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Mathematical Modeling And Optimization Of Vehicle Passive Suspension System Using Full Car Model

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Abstract:
This paper presents an optimum concept to design passenger-friendly vehicle suspension system with the help of Taguchi approach. A full car suspension is considered as an illustrative example of vehicle model to demonstrate the concept and process of optimization. The experimental have been conducted by varying the stiffness of four shock absorbers (A), damping co-efficient of four shock absorbers (B), stiffness of seat (C) and damping co-efficient of seat (D) is taken as input parameters. The values of suspension parameters have been obtained by using the Taguchi design of experimental method. The implication of input parameters on seat displacement (D_S) and settling time (S_T) has been investigated by using analysis of variation. The optimum system parameters are predicted using Taguchi analysis and verified by the confirmation analysis carried out using MSC ADAMS. In addition mathematical model using regression model is done for both seat displacement (D_S) and settling time (S_T). The results show that stiffness of shock absorber and stiffness of seat spring are there most significant parameters which affect the seat displacement, while damping coefficient of. The concept proposed in this paper is applicable to generic cases, where more complex vehicle model and pavement surface condition apply.

Keywords: *full car model, mathematical modeling for full car suspension, Taguchi method, Optimization of passive suspension system.*

1.Introduction

The vibration of vehicle and seat leads to fatigue of driver and decreases driver safety and operation stability of vehicle. Hence developing improved suspension system to achieve high ride quality is one of the important ride challenges in automotive industry .Therefore the goal of vehicle suspension systems are to decrease the acceleration of car body as well as the passenger seat. In reality, some of the vehicle parameters are with uncertainties, so that it is an important issue to deal with vehicle suspension subjected to uncertain parameters in engineering application [1]. The vehicle suspension system is responsible for driving comfort and safety as the suspension carries the vehicle-body and transmits all forces between body and road [2]. It is well known that the ride characteristics of passenger vehicles can be characterized by considering the so-called “quarter-car” model [3]. This method has been widely used to investigate the performance of passive [4], semi-active [5], and fully active [6] suspension systems. Physical models for the investigation of vertical dynamics of suspension systems are most commonly built on the quarter-car model. Greater accuracy is achieved by extensions to a half [7] or full car model [8]. It is observed from the above study that optimization of suspension parameters is not done using Taguchi approach. In this paper, suspension parameters is been optimized.

2.Passive Suspension System

The commercial vehicles today use passive suspension system to control the dynamics of a vehicle’s vertical motion as well as pitch and roll. Passive indicates that the suspension elements cannot supply energy to the suspension system. The passive suspension system controls the motion of the body and wheel by limiting their relative velocities to a rate that gives the desired ride characteristics. This is achieved by using some type of damping element placed between the body and the wheels of the vehicle, such as hydraulic shock absorber.

2.1.Experimental Setup And Procedure

The experiment is simulated using MSC ADAMS software. Here a full car suspension model is been considered, added to it seat’s cushioning effect is included. The ADAMS full car model with seat suspension is shown in figure (2). The shown full car model is made to run over a speed bump. The model is scaled down to reduce the computational time. The scaled down height of bump is about 5mm. when vehicle crossing over speed breaker the maximum force acting on the spring is about 6245N. The vertical displacement of seat (D_S) and settling time (S_T) of seat is taken as objective parameters. The stiffness of the four shock absorbers (A), damping co-efficient of four shock absorbers (B), stiffness of seat (C) and damping co-efficient of seat (D) is taken as input parameters. The values of input parameters is been varied and its effect on objective parameter is studied.

The model is made to run on the testing road, which is modeled in ADAMS. The experimental parameter is given in the table (1). The design of experiments is planned by using L27 orthogonal array with 4 factors at 3 levels. The vertical displacement of the seat is calculated from the output reading from the ADAMS software by subtracting peak value, during travelling over bump with the settling displacement. The above is demonstrated in the figure (3), while the settling time is calculated by measuring the time for stabilization of seat after crossing the speed bump. The above is demonstrated in the figure (3). The graph for tire displacement is shown in the figure (4).

