IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X
PP. 33-40
www.iosrjournals.org

Optimization of Vehicle Suspension System to Improve Comfort

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Abstract: *Design of suspension system has always been a tiresome task. This paper deals with finding the optimum values of suspension and steering parameters to give the best ride comfort as per ISO 2631-1:1997. An ADAMS model is prepared and validated, which has the capability of altering seven different influential parameters namely sprung mass, un-sprung mass, spring stiffness, damping coefficient, tire stiffness, camber and toe. In order to obtain optimal values for each parameter the Design of Experiment approach is implemented. MINITAB® is used to obtain a regression model which gives reliable values of R-sq 93.67%) and R-sq (adj) (92.41%). The ADAMS model was then tested with the optimized parameters thus attaining an accuracy of 67.86% .*

Keywords – *ADAMS, Camber angle, Damping Coefficient, DOE, Sprung mass, Ride comfort, RMS, Spring stiffness, Toe.*

I. INTRODUCTION

The mechanism that was designed and is implemented in vehicles to ensure a passenger a comfortable ride simultaneously keeping the wheels in contact with the road for any road condition is called a suspension system. As per ISO 2631-1:1997 standards, humans are more sensitive to vertical vibrations ranging from 4 to 8 Hz. In this paper as per ISO 2631-1:1997, ride comfort has been assessed in RMS acceleration of sprung mass [1]. An experiment was conducted using different cars running at different speeds on various road profiles to examine the effects of vibrations on the passengers. Many conclusions were drawn regarding the effects of vibrations related to the acceleration levels of the vehicle with respect to the road, amount of time the passengers were exposed to a particular road profile [2].The various effects of vibration can be reduced by studying in detail the parameters of the suspension system used. In a research by Yunqing Zhang et al. fractional damping had been implemented in Matlab/Simulink for investigating vehicle non-stationary vibration process. Also the response of the body was analyzed at 30 m/s with two acceleration which concluded that vibrations were more for higher accelerations. Frequency response was also analyzed using FFT (Fast Fourier Transform) Algorithm [3]. In a research by Saeed Mostaani et al. a model with 7-DOF had been created and analyzed to evaluate and optimize ride comfort and pitch angle. Hence spring and damper values for front and rear sections had been varied. In the end a DOE method had been implemented to obtain maximum ride comfort from the best values of the varied parameters [4]. In a thesis by Alexander Varghese. In Matlab/Simulink, three mathematical models were developed to analyze and evaluate the effects of tire pressure on consumption of fuel, handling of the vehicle and ride characteristics. Also evaluation in time and frequency domain was done for a 4DOF half car model that had been developed and subjected to sine input, step input and random road profile input. It had been concluded that at low tire pressure vertical accelerations were less while at high tire pressures displacement of sprung mass is negligibly less compared to low pressures [5]. In a paper by Abdelrahman Abdelghaffar et al., vibrational transmissibility in cars was analyzed due the effects of tire pressure. Also at certain frequencies, amplitudes of vibration were studied by varying tire pressure from 20 to 40 psi with the help of the FFT. It was concluded that the vibrational transmissibility was found to reduce when tire pressure was reduced, but reducing tire pressure after a threshold compromised driver's safety i.e. handling [6].

