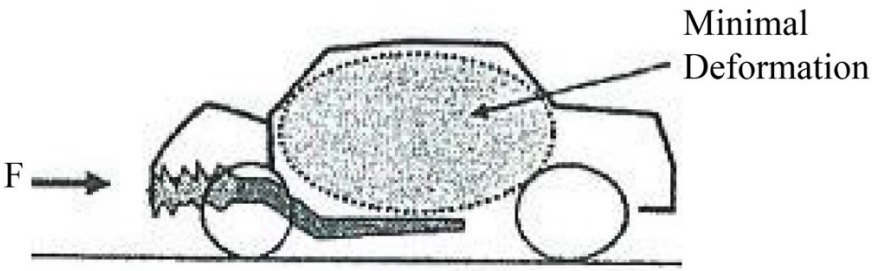

Figure 7: *Structure requirement for frontal impact (Malen, 2011)*

2.2 Properties of dummy, airbag and seat belt

After the initial evaluation of the body structure, dummy, airbag and seat belt are added to the model to evaluate the crushing performance of the test automotive using ECE R94 test procedure. Specifications of the airbag and the mass flow rate are depicted in Table 4 and Figure 8. Airbag's acceleration sensor is located on the main consul and its target value is 15 m/s. 50th percentile Hybrid III Dummy shown in Figure 9 is used in this paper. Details of dummy's model are reported in Table 5. Dummy is surrounded by a seat belt with preload of 9 to 18N. Seat belt properties used in this simulation are represented in Table 6.

Table 4: *Specifications of airbag model*

universal gas constant	8.31 j.k-1.mol-1
volume correction factor	1
the molecular fraction of the gas	1
total exhaust orifice area	3000 mm2
discharge coefficient for exhaust orifices	1
the molecular weight of the gas	0.028 KN/mol

Table 5: *Specifications of Hybrid III dummy's model*

Number of parts	50
Number of nodes	3698
Number of shells	3530
Number of joints	21

Table 6: *Properties of seat belt model*

FTOL	0.01 KN
pully ring friction coefficient	0.1
energy dissipation factor upon unloading	0.75
permanent strain factor after unloading	0.5
mass per unit length of the element	0.00013 kg/mm
strain limit for initial elastic behavior	0.01