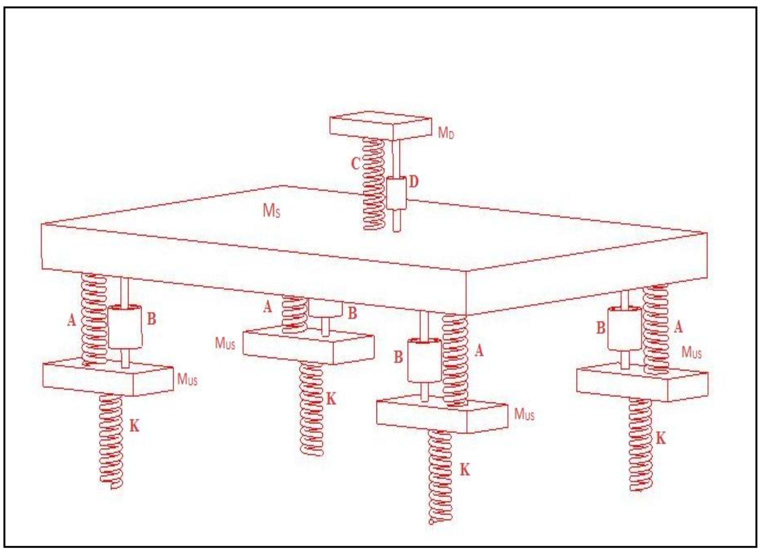

Figure 1: full car model

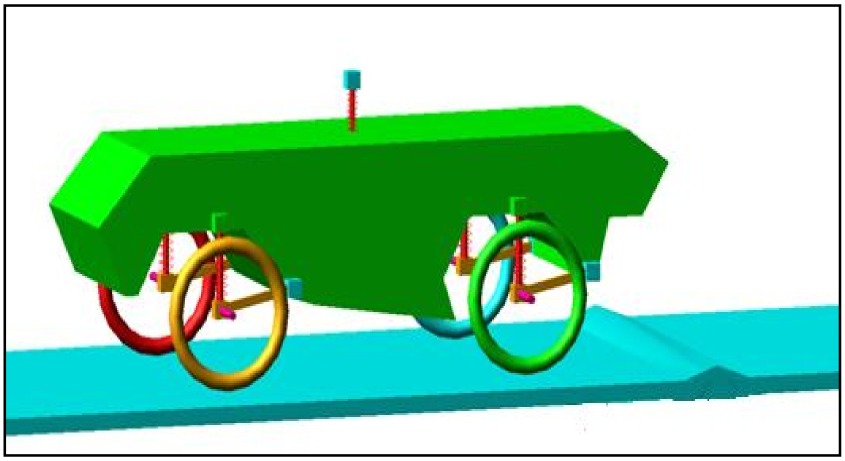

Figure 2: Full car ADAMS model

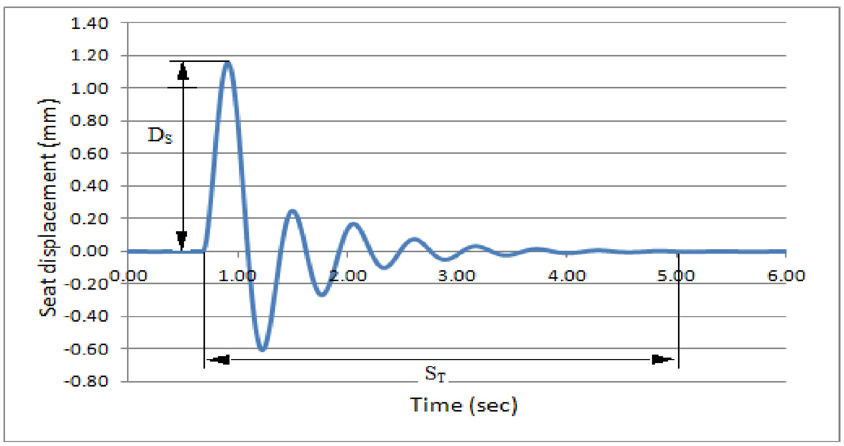

Figure 3: Demonstration graph for D_S & S_T

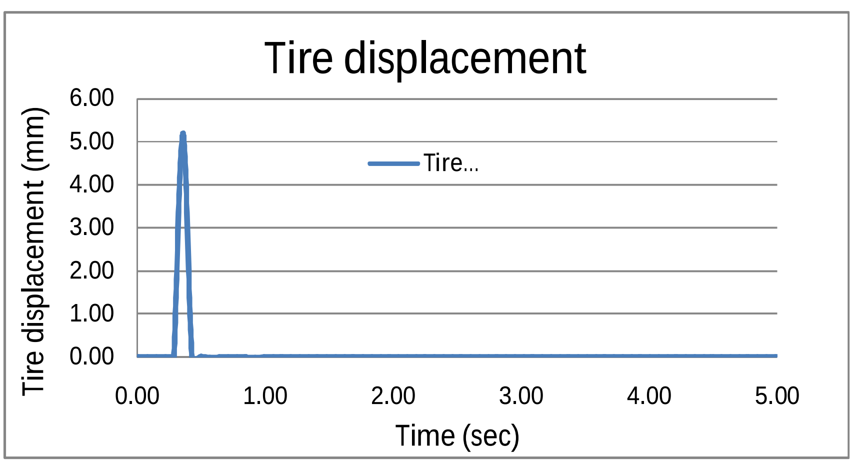

Figure 4: Input tire displacement

Experimental Parameters		
Symbol	**Value**	**Description**
M_S	2500 kg	sprung mass
M_{US}	140kg	unsprung mass
M_D	80 kg	weight of driver
D_T	5 mm	scaled down height of bump in ADAMS
K_T	100000 N/mm	stiffness of tire
A	100, 200, 300 N/mm	stiffness of each shock absorbers
B	2, 4, 6 Ns/mm	damping co-efficient of each shock absorbers
C	2, 6, 10 N/mm	stiffness of seat
D	0.2, 0.5, 0.8 Ns/mm	damping co-efficient of seat

Table 1: Experimental Parameters

Taguchi Full Car Level Table					
	units	**levels**	**level 1**	**level 2**	**level 3**
Stiffness of shock absorbers	N/mm	3	100	200	300
Damping Co-efficient of shock absorbers	Ns/mm	3	2	4	6
Stiffness of seat	N/mm	3	2	6	10
Damping Co-efficient of seat	Ns/mm	3	0.2	0.5	0.8

Table 2: Taguchi level table

2.2.Exploratory Experiments

One Variable at a Time (OVAT) is initially used for studying the vertical displacement of seat (D_S) and settling time (S_T). Here one variable at a time is varied and its effects on D_S and S_T are studied while keeping all other variables at fixed value. For each input parameter, six different levels of experiment have been done and single run is performed for each level. Though OVAT analysis doesn't provide clear picture of the phenomena over the entire range of input parameters, it accentuates some important characteristics. The range value levels for later stage experiments are decided by using this OVAT analysis.

2.3.Design Of Experiments Based On Taguchi Method