S. Prabhakar, Dr.K.Arunachalam used variable damping and stiffness parameters for carrying out the simulation of a quarter car suspension system. While implementing step and random road profile as input, ride comfort was maximized along with better road holding [7]. M. Zehsaz1 et al. have carried out the influence of the different parameters on dynamic control and ride comfort during acceleration and braking of an off road vehicle. The dynamic behavior of the vehicle as well as the road profile was developed in Matlab. Results obtained showed that decreasing spring coefficient decreases sprung mass resonance frequency. It was also concluded that ride comfort is more sensitive to rear damper [8]. Javad Marzbanrad, Masoud Mohammadi and Saeed Mostaani determined values for spring and damper in order to obtain optimum ride comfort at different speeds using Design of Experiment method (DOE) [9]. As important as analyzing various parameters individually, it is essential to combine these parameters together to find an optimum value of ride comfort for broad range of input parameter values. Based on this, A.C Mitra et al. found an optimum value of road holding as well as ride comfort for various combinations of suspension input parameters such as spring stiffness, damping coefficient, toe and camber, un-sprung and sprung mass, tire pressure and wheel speed using Design of Experiments. An average accuracy of 80% was obtained by using the obtained optimal values on the test rig [10]. A.C Mitra et al. used 2^k full factorial method to obtain optimum values of ride comfort and road holding considering damping coefficient, spring stiffness, speed and sprung mass. Test rig values were compared to the values obtained by a model prepared in SIMULINK and a correlation of 0.64 was obtained [11]. In another research A.C Mitra et al. optimized ride comfort maintaining a good value for road holding using Genetic Algorithm (GA). The objective functions of RH and RC were derived in terms of damping coefficient and spring stiffness [12]. A.C Mitra et al. modeled a 4-DOF system by using SIMULINK for analyzing ride comfort. Optimization was carried by Genetic Algorithm, using parameters such as damper coefficient, spring stiffness, sprung and un-sprung mass, tire stiffness. Results of original and optimized suspension system were compared for sprung mass acceleration, road holding as well as driver head acceleration [13].Jin Liu, Yongjun Shen, Shaopu Yang carried out two methods based on invariant point method for optimizing the spring-damper mechanism of the passive suspension system. It was concluded that the ride comfort for the two passive suspension systems had increased, also the suspension deformation was more than the original suspension system but within range and lastly, the tire deformation was the same for the optimized and original suspension system [14]. Arshad Mehmood, Ahmad Ali Khan, Ayaz Mehmood implemented parameters such as un-sprung mass, sprung mass, damping coefficient, spring stiffness and tire stiffness. Damping coefficient was considered as a parameter for optimization. Also using root locus plots stability analysis was carried out for the optimized values [15]. A. Elsawaf and T. Vampola considered front suspension stiffness, rear suspension stiffness, front dynamic coefficient and rear dynamic coefficient as parameters to be optimized. Optimization was done by Particle Swamp Optimization Technique (PSO). After simulation and assessment of the vehicle considering various speed control profiles, it was concluded that the optimized passive suspension system had better performance [16].

Zhongzhe Chi, Yuping He and Greg F. Naterer optimized a suspension system for a quarter car model concerning vertical body acceleration, suspension working space and dynamic tire load using Genetic Algorithms (GAs), Sequential Quadratic Program and Pattern Search Algorithm (PSA). The three algorithms were then compared, it was concluded that the SQP had a very strong local convergence and theoretical properties and GA and PSA are more useful to find global optimal points [17]. Anil Shirahatti et al. used Genetic algorithm to design a suspension system in order to minimize maximum seat and sprung mass bouncing acceleration, root mean square (RMS) acceleration of sprung mass and seat confining to the ISO2631 standards as well as minimizing suspension travel, tire deflection, road holding and jerk. Based on the results, it was concluded that the optimized suspension system had an improved ride comfort and road holding [18]. R Alkhatib, G Nakhaie Jazar, M.F Golnaraghi implemented genetic algorithm to optimize a 1 DOF vibration isolator. This method was then used for optimizing a linear suspension system. Results showed an optimal relation to exist between RMS of relative displacement and RMS of absolute acceleration [19].Shijil Pet al. design and analyzed a suspension system by studying the static and dynamic parameters of the suspension system. The different parameters identified were optimized to obtain a better performance [20]. M. Mahmoodi-Kaleibar et al. used MSC ADAMS to carry out optimization of the suspension system implementing Genetic Algorithm which improved ride comfort as well as handling. Simulation results showed that the optimized system had lower camber angle variations [21].P.Senthil Kumar et al. optimized a passenger vehicle suspension system considering stiffness and damping coefficient of shock absorber, stiffness and damping coefficient of the seat as input parameters. The design of experiments was planned by using L27 orthogonal array with 4 factors at 3 levels. On analysis of S/N ratio, optimum values for settling time and seat displacement were obtained [22]. A.C Mitra et al. reduced variability in the Ride comfort using Taguchi method for optimization adapted along with ANOVA and design of experiments methodology. The main aim was to find various combinations of input parameters used [23]. Adrian Florea et al. implemented various multi objective evolutionary algorithms along with different road profiles to obtain the best solution for an optimized suspension system. The optimum design variable were spring and damping coefficients in order to minimize sprung mass displacement and sprung mass acceleration constraint to suspension working space, natural frequency and maximum vehicle vertical acceleration [24].One of the basic reasons for vibration is road input. A research by Galal Ali Hassaan investigated the step response of a 2 DOF passive suspension system. The mathematical models for sprung mass acceleration and displacement of the quarter car model were used for analysis [25]. Galal Ali Hassaan showed that using a novel polynomial hump ride comfort conditions can be reached assuming linear characteristics for the passive suspension system at speeds 5 and 30 km/hr [26].

