Optimum Damping and Spring Stiffness of Semi-Trailer Truck for Minimizing Unwanted Body Motion Due to Road Irregularities Using Taguchi Method

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Abstract — **The suspension system in an automotive vehicle is the interface between the vehicle body to the chassis and the road through the wheels. The main purpose of suspension is to absorb shock and vibration when the vehicle overcoming road irregularities. However, there are still issues where passive suspension is still unable to absorb maximum shocks in large vehicles for a pleasant ride when riding on an irregular road surface. This condition can cause a major risk to the driver which will cause the vehicle to experience rollover as the road bumps can cause instability to the vehicle. Therefore, the goal of this study is to determine the optimum spring constant, damping, toe angle and camber angle of the vehicle which allows them to optimally absorb the vibration due to road irregularities. The Trucksim software is used in this study to analyze the vehicle's vertical acceleration mainly at different spring constants, damping, toe and camber angle of the truck. Methodology used in optimization of suspension system of the 3-axle semi-trailer truck subjected to road excitation is by using Taguchi method. Using Root Mean Square (RMS) measurements of vertical acceleration, the effect of suspension stiffness and suspension damping alongside with the toe and camber factor of the vehicle on vertical acceleration is investigated. The data produced from this study can be used by researchers to improve the driving behaviors and driving characteristics of heavy vehicles.**

Keywords —semi-trailer truck, damping, spring stiffness

I. Introduction

Transportation in general has changed human lives in many ways. Over the years the automobile industry has gone through evolution in which advancement of vehicle is greatly prioritized by the industry. The industry involves all kinds of vehicles from industrial trucks to conventional car and to sports car. A semi-trailer truck is a combination of a truck and a semi-trailer. Most of the semitrailer's weight is supported by the tractor unit, a removable front axle called a dolly, or the tail of another trailer. The other part of the semitrailer's weight is semi-supported by its own wheels that only support the rear of the semi-trailer. Suspension system is an important vehicle subsystem [1]. Suspension system consists of shock absorbing components such as springs and dampers. By flexibly connecting the body to the wheel, it provides a smooth ride by blocking shock and vibration caused by uneven road surfaces. This directly affects the vehicle's ride comfort, road support, cargo safety, frame fatigue and wear of vehicle components [2]. Apart from that the toe and the camber angle also plays a minor role in producing a good suspension system. The toe angle is the angle of the wheel viewed from the top while the camber angle is the angle of wheel protruded out when viewed from the front. In this study, the optimum damping and spring stiffness are determined as the major factor along with toe and camber angle as the minor factor for a semitrailer truck in minimizing unwanted body motion due to the road irregularities such as speed bumps [3, 4].

The approach used in this study is to minimize vibrations caused by road irregularities and determine the optimum damping, the ideal spring stiffness, toe angle and camber angle by using Taguchi method. To find these parameters, the Trucksim software was used in this study. Trucksim software is interfaced with Simulink for support and analysis of more complex vehicle models. The vehicle can be simulated using different parameters, of which this study focuses on the damping and spring stiffness on the bumps and holes. This software allows a wide range of tests to be conducted without being limited by test track accessibility and environmental conditions such as rain. While virtual experiences don't totally mimic real vehicle testing, generally because of the intricacies of the actual system, they do give an ideal guide in understanding the physical motion of the vehicle and in our case it's a 3-axle semitrailer truck [5]. The software is utilized to show the actual vehicle attributes while Simulink is utilized to develop extra models like the ABS and ESC frameworks. An ESC system functions in two modes: Roll Stability Control (RSC) and Yaw Stability Control (YSC) [6 - 8].

II. Simulation Parameters

In this study, input the data is obtained from the technical specification sheet of Isuzu Giga into the Trucksim software as illustrated in Fig. 1. The vehicle body can be built in Trucksim using the parameters given in the specification sheet. Upon inserting the given parameters, the system is run on a flat road surface to visualize how the truck rides smoothly.

Fig. 1 Simulation of vehicle on flat surface

Next, the ride test of the research was analyzed by inserting the spring constant and damping value of the vehicle to visualize the motion of the vehicle. The spring constant value and the damping value was set similarly for each wheel. The ride test that was used to observe the vehicle motion in this study is the medium bump. Although there are many other ride tests that can be used such as small, medium, and large bump, the medium bump was chosen as it is much frequently to be found on road compared to the other bumps. This can assist in the research in optimizing the spring constant and the damping. According to the specifications provided by the Malaysian Ministry of Road Works, the medium bump, also known as the round-top hump, has a height of 50mm to 100mm [9]. Taking the average of the hump height at 75mm, the study will be carried out at this bump height. The speed is maintained as constant at 30km/h considering that the heavy vehicle will be passing a medium bump as tabulated in Table 1.