A specifically designed experimental procedure is required to identify the performance distinctiveness of system and to evaluate the effects of input parameters on objective parameters [9, 10]. The traditional methods cannot be used because, when the number of input parameters increases, large numbers of experiments have to be done [11, 12]. In this paper, Taguchi method is used to identify the optimal suspension parameters for minimum D_S and minimum S_T in full car model. In Taguchi method the process parameters are separated into two main groups. One is control factor and another is a noise factor [13, 15, and 16]. The noise factors denote all factors that cause variation and the control factors are used to select the best input parameters. Taguchi proposed orthogonal arrays to acquire the attribute data, and to analyze the performance measure of the data to decide the optimal process parameters [10, 13, and 16]. The orthogonal array forms the basis for the experimental analysis using Taguchi method. In this paper four machining parameters were used as control factors and each factor was designed to have 3 levels (Table 2). A L27 orthogonal array table with 27 rows was chosen for the experiments (table 3).

Run	**A**	**B**	**C**	**D**	**Displacement (mm)**	**Time for stabilization of seat(sec)**	**S/N ratio of displacement (db)**	**S/N ratio of time for stabilization of seat (db)**
1	100	2	2	0.2	1.38	4.84	-2.80	-13.70
2	100	2	2	0.5	1.3	3.56	-2.28	-11.03
3	100	2	2	0.8	1.33	3.92	-2.48	-11.87
4	100	4	6	0.2	1.61	5.55	-4.14	-14.89
5	100	4	6	0.5	1.45	2.61	-3.23	-8.33
6	100	4	6	0.8	1.37	2.32	-2.73	-7.31
7	100	6	10	0.2	1.77	5.27	-4.96	-14.44
8	100	6	10	0.5	1.55	2.52	-3.81	-8.03
9	100	6	10	0.8	1.39	2.11	-2.86	-6.49
10	200	2	6	0.2	2.18	5.82	-6.77	-15.30
11	200	2	6	0.5	2.01	3.64	-6.06	-11.22
12	200	2	6	0.8	1.87	4	-5.44	-12.04