In this paper an ADAMS model is prepared which is used for analysis and data acquisition. The model has the ability to vary its sprung mass, un-sprung mass, spring stiffness, damping coefficient, tire stiffness, camber and toe for which a sin bump is used as road input and analysis is carried out at a constant speed of 20 kmph. DOE is used to check the predictability of the model and also to find a regression model which can be used to optimize suspension systems. Furthermore sensitivity analysis is carried out to examine the effect of individual parameters on ride comfort.

II. DEVELOPMENT OF MSC OF ADAMS SIMULATION MODEL

A front wheel suspension system was prepared in MSC ADAMS. The dimensions of the test-rig were measured and then an ADAMS model was developed with the measured dimensions. The model has capability to vary seven different parameters namely Sprung Mass (Ms), Un-sprung Mass (Mu), Spring Stiffness (Ks), Damping Coefficient (Cs), Tire Stiffness (Kt) and also the steering geometry parameters such as Camber (Cam) and Toe. Various simulations were carried out according to the DOE table prepared in MINITAB® using the full factorial design method. Fig.1 shows the front wheel suspension system model. Both the tires are given the same jack motion thus behaving and following the characteristics of a quarter-car model.

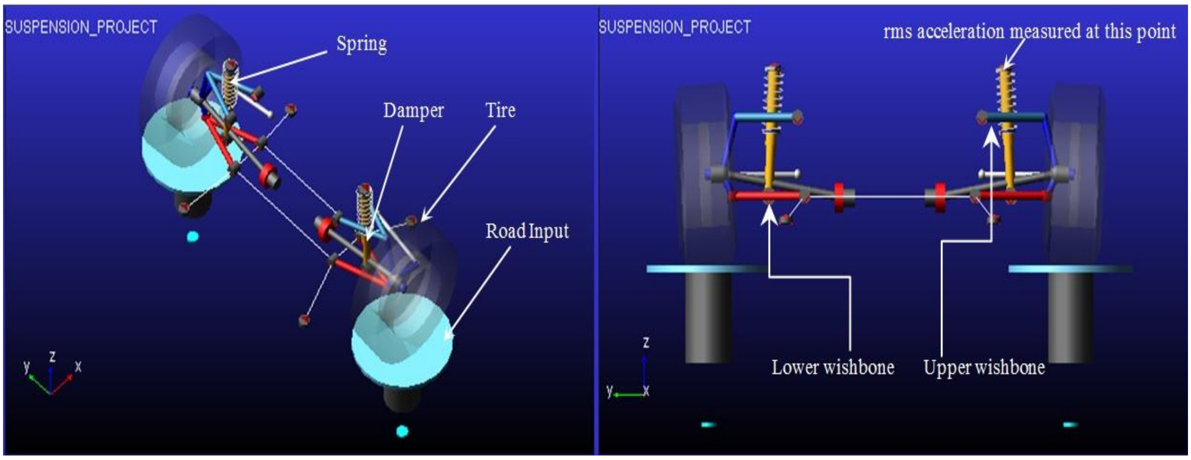

Fig.1: Developed Simulation Model in MSC ADAMS

III. DESIGN OF EXPERIMENTS

The main goal of the work is to obtain optimized values of the influential parameters and their interaction to attain the best possible ride comfort. Design of Experiments (DOE) is an instrument to determine the relationship between factors affecting a process and the output of that process. In other words, it is used to find cause-and-effect relationships. This information is needed to manage process inputs in order to optimize the output. In this paper full factorial method has been employed to carry out the DOE.

3.1 Full Factorial

Full Factorial method of DOE is used since more than two factors are considered in this research and each factors have different 'high' and 'low' or 'levels'. Full Factorial method tackles all these levels through all the factors. It also helps in understanding the effect of each factor on response variable RC and furthermore provides the effects of interactions between factors on the response variable RC. Even though full factorial method increases the number of reading it gives more accurate results.

Table 1. Upper and Lower Limits of Input Parameters

INPUT PARAMETERS	UPPER LIMIT (+1)	LOWER LIMIT (-1)	
Sprung Mass - Ms (Kg)	1250	500	
Un-Sprung Mass - Mu (Kg)	60	25	
Spring Stiffness - Ks (N/m)	10000	20000	
Damping Coefficient - Cs (N-s/m)	400	1500	
Tire Stiffness - Kt (N/m)	100000	150000	
Camber - Cam (Deg)	2	0	
Toe - Toe (Deg)	1	0	

3.2 Data Assimilation

Values of seven factors with two levels each (Upper Limit and Lower Limit) as shown in table 1, were acquired by research and market survey. The design is denoted as 2^k where *k* is the number of factors, therefore it is denoted as 2^7 giving us 128 runs and readings as shown in table 2. These tests were carried out on the simulation model with a constant speed of 20 kmph and a sine bump was used as a road input to the tires.

