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Response Surface Optimization of Car Support Jack Bar on Design Parameter via Finite Element Analysis

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ABSTRACT

The optimized design parameter of the car support jack bar is crucial in ensuring the safety of maintenance activity. Improper design of the bar and pinhole could induce the jack bar's failure when enduring the high loading of the car. This paper presents the response surface optimization on the design parameter of the car jack bar using finite element analysis. Three factors: outer diameter (A), pinhole diameter (B), and bar thickness (C), and two responses which are Von Mises stress (Y_1) and displacement (Y_2) of the jack bar, were considered in the optimization study. The design of the numerical experiment was constructed using the central composite design (CCD). The results revealed that outer and pinhole diameters are the two most significant factors in the responses. The changes in outer and pinhole diameters crucially affected the Von Mises stress and displacement of the jack bar. The optimized factors suggested in the optimization software are 49.79 mm outer diameter, 21.70 mm pinhole diameter, and 5.85 mm bar thickness. The application of optimized factors yielded the minimum responses that are 45.23 MPa Von Mises stress and 0.022 mm of displacement for the car jack bar. The optimization findings are expected to be useful for the engineer in designing the high-reliability car jack bar.

Keywords: Response surface methodology, Finite element analysis, Design optimization, Car Jack bar

1. INTRODUCTION

Optimization can be achieved in the engineering process through techniques such as response surface methodology (RSM) [1,2] and the Taguchi [3,4] method. Typically, if the optimization process is carried out by trial and error, it increases the time and cost. Therefore, in order to approach a more reasonable settlement, a systematic optimization technique should be approached. Response surface methodology (RSM) can be applied to optimize a product design parameter using central composite design (CCD) [5]. The responses influenced by the independent variables can be optimized by the design of the experiment. Therefore, the relationships between each factor are investigated by using RSM. A user-friendly design software [6] facilitates design, mathematical modeling, and optimization. By that, the simulation or experimental run can be reduced due to the combination parameters suggested by RSM. It is also efficient for multi-purpose optimization. With this aid of optimization software, the research time can be minimized during process and design problems. Therefore, research expenses and time before actual mass production can be reduced by the application of simulation analysis.

Optimization provides the engineer with an understanding of the process, such as the optimum parameter of the product. The engineering process used the reaction surface method in the experimental design (DOE) [7]. RSM is a collection of mathematical and statistical techniques for empirical model designing. The methods of mathematical and statistical data collection in RSM were used to interpret the interactions between independent and reaction variables and to adapt

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the reaction surface [8]. RSM optimized the responses, which are influenced by independent variables. A series of tests with different parameters of the independent variables were used to identify the changes in the responses. There are stages of applying the RSM in optimization [9]. The first phase involves choosing independent variables and factors. According to the goal and desirability of the study, variables that have a significant impact on the system will be chosen. Every coded factor's level is typically set between -1 and +1. The determination of the experiment design, analysis, estimation, and validation of the model equation constitutes the next stage. For the RSM model, a full quadratic equation is typically employed. The final step is determining the response and optimal points by obtaining the response surface and perturbation plots. The results can be used to determine the maximum and minimum points. Plots show the function of independent parameters.

RSM optimization has been applied in various engineering applications [10]. In automobile maintenance, the cars are raised off the ground by car jacks for maintenance and repairs. Jack stands offer secure, fixed support after raised vehicles; they do not lift them. A passenger car typically weighs 4,094 pounds [11]. When a faulty jack stand or car jack malfunctions, the person working underneath the car will likely suffer severe and possibly fatal injuries. Therefore, the optimized design of the car stand is significant in ensuring the person's safety in maintenance activities. A defect in the manufacturing and non-optimized design of the car jacks/stands could lead to unintended injuries. Thus, the car stand should be designed carefully for its safe application. The design parameters must be optimized from other perspectives, such as strength and cost. The optimum design parameters have to be decided for the stand while maintaining its strength and production cost. The current study optimizes the design parameters for the car support jack bar using finite element analysis [12, 13]. The vertical bar's stress and displacement are considered the response in the optimization.

2. MATERIAL AND METHODS

In this study, the car support jack bar model is developed using Solidworks. The developed model was then used to run a simulation Xpress [14] to determine the maximum stress and displacement. Figure 1 shows the model of the car support jack bar. The simulation Xpress obtained the von Mises stress and displacement in the analysis. In order to run the simulation, some settings need to be done. Firstly, the car support jack bar model is opened in Solidworks, and the parameters as desired for the simulation are edited. Select the tool followed by the Xpress product. After that, the fixture was set up. The fixed boundary was defined at both sides of the lowest pinhole. Plain carbon steel was considered in the simulation, and the material properties are summarized in Table 1.

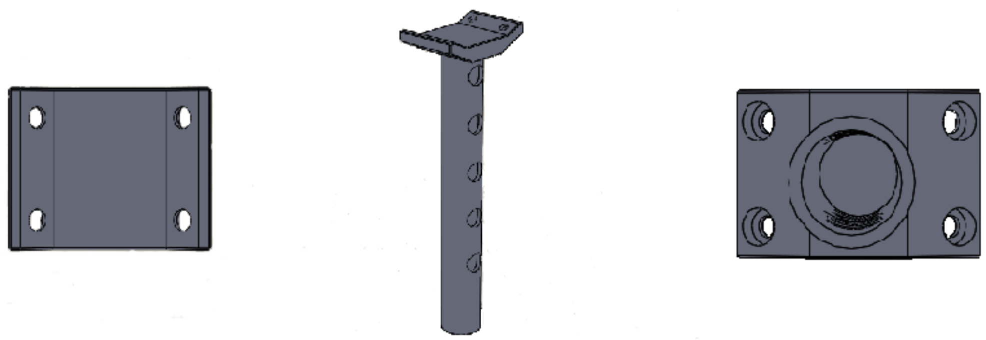


Figure 1: Solidworks model of the car support jack bar.