TABLE I. SPEED BUMP DIMENSION [10]

Material Used	Dimension
Asphaltic Premix Wearing Course	a) flat-top hump height: 75mm-100mm length: 2.5m-4m
	b) round-top hump height: 50mm-100mm length: 3.7m-4m
	c) sinusoidal hump height: 75mm-100mm length: 3.8m-4m

Trials of simulation were carried out prior to the actual simulation to first familiar with the software. Before carrying out the actual optimization process, the parameters and the trucks chosen were at random in order to first get comfortable with the software and explore into what can be done and altered to get an optimum value. The values and parameters of the semi-trailer truck were inserted as a trial where a few outputs were investigated. The parameters were locked in the software to avoid error while processing the data. There were many sections in the software where the data was unknown due to the limited information provided by the manufacturer. Hence, the default values from Trucksim were used with giving importance to the spring constant and damping value as required by this research. The visual output of this simulation was then observed. At the beginning of the research a constant speed of 20 km/h was used. After a few trials of changing the speeds, speed of 15 km/h was chosen to be the constant speed in this research. Simulation of Jack-Knife Accident for Single and Double Lane Change Tests. After a few trials to familiarize with the software, the test for this research was carried out. For this test, the 3-axle dump truck (loaded) was used to mimic the chosen vehicle which is the Isuzu Giga. The simulation was run on a medium bump with constant speed of 30 km/h. In general, the spring constant of a heavy vehicles is in the range of 80000 N/mm to 200000 N/mm whereas damping value, *c* in the range of 15000 N-sec/mm to 75000 Nsec/mm. The random spring constant was selected for this test for familiarization with the software. The chosen spring constant was 450000 N/mm with a damping value of 50600 N-sec/mm. Fig. 2 illustrates the interface of the Trucksim software where it shows on pages to input data. There are many sections of data to be inserted for the data simulation. These figures show the data page on suspension system which is important in our research.

Fig. 2 Spring constant and damping coefficient inputs

A. Simulation of varying parameters

After the familiarization process, the simulations on varying parameters were carried out. As per objective of this study, the effect of varying spring constant, damping coefficient, toe and camber angle were analyzed. Firstly, while analyzing the varying spring constant, *k*, the other parameters were kept constant on the default of the Trucksim. For each varying parameters, three parameter values were used. This is to observe the graph pattern to see if there are any major differences when the *k* is varied. The fluctuation of graph will show that the parameter indeed is an important factor in this research. The second simulation was carried out with varying damping coefficient with other parameters kept constant. The third simulation was done with varying toe angle and fourth was carried out with varying camber angle. Hence, 4 sets with 3 simulations for each parameter were carried out resulting in total of 12 simulations. Table II shows on the parameter values that was used for each part of the simulation:

TABLE II. COEFFICIENT OF VARYING PARAMETERS

	Simulation 1	Simulation 2	Simulation 3
Spring constant (N/m)	80000	140000	200000
Damping coefficient (Ns/m)	15000	45000	75000
Toe (deg)	-5	0	5
Camber (deg)	-5	0	5

B. Taguchi Method

The Taguchi process was carried out twice to get the best and most precise data [11, 12]. A typical heavy vehicle has a spring constant ranging from 80000 N/m to 200000 N/m and a damping value ranging from 15000 Ns/m to 75000 Ns/m. Hence, these range were used in the first Taguchi analysis. In this study, another two minor parameters were added to further enhance the results obtained. The toe and the camber angle were also considered in this study. The toe is a symmetric angle formed by each wheel with the vehicle's longitudinal axis whereas the camber is when viewed from the front or rear, the angle between the vertical axis of a wheel and the vertical axis of the vehicle. With having 4 parameters to be manipulated, further Taguchi optimization process was carried. The Taguchi method is an eight-step process/product optimization method that entails designing, conducting, and analyzing matrix experiment data to find the best solution for many control parameters. In this study, there are 4 parameters, and the ranges were divided into 5 levels. Hence having 4 factor and five levels, the L_{25} Orthogonal array was used for the optimization process Table III with initial parameters tabulated in Table IV.