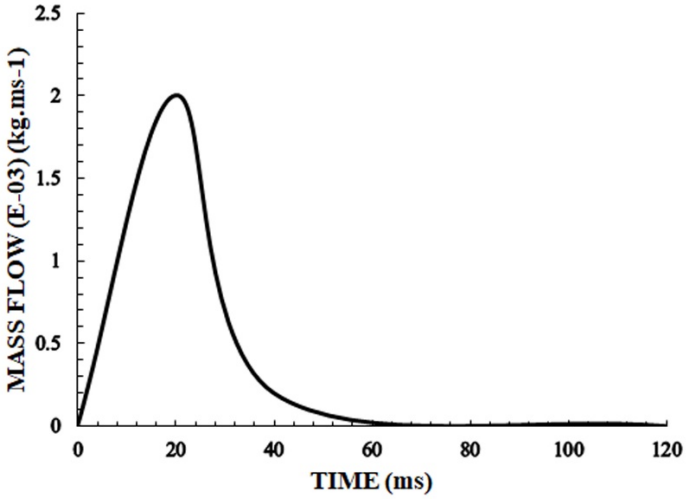

Figure 8: *The mass flow rate for airbag model*

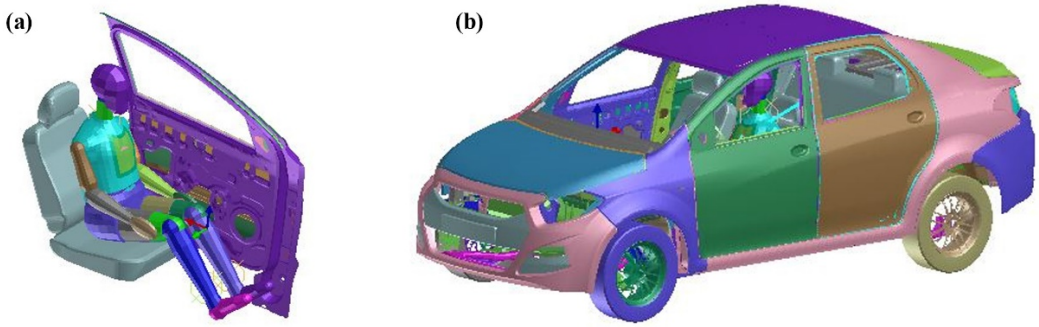

Figure 9: *a) Hybrid III 50th percentile dummy's model and b) its position on the automotive*

3 DESIGN OF EXPERIMENTS

In this paper design of experiments (DOE) is carried out using Taguchi method. Taguchi's parameter design is widely recognized as an efficient asset for robust design. It provides a practical and systematic solution to achieve optimum performance, quality, and cost based on the best selection of design parameters. In recent years, due it's high efficiency and outstanding reliability, Taguchi method has widely been recognized as a conducive optimization technique in engineering (Khalkhali et al., 2017b; Vankanti and Ganta, 2014).

According to ECE R94, the maximum head acceleration should be lower than 80 g (Liu et al., 2016). Moreover, the head performance criterion (HPC), which is also named as the head injury criterion (HIC), should not be over than 1000. The HIC36 which is used in this study as criterion can be calculated as follow (Schmitt et al., 2010):

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

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

where a is the head acceleration and t_1 to t_2 is the maximum the HIC36 period time.

In this paper, the effects of four main parameters including tank pressure, trigger time, initial inflator gas temperature and airbag distance to dummy, on peak head acceleration and the HIC36 are investigated.

Airbag distance to dummy (D): The distance between steering wheel to dummy's chest is one of the most important factors effective on injuries to the driver (Hallman et al., 2008). In fact, a driver that has less or high distance to the airbag is located out of position and it can cause significant injury to him or her. In this paper according to the body size of a human which includes short to normal men and women, three different distance level including 25 cm, 30 cm and 35 cm in considered for this factor.

Trigger time (Tt): Trigger time is the time between when the airbag sensor senses the accident and the time when the airbag starts to inflate. In this paper, according to the average of trigger time, three different times including 15, 25 and 35 ms are considered for different levels of this factor (Boran and Feltgen, 2001).

Initial inflator gas temperature (T): Airbag gas pressure and the temperature are modeled based on the ideal gas law during trigger time. According to the researches deployed on some vehicle's airbag (Im et al., 2016), three different initial inflator gas temperatures 900 k, 1000 k and 1100 k have been considered for this factor.

Tank pressure when the bag is fully inflated (P): This parameter which is an inflator property is determined using the results from an inflator tank pressure test. In the tank test, the gas generated from an inflator is charged into a fixed volume tank. The airbag inflator is triggered within a closed volume and the change in tank pressure and temperature are recorded over time (Bathe, 2001; Wang, 1991). In this paper, three levels including 100, 150 and 200 kPa are considered for the tank pressure.

To develop DOE table using Taguchi, above mentioned variables are considered as designing factors and then three different levels including low, normal and high are assigned to them. These four factors and their levels are depicted in Table 7.

Table 7: *Design factors and their levels in Taguchi analysis*

Factor	Parameter	Level 1	Level 2	Level 3
D	airbag distance to dummy	25cm	30cm	35cm
Tt	Airbag trigger time	15ms	25ms	35ms
T	Initial Inflator gas temperature	900k	1000k	1100k
P	tank pressure	100kpa	150kpa	200kpa

In the paper, the controllable factors of occupant protection in the frontal accident including the airbag distance to dummy, the Airbag trigger time, the Initial Inflator gas temperature, and the tank pressure were studied at three levels by using Taguchi L9 orthogonal array to explore their influence on the peak head acceleration and the HIC36.The design of experiments carried out using Taguchi method is represented in Table 8. According to finite element model created in section 2, the corresponding simulation for each row of orthogonal array L9 is performed and peak head acceleration and the HIC36 are calculated and reported in Table 8.