Run	A	B	C	D	Displacement (mm)	Time for stabilization of seat(sec)	S/N ratio of displacement (db)	S/N ratio of time for stabilization of seat (db)
13	200	4	10	0.2	2.11	6.04	-6.49	-15.62
14	200	4	10	0.5	1.84	2.67	-5.30	-8.53
15	200	4	10	0.8	1.63	2.39	-4.24	-7.57
16	200	6	2	0.2	1.68	6.88	-4.51	-16.75
17	200	6	2	0.5	1.45	3.45	-3.23	-10.76
18	200	6	2	0.8	1.36	1.83	-2.67	-5.25
19	300	2	10	0.2	2.62	5.82	-8.37	-15.30
20	300	2	10	0.5	2.21	4.28	-6.89	-12.63
21	300	2	10	0.8	1.89	4	-5.53	-12.04
22	300	4	2	0.2	1.82	5.41	-5.20	-14.66
23	300	4	2	0.5	1.58	2.46	-3.97	-7.82
24	300	4	2	0.8	1.44	2.11	-3.17	-6.49
25	300	6	6	0.2	2.05	6.6	-6.24	-16.39
26	300	6	6	0.5	1.73	3.08	-4.76	-9.77
27	300	6	6	0.8	1.59	2.74	-4.03	-8.76

Table 3: Experimental design using L27 orthogonal array

3.Data Analysis And Discussion

The analysis of variance was used to identify the important input parameters which effects seat displacement (D_S) and settling time (S_T). In Taguchi method [13, 14, 15, 16], a loss function is used to calculate the deviation between the experimental value and the desired value. The signal-to-noise (S/N) ratio is then derived from the loss function. Lower is better (LB), nominal is best (NB), higher is better (HB) are the three types of S/N ratios available depending upon the type of characteristics. In vehicle suspension system lower seat displacement (D_S) and lower settling time (S_T) be as a sign of better ride quality. Therefore "LB" is chosen for the both seat displacement (D_S) and settling time (S_T) and it is calculated as the logarithmic transformation of the loss function as shown below.

Lower is better characteristic η_{ij} = -10 log $\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right)$ (1)

"HB" is calculated as logarithmic transformation of loss function as shown below.

Higher is better characteristic η_{ij} = -10 log $\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right)$ (2)

The greatest value of η_{ij} corresponds to the optimal level of input parameters. The above mentioned equations [1] was applied to calculate the η_{ij} values for each experiment of L27 [table 3]. On analyzing the S/N ratio, the optimal input parameters for seat displacement (D_S) was obtained at 100 N/mm stiffness of shock absorbers (level 1), 6 Ns/mm damping co-efficient of shock absorbers (level 3), 2 N/mm stiffness of seat (level 1) and 0.8 Ns/mm damping co-efficient of seat (level 3). The effect of input parameters on seat displacement (D_S) is shown in fig (5). The optimum values of settling time (S_T) was obtained at 100 N/mm stiffness of shock absorber (level 3), 4 Ns/mm damping co-efficient of shock absorber (level 2), 2 N/mm stiffness of seat (level 1) and 0.8 Ns/mm damping co-efficient of seat (level 3). The effect of input parameters on settling time (S_T) is shown in fig (6). Accurate and optimum combination of machining parameters and their relative importance on surface roughness and material removal rate was obtained using ANOVA. The result of ANOVA is shown in [tables 4, 5, 6, 7] respectively. From the fig (5) stiffness of shock absorbers and stiffness of seat are the most significant parameters which effect seat displacement (D_S), while the effects of damping co-efficient of shock absorbers and damping co-efficient of seat on seat displacement (D_S) were insignificant. From fig (6) we can conclude that damping co-efficient of shock absorbers and damping co-efficient of seat is the most significant parameter which effect settling time (S_T), while stiffness of shock absorbers and stiffness of seat have less effect on settling time (S_T).

S/N ratio response table for displacement				
	A	**B**	**C**	**D**
level 1	-3.25	-5.178	-3.367	-5.495
level 2	-4.967	-4.274	-4.821	-4.391
level 3	-5.35	-4.117	-5.382	-3.683
delta	2.1	1.06	2.015	1.812
rank	1	4	2	3

Table 4: Analysis of Variation Test for Seat displacement (D_S) using S/N ratios

Mean response table for displacement				
	A	**B**	**C**	**D**
level 1	1.46	1.865	1.482	1.913
level 2	1.792	1.65	1.762	1.68
level 3	1.881	1.6189	1.89	1.541
delta	0.421	0.246	0.408	0.372
rank	1	4	2	3