 DOI: 10.9790/1684-17010013340

Table 2. Observation Table

Run Order	Ms	Mu	Ks	Cs	Kt	Cam	Toe	RC
1	500	25	20000	400	150000	2	0	0.3779
2	500	60	10000	1500	150000	2	1	0.7083
3	500	25	20000	400	150000	0	1	0.3831
4	1250	25	20000	400	100000	0	1	0.1894
5	1250	60	20000	400	100000	0	1	0.167
6	500	60	20000	400	150000	2	0	0.2224
7	1250	25	20000	1500	150000	2	0	1.2454
8	500	60	20000	1500	150000	2	0	0.7283
9	1250	25	10000	1500	150000	0	0	0.6026
10	1250	25	20000	400	150000	0	0	0.341
11	1250	25	10000	1500	100000	2	0	0.4536
12	1250	60	10000	400	100000	2	0	0.1595
13	500	60	20000	1500	100000	2	0	0.5404
14	500	25	20000	1500	100000	0	0	0.4758
15	500	25	20000	400	150000	2	1	0.3633
16	1250	25	20000	400	100000	0	0	0.1892
17	1250	60	10000	400	150000	0	0	0.2294
18	500	25	10000	400	100000	2	0	0.1584
19	500	25	10000	400	150000	0	1	0.2177
20	500	60	10000	1500	150000	2	0	0.7124
21	500	25	20000	1500	150000	2	0	1.3114
22	500	60	20000	400	100000	0	0	0.1726
23	500	60	10000	400	100000	0	1	0.1709
24	500	25	10000	400	150000	2	0	0.2139
25	1250	25	10000	1500	150000	2	1	1.2961
26	500	60	20000	400	100000	2	1	0.169
27	500	25	10000	1500	100000	0	0	0.4581
28	1250	60	10000	400	100000	0	1	0.1717
29	500	25	20000	400	100000	0	1	0.1894
30	500	25	20000	400	150000	0	0	0.3831
31	500	60	20000	1500	100000	0	1	0.5828
32	500	60	20000	400	150000	0	1	0.2405
33	1250	60	10000	1500	100000	0	1	0.577
34	1250	25	20000	1500	150000	0	1	1.3277
35	500	25	20000	1500	150000	0	0	1.3277
36	1250	25	10000	1500	100000	2	1	0.4722
37	1250	60	20000	400	150000	0	0	0.2364
38	500	25	10000	1500	150000	2	0	1.2541
39	500	25	20000	1500	100000	2	0	0.4834
40	1250	60	10000	400	150000	2	1	0.2256
41	500	60	10000	400	100000	2	1	0.1733
42	500	25	20000	400	100000	0	0	0.1897
43	1250	25	10000	400	150000	0	1	0.2241
44	500	25	10000	400	100000	0	0	0.1758
45	1250	25	10000	400	100000	0	0	0.1758
46	500	60	20000	400	100000	2	0	0.1697
47	1250	60	10000	400	150000	0	1	0.2294
48	500	25	10000	1500	150000	0	0	0.6138
49	500	60	10000	400	150000	2	0	0.2094
50	1250	25	20000	400	150000	2	0	0.3779
51	1250	25	10000	400	100000	2	0	0.1686
52	1250	60	10000	1500	150000	2	0	0.7386
53	500	60	10000	1500	100000	2	1	0.5737
54	1250	25	10000	1500	100000	0	0	0.4653
55	1250	60	10000	400	150000	2	0	0.2269
56	500	25	20000	1500	150000	0	1	0.765
57	1250	25	20000	1500	100000	0	0	0.4832
58	1250	60	10000	1500	150000	0	1	0.7307
59	500	25	20000	400	100000	2	0	0.1821
60	500	60	10000	400	150000	0	1	0.2321
61	500	60	10000	1500	100000	2	0	0.5737
62	1250	60	10000	400	100000	0	0	0.1709
63	500	60	20000	1500	150000	0	0	0.7431