TABLE III. SIMULATION LAYOUT L_{25} ORTHOGONAL ARRAY

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

TABLE IV. PARAMETERS AND LEVELS

Simulation Parameters	Level 1	Level 2	Level 3	Level 4	Level 5
Spring constant, k (N/m)	80000	110000	140000	170000	200000
Damping coefficient, c (Ns/m)	15000	30000	45000	60000	75000
Toe (degree)	-5	-2.5	0	2.5	5
Camber (degree)	-5	-2.5	0	2.5	5

III. OPTIMIZATION USING TAGUCHI

A. First Taguchi method

There are 4 parameters that is being manipulated in this research; the spring constant and damping which acts as the major manipulative variable and the toe and camber which acts as the minor manipulative variable. The L_{25} Orthogonal array was used in this research as there are 4 factors and 5 levels. Hence, 25 simulations with the combination of these factors and levels were carried out using Trucksim to study on the vertical acceleration of the heavy vehicle when overcoming the bump. Based on the data of vertical acceleration of the heavy truck, the RMS value was calculated.

TABLE V. PARAMETERS AND LEVEL OF FIRST TAGUCHI METHOD

Design Parameters	Level 1	Level 2	Level 3	Level 4	Level 5
spring constant, k	80000	110000	140000	170000	200000
damping coefficient, c	15000	30000	45000	60000	75000
toe	-5	-2.5	0	2.5	5
Camber	-5	-2.5	0	2.5	5

TABLE VI. SIMULATION LAYOUT FOR FIRST TAGUCHI PROCESS

Simulation number	*k*	*c*	toe	camber	RMS
1	80000	15000	-5	-5	0.186865859
2	80000	30000	-2.5	-2.5	0.149954289
3	80000	45000	0	0	0.132806972
4	80000	60000	2.5	2.5	0.136615182
5	80000	75000	5	5	0.159368004
6	110000	15000	-2.5	0	0.165883439
7	110000	30000	0	2.5	0.13975105
8	110000	45000	2.5	5	0.12443773
9	110000	60000	5	-5	0.124447677
10	110000	75000	-5	-2.5	0.148336027
11	140000	15000	0	5	0.147257445
12	140000	30000	2.5	-5	0.144950549
13	140000	45000	5	-2.5	0.12196893
14	140000	60000	-5	0	0.131495058
15	140000	75000	-2.5	2.5	0.151876345
16	170000	15000	2.5	-2.5	0.136305958
17	170000	30000	5	0	0.145742114
18	170000	45000	-5	2.5	0.12772888
19	170000	60000	-2.5	5	0.132947185
20	170000	75000	0	-5	0.153460265
21	200000	15000	5	2.5	0.152154363
22	200000	30000	-5	5	0.141517443
23	200000	45000	-2.5	-5	0.127185175
24	200000	60000	0	-2.5	0.127381926
25	200000	75000	2.5	0	0.153462005

Since for this research, the goal is to get a vertical acceleration with a lower RMS value. Hence, the Signal-toNoise ratio of the smaller the better characteristics was used to meet the requirements. The equation of Signal-to-Noise ratio is as below:

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

The *n* in the formula represents the number of repetitions. In this study, it was set to 1. The ISE in the formula represents the RMS value that was calculated earlier. The SNR values were calculated for each level and factor.

TABLE VII. SNR VALUES FOR FIRST TAGUCHI

Level	*k*	*c*	toe	camber
1	16.37	16.1	16.72	16.73
2	17.09	16.81	16.78	17.31
3	17.13	17.94	17.09	16.75
4	17.15	17.69	17.15	17
5	17.09	16.29	17.09	17.04
Total	84.83	84.83	84.83	84.83

These values are then plotted against all the 5 levels from the procedure of Taguchi method. A maximum signal to noise ratio shows that the data produce has a better signal with lesser ratio in which the data produced are mostly signal and not noise dominated. Based on the plotted data, the maximum values for each parameter are k = 17.15 (level 4), c =17.94 (level 3), toe =17.15 (level 4), camber =17.31 (level 2).