Table 8: *The design of experiments by Taguchi method response value and signal to noise values for each experiment*

Simulation number	Factors				Response		S/N ratio for peak head acceleration	S/N ratio for HIC36
	D	Tt	T	P	Peak head acceleration	HIC36		
1	1	1	1	1	45.6	140	-33.18	-42.92
2	1	2	2	2	59.6	247.6	-35.50	-47.87
3	1	3	3	3	70.4	397.5	-36.95	-51.99
4	2	1	2	3	44.3	136.5	-32.93	-42.70
5	2	2	3	1	60	256.1	-35.56	-48.17
6	2	3	1	2	58.2	241.7	-35.30	-47.67
7	3	1	3	2	35.2	84.4	-30.93	-38.53
8	3	2	1	3	36.8	88.6	-31.32	-38.95
9	3	3	2	1	47.8	165.3	-33.59	-44.37

4 RESULTS AND DISCUSSION

According to the Table 8, response value for peak head acceleration and the HIC36 for all computer experiments satisfy the criteria of 80 g and 1000 based on ECE R94 regulation. Maximum and minimum response for peak head acceleration and the HIC36 are related to the simulations 3 and 7. Side view of NP01 frontal impact simulation results at 5, 30, 55 and 75 ms for simulation 3 and 7 are shown in Figure 10. Simulation 3 has a lower airbag distance to dummy, more trigger time and tank pressure than simulation 7, but the same initial inflator gas temperature as simulation 7.

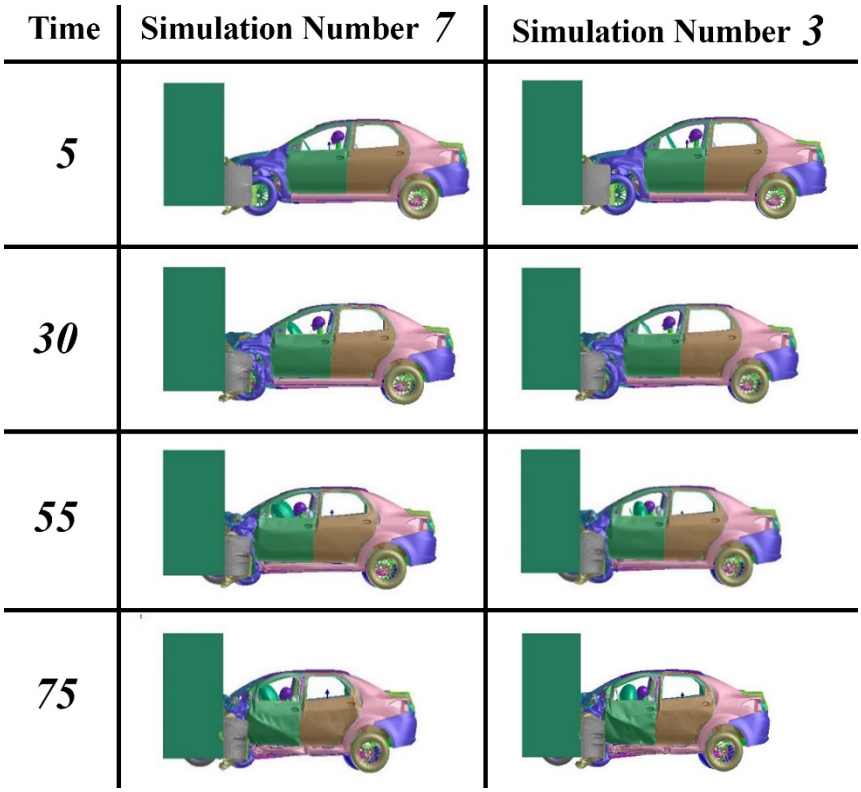

Figure 10: *Side view of NP01 frontal impact simulation results at 5, 30, 55 and 75 ms for simulation 3 and 7*