64	500	60	20000	400	150000	0	0	0.654
65	500	25	20000	1500	100000	2	1	0.484
66	1250	25	20000	400	150000	0	1	0.4009
67	1250	25	10000	1500	150000	0	1	1.2761
68	1250	60	10000	1500	150000	0	0	0.7263
69	500	60	10000	400	100000	2	0	0.1695
70	1250	60	20000	400	100000	2	1	0.1538
71	1250	25	10000	400	150000	2	0	0.2294
72	500	60	10000	400	150000	0	0	0.2155
73	1250	25	20000	1500	100000	2	1	0.4775
74	500	25	20000	400	100000	2	1	0.1846
75	500	25	10000	400	100000	2	1	0.178
76	1250	60	20000	1500	150000	2	1	0.7947
77	1250	60	20000	400	100000	0	0	0.1787
78	500	25	10000	400	150000	0	0	0.2467
79	500	60	10000	400	100000	0	0	0.1842
80	1250	60	10000	1500	100000	0	0	0.6051
81	1250	25	20000	1500	100000	2	0	0.5018
82	1250	25	10000	400	100000	2	1	0.1784
83	1250	60	20000	400	150000	0	1	0.2367
84	500	60	20000	400	150000	2	1	0.2685
85	1250	25	20000	400	150000	2	1	0.4656
86	500	60	20000	1500	150000	2	1	0.7544
87	1250	60	10000	1500	100000	2	1	0.634
88	500	60	20000	1500	100000	0	0	0.6415
89	1250	60	20000	400	100000	2	0	0.1726
90	1250	60	20000	1500	100000	2	1	0.6661
91	1250	60	10000	1500	100000	2	0	0.5764
92	1250	25	10000	400	100000	0	1	0.1747
93	1250	25	20000	400	100000	2	1	0.186
94	500	60	20000	1500	150000	0	1	0.7345
95	500	25	10000	400	100000	0	1	0.1775
96	1250	60	20000	1500	100000	0	1	0.6093
97	1250	60	20000	400	150000	2	1	0.2339
98	1250	25	20000	1500	100000	0	1	0.47
99	500	60	10000	1500	100000	0	1	0.657
100	500	60	10000	1500	150000	0	0	0.7487
101	500	25	10000	1500	150000	2	1	1.3666
102	1250	60	20000	1500	150000	2	0	0.6966
103	1250	25	20000	1500	150000	0	0	1.3023
104	500	60	10000	1500	100000	0	0	0.555
105	500	60	20000	400	100000	0	1	0.1787
106	500	60	20000	1500	100000	2	1	0.5512
107	500	25	10000	1500	150000	0	1	1.3833
108	500	60	10000	1500	150000	0	1	0.7487
109	1250	60	20000	400	150000	2	0	0.2439
110	500	25	10000	400	150000	2	1	0.2338
111	1250	25	10000	1500	150000	2	0	1.3666
112	1250	25	10000	1500	100000	0	1	0.487
113	1250	60	20000	1500	100000	2	0	0.5537
114	1250	60	10000	1500	150000	2	1	0.7337
115	500	25	10000	1500	100000	0	1	0.4895
116	500	25	10000	1500	100000	2	1	0.4765
117	500	60	10000	400	150000	2	1	0.2151
118	1250	60	10000	400	100000	2	1	0.1894
119	1250	60	20000	1500	150000	0	0	0.7345
120	500	25	20000	1500	100000	0	1	0.4902
121	500	25	20000	1500	150000	2	1	1.4089
122	1250	25	20000	1500	150000	2	1	1.4089
123	1250	25	10000	400	150000	2	1	0.2319
124	1250	60	20000	1500	150000	0	1	0.7563
125	1250	25	10000	400	150000	0	0	0.2467
126	1250	25	20000	400	100000	2	0	0.1863
127	500	25	10000	1500	100000	2	0	0.4802
128	1250	60	20000	1500	100000	0	0	0.5874