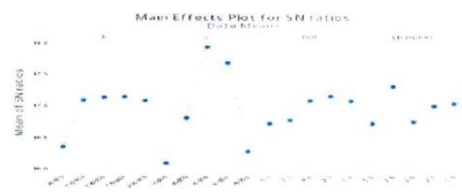

Fig. 3 Graph of SNR for first Taguchi

After determining the optimum values for each parameter, the ANOM was calculated. The analysis of means is a statistical approach for visually representing significant differences between sets of data. It is mostly involved in quality control. To find statistical differences of significance, the ANOM methodology compares the average of each group to the mean of the total process. The ANOM for SNR can be calculated using the formula below:

$$ANOM = \frac{1}{x}\sum_{i=1}^{x} SNR_i \quad (2)$$

TABLE VIII. ANOM FOR FIRST TAGUCHI

Level	*k*	*c*	toe	camber
1	3.274	3.22	3.344	3.346
2	3.418	3.362	3.356	3.462
3	3.428	3.588	3.418	3.35
4	3.428	3.538	3.43	3.4
5	3.418	3.258	3.418	3.408
Total	16.966	16.966	16.966	16.966

Lastly the analysis of ANOVA was performed. The ANOM value from the previous calculations were used to investigate the effect of the 4 parameters on the vertical acceleration of the 3-axle semi-trailer truck due to road irregularities. The analysis of variance (ANOVA) is used to see if there are any statistically significant differences between the parameters. ANOVA is calculated using the equation below:

$$SS = x\sum_{i=1}^{x}\left(m_i - m_{avg}\right)^2 \quad (3)$$

Table below shows the influence percentage of the parameters in improving the ride experience in heavy vehicle.

TABLE IX. PERCENTAGE INFLUENCE OF PARAMETERS

Parameters	Influence parameters (%)
k	12.63033
c	76.48912
toe	4.450542
camber	6.430006

It is observed that the spring constant has a influence of 12.63%, damping value with 76.49%, toe with 4.45% and finally camber at 6.43%. The damping coefficient has the major contribution of 76.49% in optimizing the suspension system of a vehicle. Hence, it is understood that the damping coefficient has the most impact in improving the vertical acceleration of the 3-axle semitrailer truck. As a result of the Taguchi optimization method, it is concluded that the optimized value for spring constant is 170000 N/m, damping coefficient at 45000 Ns/m, toe at 2.5 degree and camber at -2.5 degree. It is also concluded that the damping coefficient is the most important parameter in this research. These optimization values are used to carry out second Taguchi method to further narrow to down to smaller range for a better outcome.

B. Second Taguchi method

The second Taguchi was performed to provide a better outcome. This is because the differences by levels were large. Hence a second Taguchi was performed. The optimized value from the first Taguchi was used in the second Taguchi. The lowest RMS value from the first set of simulations has a combination of k = 140000 N/m, c = 45000 Ns/m, toe=5 and camber = -2.5. When comparing this data and the optimized value, a new range of levels were constructed to further narrow down to better optimization. Orthogonal array of L_{25} was again used. The same Taguchi process was repeated twice.

TABLE X. PARAMETERS AND LEVELS FOR SECOND TAGUCHI

Simulation Parameters	Level 1	Level 2	Level 3	Level 4	Level 5
Spring constant, *k*	110000	125000	140000	155000	170000
Damping coefficient, *c*	30000	37500	45000	52500	60000
Toe	2.5	3.75	5	6.25	7.5
Camber	-5	-3.75	-2.5	-1.25	0

TABLE XI. L25 SIMULATION RESULT FOR SECOND TAGUCHI

Simulation number	*k*	*c*	toe	camber	RMS
1	110000	30000	2.5	-5	0.139751
2	110000	37500	3.75	-3.75	0.133454
3	110000	45000	5	-2.5	0.124438
4	110000	52500	6.25	-1.25	0.122141
5	110000	60000	7.5	0	0.124448
6	125000	30000	3.75	-2.5	0.144764
7	125000	37500	5	-1.25	0.133167
8	125000	45000	6.25	0	0.122675
9	125000	52500	7.5	-5	0.122534
10	125000	60000	2.5	-3.75	0.131117
11	140000	30000	5	0	0.144951
12	140000	37500	6.25	-5	0.132336
13	140000	45000	7.5	-3.75	0.121958
14	140000	52500	2.5	-2.5	0.123007
15	140000	60000	3.75	-1.25	0.131495
16	155000	30000	6.25	-3.75	0.143425
17	155000	37500	7.5	-2.5	0.133385
18	155000	45000	2.5	-1.25	0.123878
19	155000	52500	3.75	0	0.123713
20	155000	60000	5	-5	0.131016
21	170000	30000	7.5	-1.25	0.145742
22	170000	37500	2.5	0	0.138434
23	170000	45000	3.75	-5	0.127729
24	170000	52500	5	-3.75	0.122589
25	170000	60000	6.25	-2.5	0.132947