Head acceleration for all of 9 simulations is shown in Figure 11. According to this figure, peak head acceleration (see Table 9) occurs at 45 to 65 ms and the obtained graphs can be classified into three categories; first category: simulations 1, 4 and 7, second category: simulations 2, 5 and 8, third category: simulations 3, 6 and 9. Trigger time at the first, second and third category are 15ms, 25ms and 35ms, respectively. As can be seen from Figure 12, peak head acceleration occurs at around 45ms, 55ms and 65ms for first, second and third categories. Figure 12 shows the categorized response for peak head acceleration and the HIC36 respectively. Results of head acceleration show

the average of peak head acceleration increases by increasing the trigger time. Moreover, peak head acceleration and the HIC36 in each decreases by increasing airbag distance to the dummy.

Table 9: *peak head acceleration values and the corresponding time for each simulation*

simulation number	peak head acceleration (mm/ms^2)	Time (ms)
1	0.456496686	45
2	0.596122921	51
3	0.704163671	57
4	0.443487465	45
5	0.59940362	54
6	0.581631422	63
7	0.352236658	45
8	0.367575675	57
9	0.477917075	63

The Effect of trigger time and airbag distance approximately was analyzed here considering results represented in Figure 12. However, comprehensive analysis of the effects of effective parameters is not possible using such simple method. Therefore, Taguchi and ANOVA methods are used in continue.

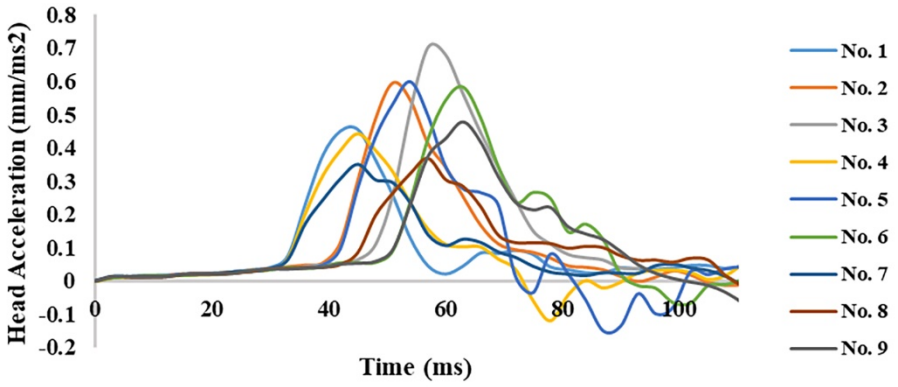

Figure 11: *Head acceleration variation versus time obtained from the simulations*