3.3 Goodness of Fit

Table 3 gives us a quantitative effect of each parameter on RC and this is analyzed by deducing the value of 'P'. Table 3 also gives us a measureable 'effect' of each parameter and interactions (combinations of two or more factors) on the response which in turn is calculated by considering the average effects of the remaining parameters. The 'coefficient' term in table is the slope of the regression line and gives the predicted change in mean response with per unit increase in the factor keeping all other factors constant. The exactness of effect and coefficient is evaluated by standard error of coefficient or 'SE-coefficient'. 'T-value' is the ratio of coefficient and SE-coefficient according to which the 'P-value' is decided. If the 'P-value' is less than 0.05 i.e. a confidence level of 95% for the model, it is regarded as 'sensitive' and the null hypothesis is rejected as per TYPE-I error. Kt*Cam*Toe, Mu*Ks*Cs, Ms*Ks, Ms*Kt are few interactions which have value of 'P' greater

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than 0.05 hence are marked as insensitive. These analysis are carried out repetitively by eliminating the insensitive interactions until only the significant factors and interactions are attained. Insensitive parameters such as Cam, Toe, Ks*Cam, Ks*Toe, Kt*Cam and Cam*Toe, are essential to obtain the regression model. After removal of insignificant factors, the 'Goodness of Fit' is calculated signifying how close the predicted values are to the observed data values. 'S' from Table 4 stands for standard error which is an approximation of errors or noise in the model. Smaller the value of S, greater is the accuracy of the analysis. Coefficient of determination or 'R-sq' indicates the model is justified by input parameters. Value of R-sq obtained in this research was 93.67%. It is better to have high values of R-sq as it gives a better fit and gives a low value of variance, but having too many insignificant parameters can also result in a high R-sq value. To overcome this, R-sq (adj) is evaluated whose value should be close to the R-sq value to prove its legitimacy and its fitment to the model, 92.41% obtained in this research. PRESS and R-sq (pred) values evaluates the predictability. R-sq (pred) shows the predictability of the model and minor difference between R-sq (pred) and R-sq signifies that the model is not over fit. Values obtained as per this experiment is given in table 4.

Table 3. Estimated Effects and Coefficients for RC

Terms	Effect	Coefficient	SE Coefficient	T	P
Constant		0.49118	0.008450	58.13	0.000
Mu	-0.10282	-0.05141	0.008450	-6.08	0.000
Ks	0.04657	0.02329	0.008450	2.76	0.007
Cs	0.52323	0.26162	0.008450	30.96	0.000
Kt	0.27086	0.13543	0.008450	16.03	0.000
Cam	0.02208	0.01104	0.008450	1.31	0.194
Toe	0.02157	0.01079	0.008450	1.28	0.205
Mu*Cs	-0.07314	-0.03657	0.008450	-4.33	0.000
Mu*Kt	-0.15606	-0.07803	0.008450	-9.23	0.000
Mu*Cam	-0.04295	-0.02147	0.008450	-2.54	0.012
Ks*Kt	0.04201	0.02100	0.008450	2.49	0.014
Ks*Cam	-0.01575	-0.00787	0.008450	-0.93	0.353
Ks*Toe	-0.03227	-0.01613	0.008450	-1.91	0.059
Cs*Kt	0.16394	0.08197	0.008450	9.70	0.000
Cs*Cam	0.03629	0.01815	0.008450	2.15	0.034
Kt*Cam	0.02873	0.01436	0.008450	1.70	0.092
Kt*Toe	0.01246	0.00623	0.008450	0.74	0.462
Cam*Toe	0.00255	0.00128	0.008450	0.15	0.880
Mu*Cs*Kt	-0.13465	-0.06733	0.008450	-7.97	0.000
Mu*Kt*Cam	-0.03811	-0.01906	0.008450	-2.26	0.026
Ks*Cam*Toe	0.04418	0.02209	0.008450	2.61	0.010
Cs*Kt*Cam	0.03813	0.01907	0.008450	2.26	0.026

Fig. 2 shows the Pareto chart which determines the magnitude and significance of a parameter or interaction visually. It comprises of a red line or a reference line corresponding to the critical t-value exceeding which any effect is significant. According to the chart parameters like toe, camber, sprung mass and interactions like Ks*Toe, Kt*Cam, Ks*Cam, Cam*Toe are insignificant to evaluate RC.To assess the 'Goodness of Fit' qualitatively residual plots are examined. Fig. 3 shows such a residual 4-in-1 plot. In 'Normal Probability Plot' the plot follows a straight line if the errors are distributed normally. If the plotted points are at a substantial distance from the straight line it indicates inaccuracy in the model. Few large residual points are present which are considered as outliners. Histogram shows the residual points from all observations and forms a bell shaped graph. In residual vs fitted plot if the plot is dispersed along a constant horizontal line the model is known as homoscedastic i.e. all the parameters have the same finite variance and any curve or pattern shows that there are chances of heteroscedasticity. In this model since the plot shows a random distribution it states that the variance is constant throughout. The residual vs order plot shows the residual points in the order which they were carried out, it helps in determining the relationship between in the residuals. Since the graph shows no clear trend it signifies random variation in the experimental data.

Table 4. Regression Statics for RC

S	Standard Deviation	0.0955977
PRESS	Prediction Sum of Squares	1.41257
R-Sq	Coefficient of Multiple Determination	93.67%
R-Sq (pred)	Predicted Coefficient of Determination	90.76%
R-Sq (adj)	Adjusted Coefficient of Determination	92.41%