Table 5: Analysis of Variation Test for Seat displacement (D_S) using Means

S/N ratio response table for time for stabilization				
	A	B	C	D
level 1	-10.67	-12.791	-10.924	-15.227
level 2	-11.449	-10.135	-11.556	-9.791
level 3	-11.539	-10.736	-11.182	-8.645
delta	0.87	2.656	0.632	6.582
rank	3	2	4	1

Table 6: Analysis of Variation Test for settling time (S_T) using S/N ratios

Mean response table for time for stabilization				
	A	B	C	D
level 1	3.63	4.431	3.829	5.803
level 2	4.08	3.507	4.04	3.141
level 3	4.056	3.831	3.9	2.824
delta	0.45	0.924	0.211	2.979
rank	3	2	4	1

Table 7: Analysis of Variation Test for settling time (S_T) using Means

4.Mathematical Modelling

The Mathematical modeling approach is used to identify the relationship between independent variables and the associated dependent variables, and to predict the trend of dependent variables as a function of independent variables. In this paper, the seat displacement (D_S) and settling time (S_T) are independent variables, whereas suspension parameters are independent variables. The mathematical model for the seat displacement (D_S) and settling time (S_T) is shown in the equation 3, 4.

$$\begin{aligned} \text{Seat Displacement}(D_S) = {} & 0.666 + 0.00900\,A - 0.141\,B + 0.163\,C - 0.180\,D \\ & - 0.000010\,AA + 0.0286\,BB - 0.00564\,CC + 0.525\,DD \\ & - 0.000510\,AB - 0.00711\,BC - 0.0103\,CD - 0.00177\,DA \\ & - 0.0805\,BD - 0.00500\,BCD - 0.000368\,CDA + 0.000074\,ABCD \end{aligned} \tag{3}$$

$$\begin{aligned} \text{Time for stabilization of seat}(S_T) = {} & 4.57 + 0.0120\,A + 0.257\,B + 0.707\,C - 7.57\,D \\ & - 0.000038\,AA + 0.0738\,BB - 0.0229\,CC + 13.0\,DD \\ & + 0.00081\,AB - 0.106\,BC - 1.85\,CD - 0.00800\,DA \\ & - 2.16\,BD + 0.337\,BCD + 0.00438\,CDA \\ & - 0.000543\,ABCD \end{aligned} \tag{4}$$

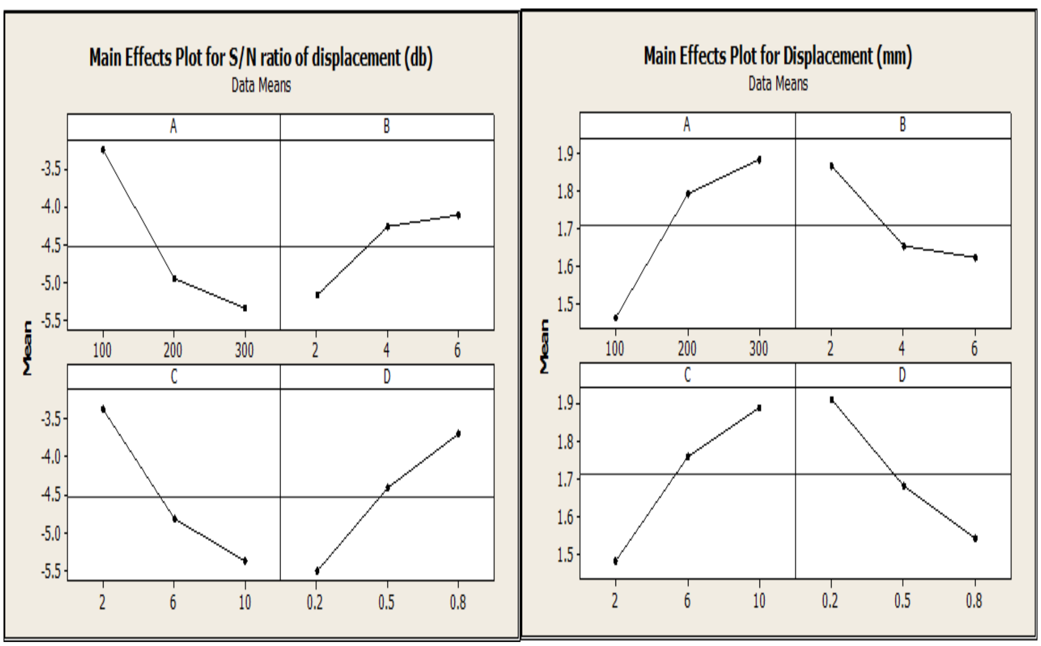

Figure 5: S/N Ratio and Mean Plot for Minimization of Seat displacement (D_S)