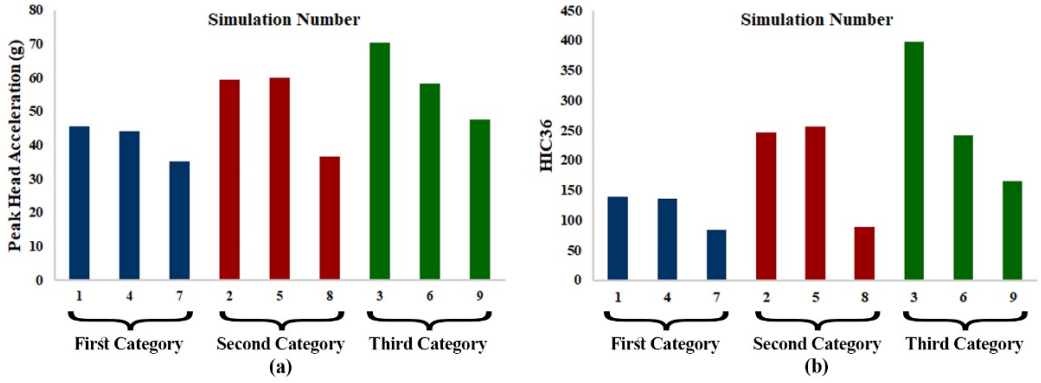

Figure 12: *a) The categories response of peak head acceleration obtained from the simulation; b) The categorized response of the HIC36 obtained from the simulation*

4.1 Taguchi analysis

Taguchi method is a designed experiment that lets you choose a product or process that functions more consistently in the operating environment to achieve optimum performance, quality and cost. Taguchi design tries to identify controllable factors that minimize the effect of uncontrollable factors which are called noise factors. A

process designed with this goal will produce more consistent output regardless of the effects of uncontrollable factors.

In recent years, due to its high efficiency and outstanding reliability, Taguchi method has widely been recognized as a conductive optimization technique in engineering (Khalkhali et al., 2017b). For this purpose, the levels of each quality factor should first be determined so can be used in designing an orthogonal array. The orthogonal array, which indicates the balance of the design, estimates the effects of factors on the response mean and variation. So each factor can be assessed independently of all the other factors. Therefore, the effect of one factor does not affect the estimation of another factors. Later, experimental results, resulted from conducting the matrix experiment, are analyzed using S/N and ANOVA analyses.

The mean value and S/N ratio play a major role in Taguchi based sensitivity analysis and optimization. The S/N ratio characteristics can be classified into three categories: the nominal- the better, the smaller-the better, and the higher-the better in a case of continuity of the quality characteristics for engineering purposes. The lower the better is used where it is desirable to minimize the output parameter, also the higher the better is employed where the higher value of the output parameter is desirable. The nominal the better is used where the nominal or target value and variation about that value are minimum. These categories correspond to different formulations for calculation of S/N ratio.

In the present investigation, the peak head acceleration and the HIC36 as two output parameters are to be minimized, thus the smaller-the better approach has been used for both based on the following formulation for calculating S/N ratio (Khalkhali et al., 2017a):

$$\frac{S}{N} = -10\log\left(\frac{1}{N}\sum_{i=1}^{n}\left(y_i\right)^2\right) \quad (2)$$

Where y_i denotes the value of each objective function, and n represents the number of repetition of each experiment.

The goal of Taguchi methods is to determine factor settings that will minimize the variability of the response about some ideal target. Taguchi methods do this by concentrates on minimizing variability. So Taguchi methods set all factors that have a significant effect on the S/N ratio at the level where the S/N is maximized. Values of S/N ratio for each computer experiment is reported in Table 8 and also Figure 13. Mean value of S/N ratio for the HIC36 and peak head acceleration are tabulated in Tables 10 and 11. Each level providing the largest S/N ratio would be considered as the optimum one.

Table 10: *Signal to noise ratio for the HIC36*

Level	T	Tt	D	P
1	-43.18	-41.38	-47.59	-45.15
2	-44.98	-45.00	-46.18	-44.69
3	-46.23	-48.01	-40.61	-44.55
Delta	3.05	6.62	6.98	0.61
Rank	3	2	1	4
optimum level	1	1	3	3
1	-43.18	-41.38	-47.59	-45.15

Table 11: *Signal to noise ratio for peak head acceleration*

Level	T	Tt	D	P
1	-33.26	-32.35	-35.21	-34.11
2	-34.01	-34.13	-34.60	-33.91
3	-34.48	-35.28	-31.95	-33.73
Delta	1.22	2.93	3.27	0.38
Rank	3	2	1	4
optimum level	1	1	3	3
1	-33.26	-32.35	-35.21	-34.11