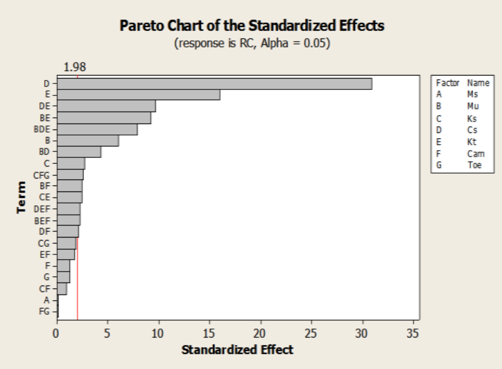

Fig.2: Pareto Chart of parameters in RC

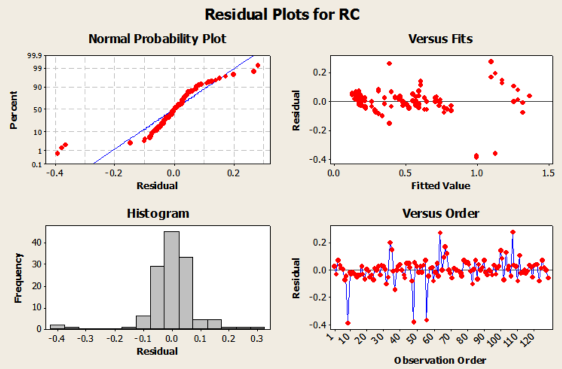

Fig.3: 4-in-1 Residuals Plots for RC

3.4 Analysis of Variance (ANOVA)

Table 5 shows the ANOVA (Analysis of Variance), the degree of freedom (DF) expresses the extent of information in each source and the source column consists of all the important parameters which may have a significant impact on variance in the model. Sequential sum of squares (Seq SS) and adjusted sum of squares (Adj SS) shows the variance considering that the previous parameters are present and considering all the parameters in the model respectively. Values of Seq SS and Adj SS are same stating that the design is orthogonal. Mean square (MS) shows the ratio of sum of squares by the degree of freedom. The ratio of mean square treatments and mean square error gives us the F-ratio, the F-ratio increases with the extent of effect of different factors.

IV. REGRESSION ANALYSIS

Regression analysis is a statistical process for estimating the relationships among variables. It includes many techniques for modeling and analyzing several variables, when the focus is on the relationship between a dependent variable and one or more independent variables. In regression analysis, an equation is formed for the dependent variable in terms of all the influential parameters affecting the output. The following equation (1) is obtained from regression analysis using MINITAB®:

Table 5. ANOVA Table

SOURCE	DF	SEQ SS	ADJ SS	ADJ MS	F	P
Main Effects	6	11.5465	11.5465	1.92442	210.57	0.000
2-Way Interactions	11	2.0411	2.0411	0.18555	20.30	0.000
3-Way Interactions	4	0.7357	0.7357	0.18392	20.12	0.000
Residual Error	106	0.9687	0.9687	0.00914		
Lack of Fit	42	0.6797	0.6797	0.01618	3.58	0.000
Pure Error	64	0.2890	0.2890	0.00452		
Total	127	15.2920				

$$\begin{aligned}RC = {} & 0.741409 - 0.014478(Mu) - 7.12625E\text{-}06(Ks) - 0.00145416(Cs) - 7.84143E\text{-}06(Kt) - \\ & 0.018095(Cam) + 0.186044(Toe) + 3.11753E\text{-}05(Mu\times Cs) + 1.31016E\text{-}07(Mu\times Kt) + \\ & 0.0042175(Mu\times Cam) + 1.68025E\text{-}10(Ks\times Kt) - 5.99281E\text{-}06(Ks\times Cam) - \\ & 1.52887E\text{-}05(Ks\times Toe) + 1.64664E\text{-}08(Cs\times Kt) - 1.4033E\text{-}04(Cs\times Cam) + \\ & 1.10848E\text{-}06(Kt\times Cam) + 4.98500E\text{-}07(Kt\times Toe) - 0.129984(Cam\times Toe) - \\ & 4.35571E\text{-}08(Mu\times Kt\times Cam) - 2.79799E\text{-}10(Mu\times Cs\times Kt) + 8.83562E\text{-}06(Ks\times Cam\times Toe) + \\ & 1.38659E\text{-}09(Cs\times Kt\times Cam) \qquad \ldots\ldots (1)\end{aligned}$$

V. SENSITIVITY ANALYSIS

This experiment consists of many parameters which may affect the ride comfort either directly or indirectly. Sensitivity analysis helps in determining the behavior of response depending upon these parameters.Main effect plot in fig. 4 shows the impact of an individual parameter on the response, considering an average effect of all the other parameters. These parameters can be studied by observing their slope. A horizontal plot shows the incompetence of the parameter on the response whereas a vertical plot signifies that the parameter is highly sensitive. Fig shows an almost vertical plot for Cs and Kt signifying they are sensitive parameters for RC which is also verified by their P-value. Interaction plot in fig. 5 shows a plot consisting of

 DOI: 10.9790/1684-17010013340

two parameters which are dependent on each other. It shows combination of factors which have a particular effect on RC. Factors having insignificant main effect may have a significant interaction which effects the response (RC). In Fig the parallel lines in the plot shows absence of interaction effect whereas intersecting lines indicates interaction between the two factors.