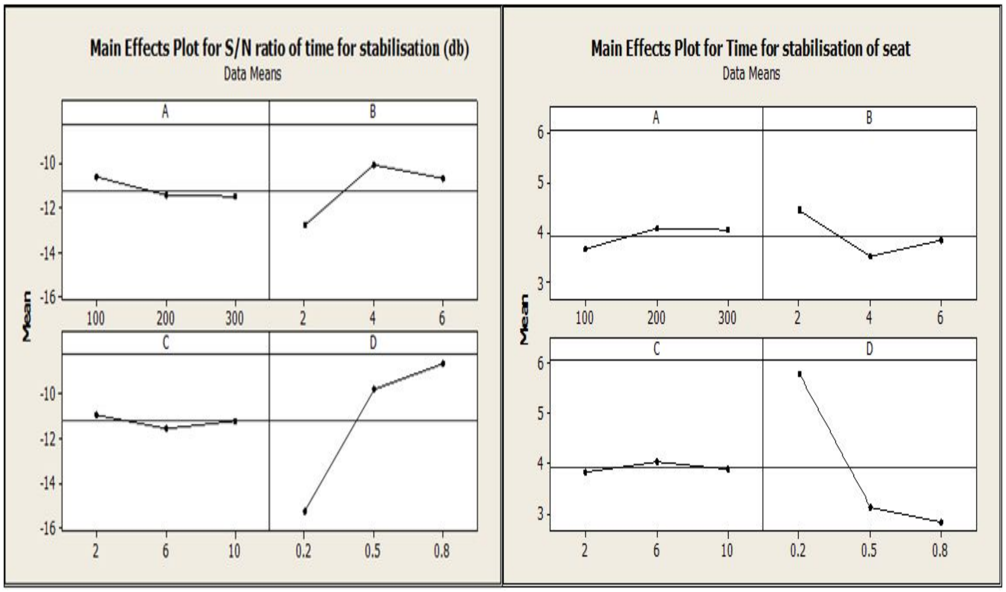

Figure 6: S/N Ratio and Mean Plot for Minimization of settling time (S_T)

Predictor	**Coef**	**SE Coef**	**T**	**PE**
Constant	0.6658	0.118	5.64	0
A	0.009002	0.000798	11.28	0
B	-0.14063	0.03126	-4.5	0.001
C	0.16349	0.01144	14.3	0
D	-0.1802	0.1493	-1.21	0.255
AA	-9.7E-06	1.31E-06	-7.43	0
BB	0.028562	0.003099	9.22	0
CC	-0.00564	0.00082	-6.88	0
DD	0.52469	0.08253	6.36	0
AB	-0.00051	9.17E-05	-5.56	0
BC	-0.00711	0.002292	-3.1	0.011
CD	-0.01028	0.03922	-0.26	0.799
DA	-0.00177	0.000451	-3.93	0.003
BD	-0.08048	0.02255	-3.57	0.005
BCD	-0.005	0.006458	-0.77	0.457
CDA	-0.00037	0.000129	-2.85	0.017
ABCD	7.38E-05	1.99E-05	3.72	0.004
S = 0.0181936		R-Sq = 99.9%		R-Sq(adj) = 99.7%

Table 8: ANOVA for Regression Model of seat displacement (D_S)

The R^2 of the mathematical model of seat displacement (D_S) and settling time (S_T) is 99.9% and 98.7% respectively. The predicted R^2 value of the model of MRR and Ra is 99.7% and 96.7% respectively. The models were developed for seat displacement (D_S) and settling time (S_T) using MINITAB package. The regression models provide an excellent relationship between the independent variables (factors) and the responses. The associated P-Value for the model is lower than 0.05 (i.e., 95% confidence) indicates that the model is considered to be statistically significant. Tables 8 and 9 are used to demonstrate the ANOVA test for the models. The normal probability plot of the residuals for seat displacement (D_S) and settling time (S_T) are shown in figures 7 and 8 respectively. It can be observed that the residuals are located on a straight line, which shows that the errors are normally distributed and the non-linear models are fairly well fitted with the experimental values.