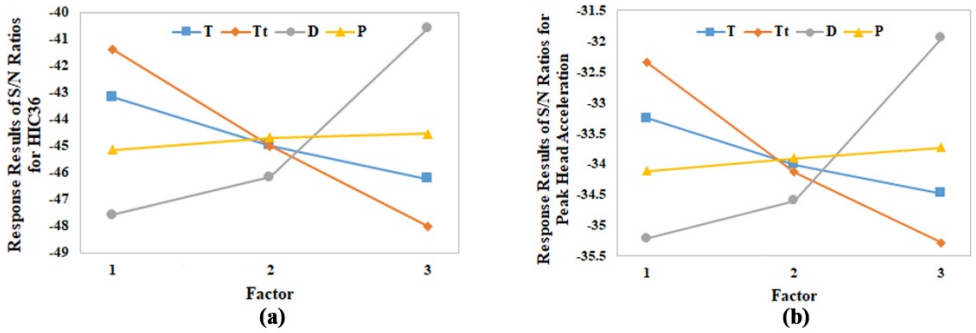

Figure 13: *a) S/N graph variation of the HIC36; b) S/N graph variation of peak head acceleration*

Mean values for the HIC36 and peak head acceleration are shown in Figure 14. It must be pointed out that in these curves, the sharper the slope of the line, the more effective that particular design parameter on output parameters. Mean values for the HIC36 and peak head acceleration are also reported in Tables 12 and 13. In these tables, the value of delta which is a difference between the maximum value and the minimum value of output, is used for sensitivity analysis. Based on the obtained results, it is evident that airbag distance to the dummy (D), trigger time (Tt), initial inflator gas temperature (T) and tank pressure (P) are ranked as the 1st to 4th dominant factor in determining peak head acceleration and the HIC36, respectively.

Table 12: *Mean response of the HIC36 Mean*

level	T	Tt	D	P
1	156.8	120.3	261.7	187.1
2	183.1	197.4	211.4	191.2
3	246.0	268.2	112.8	207.5
Delta	89.2	147.9	148.9	20.4
Rank	3	2	1	4
optimum level	1	1	3	1

Table 13: *Mean response of peak head acceleration Mean*

level	T	Tt	D	P
1	46.87	41.70	58.53	51.13
2	50.57	52.13	54.17	51.00
3	55.20	58.80	39.93	50.50
Delta	8.33	17.10	18.60	0.63
Rank	3	2	1	4
optimum level	1	1	3	3

Moreover, it is clear from Figure 14 that peak head acceleration and the HIC36 are decreased by increasing of airbag distance to the dummy. On the other hand, peak head acceleration and the HIC36 are increased by increasing in trigger time and initial inflator gas temperature. It is noteworthy that the responses change a little bit by changing in tank pressure.

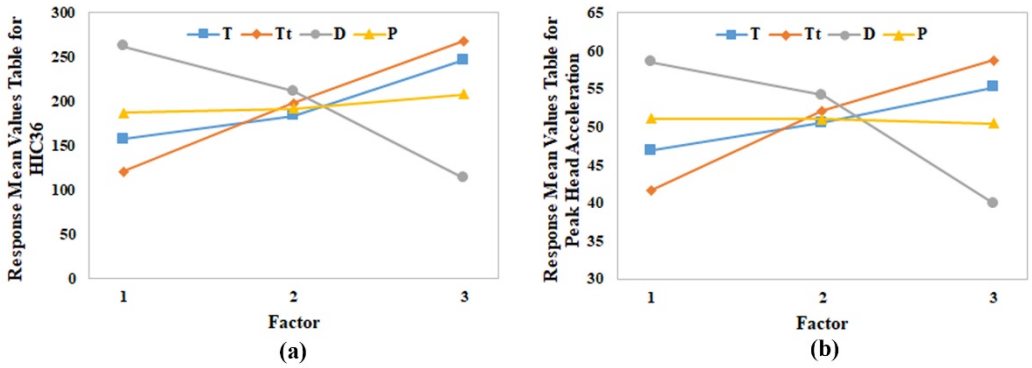

Figure 14: *a) Mean response graph variation of the HIC36; b) Mean response graph variation of peak head acceleration*