The signal to noise ratio was then calculated to extract the data of the most optimized combination of data. The type of signal to noise used was the similar as the previous simulation set which is the "smaller the better". The calculations were performed and tabulated as below:

TABLE XII. SNR VALUE FOR SECOND TAGUCHI

Level	*k*	*c*	toe	camber
1	17.81	16.85	17.65	17.68
2	17.68	17.45	17.59	17.71
3	17.69	18.12	17.65	17.62
4	17.66	18.22	17.69	17.65
5	17.51	17.71	17.77	17.69
Total	88.35	88.35	88.35	88.35

Based on the calculation, the graph of Signal to Noise ratio was calculated to further present the data clearly as to which set of data produce the optimized result.

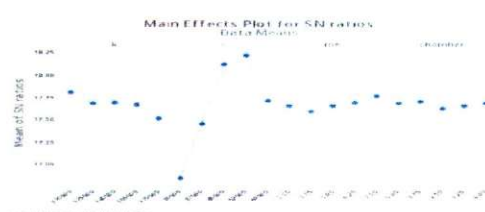

Fig. 4 SNR graph for second Taguchi

Based on the graph we can conclude that the combination of data of k = 110000 N/m (level 1), c = 52500 Ns/m (level 4), toe = 7.5 (level 5) and camber = -3.75 (level 2). Next the ANOM was calculated to compare the average of each parameter. ANOM was calculated and tabulated as portrayed below:

TABLE XIII. ANOM FOR SECOND TAGUCHI

Level	*k*	*c*	toe	camber
1	3.562	3.37	3.53	3.537
2	3.536	3.49	3.518	3.54
3	3.538	3.624	3.53	3.524
4	3.532	3.644	3.538	3.53
5	3.502	3.542	3.554	3.539
Total	17.67	17.67	17.67	17.67

The ANOVA was calculated to justify again the dominant parameter in this set of simulation. The ANOVA was calculated and tabulated as below:

TABLE XIV. PERCENTAGE OF PARAMETER EFFECT ON SECOND TAGUCHI

Parameters	Effect of parameters (%)
k	3.535451002
c	94.74699911
toe	1.358601258
camber	0.358948628

Again, it is justified that the damping coefficient plays an important role in producing a good suspension system when overcoming road irregularities.

C. Comparison Of Optimized And Unoptimized

Graphs of vertical acceleration , pitch rate, and vertical forces at each wheel were plotted with comparing the optimized and unoptimized set of data. This is to conclude if the optimized set of data is really an optimum value and manage to overcome and perform better that the existing set of data.

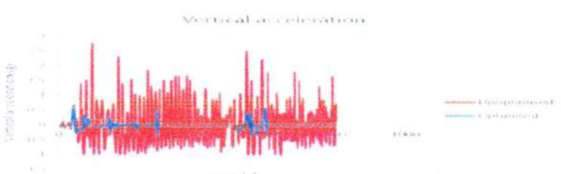

Fig. 4 Vertical acceleration of optimized and unoptimized

The graph above shows the difference in vertical acceleration of optimized and unoptimized set of parameters. The optimized value was plotted based on the outcome of the Taguchi. It is obvious that there is a huge difference on the vertical acceleration of the two sets of data. The vertical acceleration of the optimized parameters gives a much lower vertical acceleration in which it is reduced by 5 time from the unoptimized spring constant, damping coefficient, toe angle and camber angle. From the result, it can be observed that the vehicle is stable in terms where it does not accelerate vertically at a massive rate, and it only accelerates slightly when going up and coming down the bump.