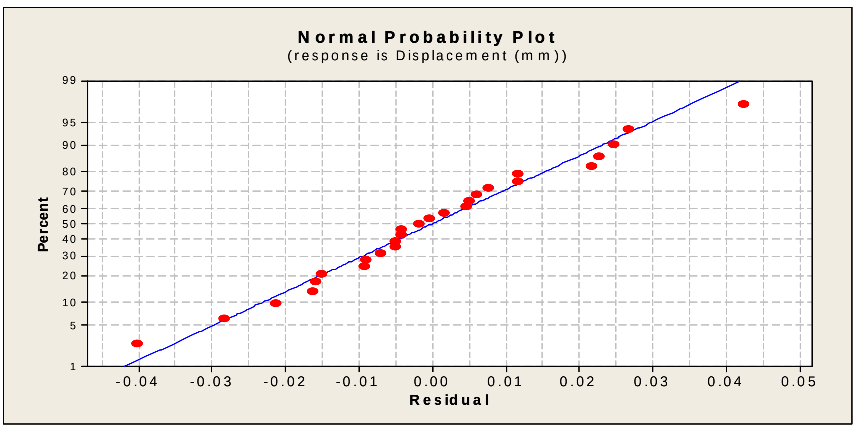

Figure 7: Normal plot of residuals for best Model of seat displacement (D_S)

Predictor	**Coef**	**SE Coef**	**T**	**PE**
Constant	4.566	1.809	2.52	0.03
A	0.01196	0.01223	0.98	0.351
B	0.2574	0.479	0.54	0.603
C	0.7071	0.1752	4.04	0.002
D	-7.575	2.288	-3.31	0.008
AA	-3.8E-05	2.01E-05	-1.87	0.091
BB	0.07382	0.04748	1.55	0.151
CC	-0.02286	0.01256	-1.82	0.099
DD	13.031	1.264	10.31	0

Predictor	Coef	SE Coef	T	PE
AB	0.000812	0.001405	0.58	0.576
BC	-0.10645	0.03512	-3.03	0.013
CD	-1.8456	0.6009	-3.07	0.012
DA	-0.008	0.006908	-1.16	0.274
BD	-2.1588	0.3454	-6.25	0
BCD	0.33732	0.09894	3.41	0.007
CDA	0.004377	0.001979	2.21	0.051
ABCD	-0.00054	0.000304	-1.78	0.105
S = 0.278734		R-Sq = 98.7%		R-Sq(adj) = 96.7%

Table 9: ANOVA for Regression Model of settling time (S_T)

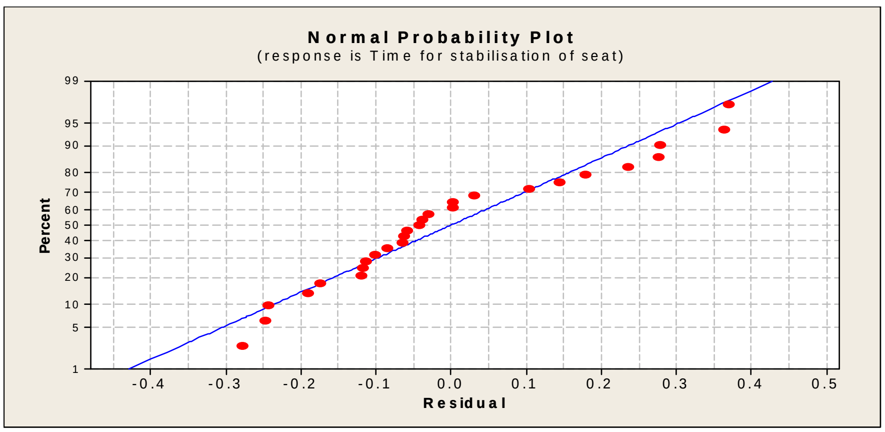

Figure 8: Normal plot of residuals for best Model of settling time (S_T).

5.Confirmation Experiments

The confirmation experiment is the final step in the first iteration of the design of experiment process. Confirmatory experiments are done to validate the conclusion drawn from the analysis phase. The confirmatory experiment is performed with specific levels previously evaluated. In this study after predicting the response under optimum conditions, a new experiment was conducted with the most favorable levels of system parameters. The results of experimental confirmation using optimal system parameters are shown in [table 10]. The optimum level for Seat displacement (D_S) was predicted as A1B3C1D3 and the predicted result is 1.10. The experimental result is about 1.25 with an error percentage of about 13.6%. The optimum level for settling time (S_T) was predicted as A1B2C1D3 and the predicted value is 2.16, while the experimental result is about 2.32 with an error percentage of about 7.40%. The error percentage could be further reduced by increasing the number of levels. The figure (9) shows the graph of vehicle seat displacement for optimal level of Seat displacement (D_S) and figure (10) shows the graph of vehicle seat displacement for optimal level of settling time (S_T).