Additionally, the optimum design considering this quality becomes $D_3Tt_1T_1P_3$, meaning that from the standpoint of peak head acceleration and the HIC36 from Tables 10 and 11, the best setting is predicted provided that parameter D (airbag distance to dummy) is in the third level or 35 cm (D_3), parameter Tt (trigger time) is in the first level or 15 ms (Tt_1), parameter T (initial inflator gas temperature) is in the first level or 900 K (T_1), and finally parameter P (tank pressure) is selected in the third level or 200 KPa (P_3).

4.2 ANOVA analysis

In this study, the aim of ANOVA is an evaluation of the significance of each design parameter on peak head acceleration and the HIC36. In fact, by calculating the contribution percentage of each design parameter, this analysis can shed light on the importance of each design parameter with respect to objective functions (Khalkhali et al., 2017a). ANOVA analysis for the HIC36 and peak head acceleration are shown in Tables 14 and 15. As seen in tables, there is a statistical tool called an F test to see which design parameters have a significant effect on the quality characteristic. Usually, when $F > 4$, it means that the change of the design parameter has a significant effect on the quality characteristic. The contribution of each factor is calculated according to the sum of squares to the total sum of squares ratio. The most amount of contribution on peak head acceleration and the HIC36 is related to airbag distance to dummy with 50.7% and 42.7%, respectively. Tank pressure has very low contribution with 0.9% and 0.06%.

Table 14: *Results of ANOVA of output for the HIC36*

Factor	Sum of squares	% contribution	Degrees of freedom	Mean square
D	34443.0	42.7	2	17221.5
Tt	32817.3	40.7	2	16408.7
T	12610.0	15.6	2	6305.0
P	698.7	0.9	2	349.3
Error			0	
Total	80569.0	100	8	

Table 15: *Results of ANOVA of output for peak head acceleration*

Factor	Sum of squares	% contribution	Degrees of freedom	Mean square
D	567.62	50.7	2	283.81
Tt	445.71	39.8	2	222.85
T	104.60	9.3	2	52.30
P	0.67	0.06	2	0.33
Error			0	
Total	1118.60	100	8	

4.3 Optimum levels, out-of-position, and the worst case analysis

Based on the results obtained from Taguchi optimization process, the optimum level settings for peak head acceleration is $D_3Tt_1T_1P_3$. As a result, concerning the values listed in Table 13, the optimum peak head acceleration is predicted as follows (Tansel et al., 2011):

Predicted minimum peak head acceleration: $D_3+ Tt_1+ T_1+ P_3-3 \times (\bar{R}) = 39.93+41.70+46.87+50.50-3 \times 50.88=26.36g$

where $\bar{R}$ is an average of total responses for peak head acceleration.

Once the optimum level of the design parameters is selected, it is needed to verify the improvement of the output parameters using these optimum values. To this aim, a frontal impact simulation is performed in which peak head acceleration is calculated. The optimum value of peak head acceleration corresponding to the optimum setting of $D_3Tt_1T_1P_3$ is obtained 28.8g, which in comparison to predicted value, it is approximately equal to predicted value.

To evaluate the optimum design in out-of-position conditions some additional analysis are performed. As mentioned earlier, according to the results coming from Taguchi and ANOVA analysis, airbag distance to dummy has the most effect on the peak head acceleration. It is also obtained that the peak head acceleration is increasing by decreasing airbag distance to the dummy. Therefore, two different airbag distance to dummy is considered as out-of-position conditions. It can model simply changing in driver's seat position, according to its ability for going to front and back. Peak Head acceleration value according to changes of airbag distance to dummy while the other design factors are at the optimum point, are shown in Figure 15. It is clear from this figure that in two out-of-position points, head acceleration is in standard range and has a good sentiment.