VI. RESPONSE OPTIMIZATION

Response Optimization is a function in Minitab® which calculates the optimum setting of the combination of all the included parameters as per the requirement of the user whether to minimize, maximize or achieve the target value for the response variable i.e. RC in our case. Minimization of RC was done using this tool and the value of all the influential parameters was obtained for the minimum value RC. This was then tested in the developed simulation model and compared with each other. Fig. shows the optimum values obtained for the different parameters. Table 6 shows the results for RC using the Response Optimization values, in the simulation model.

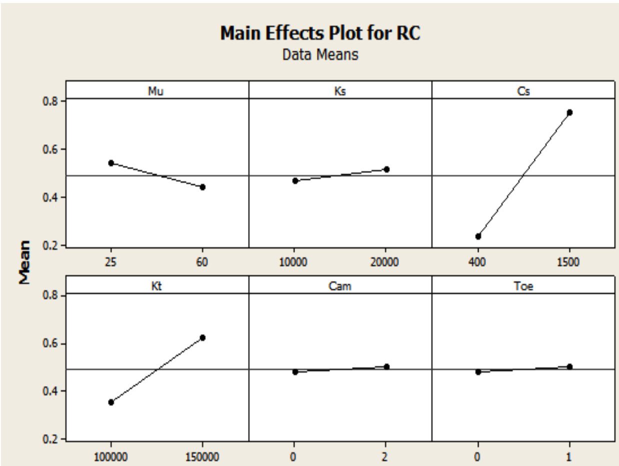

Fig.4 Main Effect Plot for RC

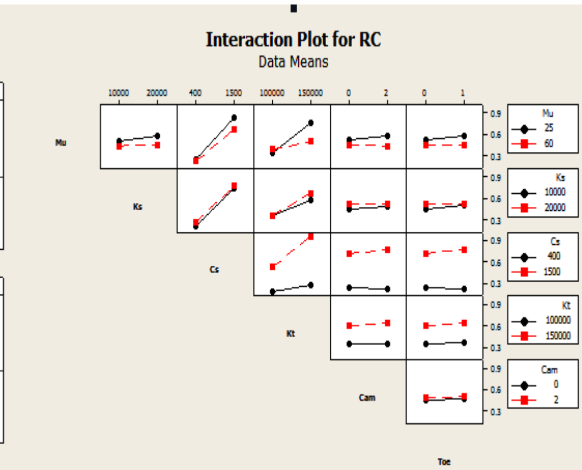

Fig.5 Interaction Plot for RC

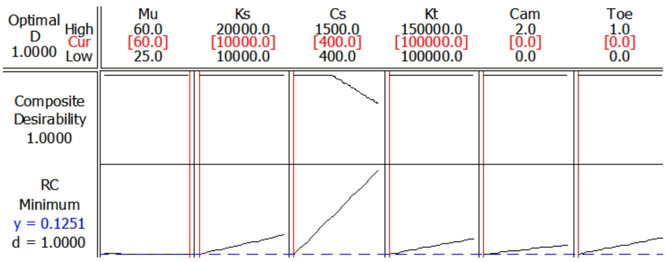

Fig. 6: Values of parameters obtained from Response Optimization.

Table 6: Verification of the RC value obtained in Response Optimization.

Un-Sprung Mass(Mu)	Spring Stiffness(Ks)	Damping Coefficient(Cs)	Tire Stiffness(Kt)	Cam (deg)	Toe (deg)	RC(Response Optimizer)	RC(Simulation Model)	Accuracy
60	10000	400	100000	0	0	0.1251	0.1653	67.86%

VII. CONCLUSION

In this study, RMS acceleration of sprung mass at a vehicle speed of 20 kmph was obtained through ADAMS by altering various parameters like sprung and un-sprung mass, spring and damping coefficients, tire stiffness, camber and toe of quarter car simulations model. The minimum value of RC is obtained when Ks, Cs, Kt, Cam and Toe are set to low and Mu is set to high according to the specified range. The response optimization plot can also be used to obtain desirable RC values by altering the position of the vertical bar for various parameters. With the implementation of 2^k Factorial Method, optimum values for the input parameters were obtained to obtain the best Ride Comfort value. The results obtained show that the difference between R-sq (93.67%) and R-sq (adj) (92.41%) is less. Such a model can be used not only to find the effect of individual parameters but also to find the effect of mutual interactions between them.

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