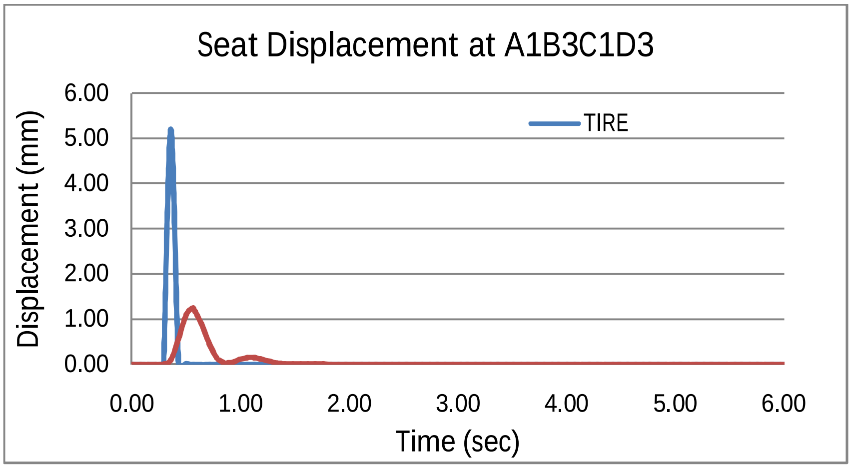

Figure 9: Graph for optimal level of seat displacement (D_S) (A1B3C1D3)

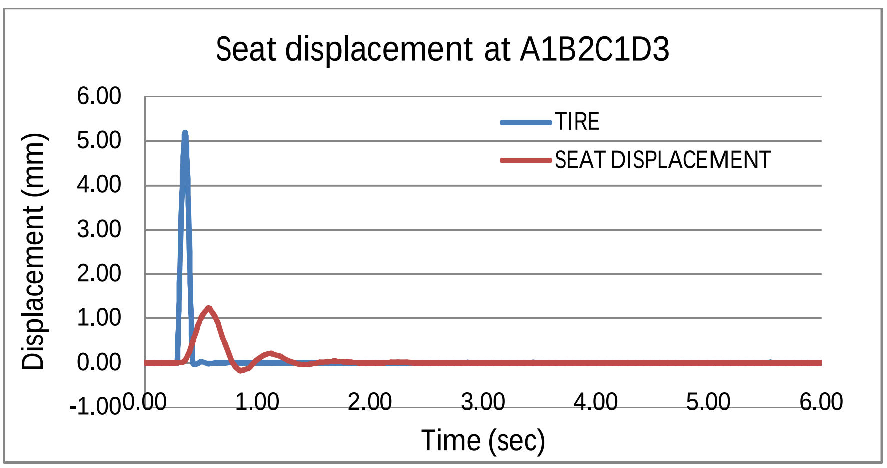

Figure 10: Graph for optimal level of settling time (S_T) (A1B2C1D3)

Output Parameters	Optimum Levels	Predicted Result	Experimental Result
Displacement (mm)	A1B3C1D3	1.10	1.25
Time for stabilization (sec)	A1B2C1D3	2.16	2.32

Table 10: Confirmation experiment

6.Conclusion

From the above experiments following observations are made.

- The factors like The stiffness of four shock absorbers (A), damping co-efficient of four shock absorbers (B), stiffness of seat (C) and damping co-efficient of seat (D) are selected for minimization of Seat displacement (D_S) and minimization of settling time (S_T) of seat for the full car model.
- From analysis we can come to the conclusion that stiffness of shock absorbers at level 1 and stiffness of seat at level 1 is recommended for minimization of Seat displacement (D_S). Damping co-efficient of shock absorbers at level 2 and damping co-efficient of seat at level 3 is recommended for the minimization of settling time (S_T).
- The results of the confirmation experiment well satisfied with the predicted optimal settings. An error of about 13.6% is observed for Seat displacement (D_S) and an error of about 7.40% is found with settling time (S_T). It is expected that the error can be reduced if more number of replications are taken during experimental stage.
- The mathematical model for seat displacement (D_S) and settling time (S_T) is done.
- It is to be noted that the optimal levels of factors for both the objective differ widely. In future, the mathematical models for the output response will be generated to optimize both the objective functions.

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