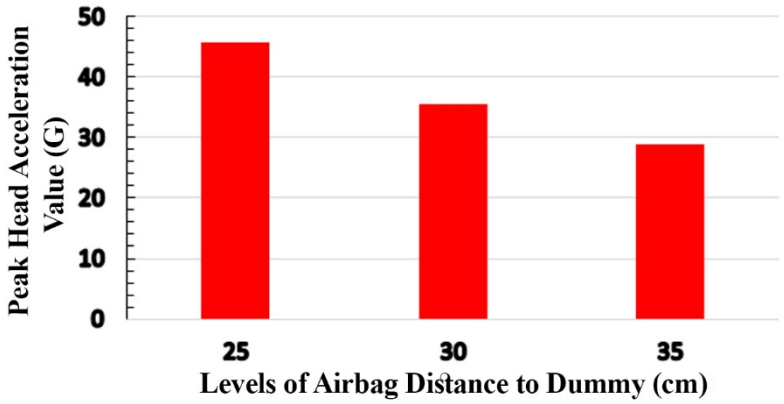

Figure 15: *Peak Head acceleration values according to changes of airbag distance to dummy while the other design factors are at optimum levels*

Obtained results show that for all 9 experiments designed by Taguchi and also two out-of-position conditions ECE R94 requirement are satisfied. In this section, the worst case of the design which is not considered in those 9 experiments is also predicted using Taguchi and re-evaluated using finite element simulation. Based on the results obtained from Taguchi, the worst level settings for peak head acceleration is $D_1Tt_3T_3P_1$. Concerning the values listed in Table 13, the worst peak head acceleration is predicted as follows:

Predicted maximum peak head acceleration: $D_1+ Tt_3+ T_3+ P_1-3 \times (\bar{R}) = 58.53+58.80+55.20+51.13-3 \times 50.88=71.02$

To verify the accuracy of the predicted value, a frontal impact simulation is performed in which peak head acceleration is calculated. The maximum value of peak head acceleration corresponding to the worst setting of $D_1Tt_3T_3P_1$ is obtained 70.3g, which in comparison to predicted value, it is approximately equal to predicted value. The agreement between simulation and predicted results for optimum and the worst cases can very well validate the accuracy of the present study. It should be noted that, in comparison with the HIC36, peak head acceleration is so close to the border of the criteria and therefore its value is only computed in this section.

5 CONCLUSIONS

In this paper, an automotive frontal impact was simulated and occupant head injury investigated based on ECE R94 regulation. In this way, Taguchi and ANOVA were used for sensitivity analysis and optimization process. The following conclusions can be drawn from this study:

- Each one of nine different designs of Taguchi array represented in this paper meets the requirements of ECE R94.
- Airbag distance to the dummy (D), trigger time (Tt), initial inflator gas temperature (T) and tank pressure (P) are ranked as the 1st to 4th dominant factor in determining peak head acceleration and the HIC36, respectively.
- Response values of Peak head acceleration and the HIC36 decrease by increasing of airbag distance to the dummy. Those response values increase by increasing in trigger time and initial inflator gas temperature. However, there is a negligible change in the response values by changing in tank pressure comparing to the other input parameters.
- Best setting provided that parameter D (airbag distance to dummy) is in the third level or 35 cm (D_3), parameter Tt (trigger time) is in the first level or 15 ms (Tt_1), parameter T (initial inflator gas temperature) is in the first level or 900 K (T_1), and finally parameter P (tank pressure) is selected in the third level or 200 KPa (P_3).
- In the case of optimum design, the driver can reduce his (or her) distance to the airbag around 10 cm without failing the ECE R94 requirements.
- The worst design was also obtained by Taguchi method. Results showed that considering values represented in this paper, ECE R94 requirements are satisfied in the worst case.

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