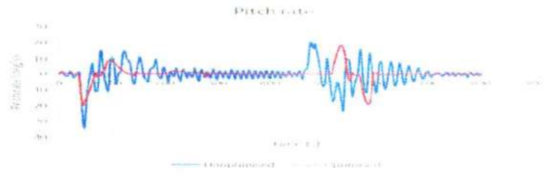

Fig. 5 Pitch rate of optimized and unoptimized

Apart from analyzing in vertical acceleration alone, the pitch rate was also analyzed. From the graph above we can see that at the unoptimized suspension system, the vehicle continuously pitching at certain rate until the end. However, when compared to the optimized suspension system, it is observed that the vehicle is only pitching when overcoming the bump. In which when going up the bump seen on the first half of the graph and when coming down the bump as seen in the second half of the graph. Comparing these two sets of data, it is also concluded that the optimized suspension gives s smaller pitching rate as seen at time of 50 seconds. At that time, the optimized suspension gives a pitch rate of -20 deg/s however the unoptimized suspension gives a -30 deg/s of pitch rate.

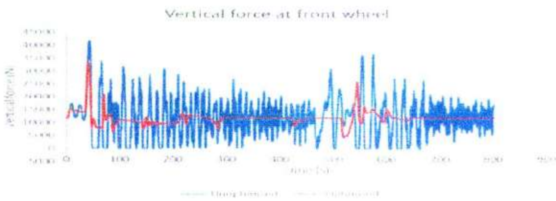

Fig. 6 Vertical force (front wheels) of optimized and unoptimized

The graph above shows the vertical forces exerted on the front wheel when overcoming the road irregularities [13, 14]. From the graph, it is depicted that the unoptimized suspension has the highest vertical force at 42000 N. The maximum vertical force for optimized suspension is 32000 N. This shows that the optimized suspension has significantly reduced the vertical force exerted on the wheel by 10000N. It is also observed that for the unoptimized suspension the vertical force is constantly being exerted rapidly on the vehicle. However, for the optimized suspension the vertical force exerted is more stable as it only increases at the beginning of going on the bump and when coming down the bump.

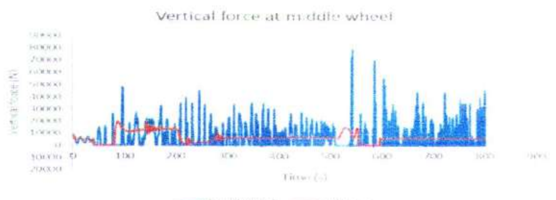

Fig. 7 Vertical force (middle wheel) of optimized and unoptimized

The graph above shows the vertical force exerted on the middle wheel. As for the middle wheel, it is observed that the optimized suspension has reduced the vertical force greatly. This is because the highest vertical force exerted is 80000 N and when comparing the maximum force of the optimized suspension which is at 50000 N, it is concluded that the vertical force has been reduced by 30000 N. The vertical force exerted by the optimized parameters gives a more consistent value than the unoptimized value which increases and decreases frequently over the time [15, 16].

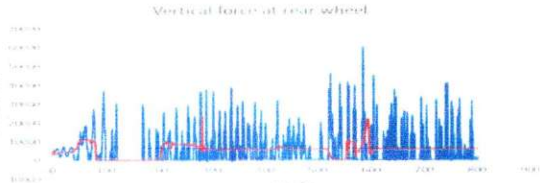

Fig. 8 Vertical force (rear wheel) for optimized and unoptimized

The graph above shows the vertical forces exerted on the rear wheels when overcoming the medium bump. The line in red represents the graph of optimized set of data and the line in blue shows the unoptimized set of data. From the graph when comparing the maximum values of both optimized and unoptimized suspension system, it is concluded at a difference of 60000 N to 38000 N the optimized suspension has greatly reduced the vertical force on the rear wheels as well. The optimized suspension minimizes the vertical force whereby from the graph the rise was only observed at certain part which is when inclining and declining the bump.

IV. CONCLUSION

Based on this Taguchi method analysis, the set of data that produces the most optimized value is spring constant of 110000 N/m, damping coefficient of 52500 Ns/m, toe angle of 7.5 deg and camber angle of -3.75 deg. This can further be proved that the second Taguchi gives a more optimized data set than the first Taguchi. It can be proved when comparing the smallest RMS value produced by both set of simulation. In the first Taguchi, the smallest RMS is 0.12196893. In the second Taguchi, the smallest RMS is 0.12195893. It shows that the second optimization performs better giving a lower vertical acceleration to the vehicle when overcoming the medium bump. When comparing the data from the Taguchi to the current default system of the vehicle, in terms of vertical acceleration, pitch angle, pitch rate and vertical forces it is concluded that the optimized system indeed gives a better and much upgraded performances in all four terms when compared to each other.

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