Table 1: Material properties of plain carbon steel used in the simulation [15].

Property (Units)	Value
Elastic modulus (N/mm^2)	210000
Poisson's ratio	0.28
Mass density (kg/m^3)	7800
Tensile strength (N/mm^2)	399.83
Yield strength (N/mm^2)	220.59
Shear modulus (N/mm^2)	79000

In the RSM optimization, the design of numerical experimental runs was constructed based on the three selected factors: outer diameter (A), pinhole diameter (B), and bar thickness (C). The RSM software generated a total of 20 numerical runs. Table 2 shows the parameters with three actual and coded levels each. The factors varied over three levels, between -1 and +1. The lowest coded level is -1, the middle coded level is 0, and the coded level for the highest is +1. The range of the factor was considered according to the actual car stand available in the market.

Table 2: Actual and coded values for the factor of CCD design.

	Coded value		
Factor (symbol)	-1	0	1
	Actual value		
A: Outer diameter (mm)	30	40	50
B: Pinhole diameter (mm)	15	20	25
C: Bar thickness (mm)	4	6	8

3. RESULTS AND DISCUSSION

Table 3 shows the data obtained from a group of twenty Central Composite Design (CCD) runs conducted in this study. Both simulation and predicted results from ANOVA response models of response (Y) are summarized. The target of the runs is to minimize von Mises Stress (Y_1) and displacement (Y_2) on the car support jack bar. Enormous stress and displacement weaken the car support jack bar during its use. Thus, the optimization goal is to avoid this problem and find the minimized parameter for this car support jack bar. An ideal parameter usually aims to improve quality and productivity and minimize manufacturing costs. The lowest displacement (Y_2=0.0248) was observed in Run 11 when the car support jack bar was designed with the largest outer diameter, smallest pinhole diameter, and highest bar thickness.

In the manufacturing process, this condition is considered because it can reduce the cost and production cycle time. However, the highest von mises stress (Y_1= 662.2MPa) was identified in Run 15 when the smallest outer diameter, highest pinhole diameter, and lowest bar thickness were applied. The largest outer diameter, lowest pinhole diameter, and highest thickness indicated the lowest Von Mises stress (Y_1= 61.11MPa). Therefore, the design that induces the highest Von Mises stress and displacement is not recommended for the car support jack bar. The effects of each independent variable (A, B, and C) on the responses (Y_1 and Y_2) are explained in the subsequent sections.

Table 3: Design of experiment and results.

Run order	Factor (coded)			Responses (Y)			
				Simulation		Model predicted	
	A	B	C	Y_1	Y_2	Y_1	Y_2
1	0	0	-1	173.30	0.0661	176.29	0.0690
2	1	1	-1	135.70	0.0542	37.56	0.0509
3	1	0	0	89.25	0.0340	89.76	0.0220
4	0	0	0	113.70	0.0481	106.46	0.0460
5	0	0	0	113.70	0.0481	106.46	0.0460
6	1	-1	-1	124.80	0.0448	86.20	0.0545
7	0	0	0	113.70	0.0481	106.46	0.0460
8	0	0	1	94.20	0.0398	112.91	0.0450
9	0	1	0	143.80	0.0586	235.43	0.0826
10	-1	1	1	645.30	0.1894	514.32	0.1765
11	1	-1	1	61.11	0.0248	60.58	0.0307
12	-1	-1	1	139.00	0.0588	67.56	0.0609
13	0	0	0	113.70	0.0481	106.46	0.0460
14	-1	0	0	266.10	0.0927	252.68	0.1120
15	-1	1	-1	662.20	0.2098	554.3	0.2007
16	0	0	0	113.70	0.0481	106.46	0.0460
17	0	0	0	113.70	0.0481	106.46	0.0460
18	0	-1	0	106.30	0.0425	36.37	0.0266
19	-1	-1	-1	231.50	0.0891	144.86	0.0883
20	1	1	1	71.040	0.0308	71.9	0.0303

Factor A = outer diameter, Factor B = pinhole diameter, and Factor C = bar thickness.
Response Y_1 = Von mises stress (MPa), and Response Y_2 = displacement (mm).

3.1 Regression model and ANOVA

The optimization software was used to choose the regression models for responses, maximum Von Mises stress (Y1), and maximum displacement (Y2) based on the highest-order polynomials, significant additional terms, and lack of aliased models. All significant model terms (values of "Prob > F" less than 0.05) were best fitted by the quadratic model (eqs.1-2), as recommended by the software. The final empirical models in terms of coded factors (A = outer diameter, B = pinhole diameter, and C = bar) are as follow :

$$Y1 = 106.46 - 146.22A + 99.53B - 31.69C + 82.07A^2 + 29.44B^2 + 38.14C^2 - 114.52AB - 2.37AC + 9.33BC \quad (1)$$

$$Y2 = 0.046 - 0.045A + 0.028B - 0.012C + 0.021A^2 + 8.595e\text{-}003B^2 + 0.011C^2 - 0.029AB + 9.075e\text{-}004AC + 8.050e\text{-}004BC \quad (2)$$

Tables 4 and 5 summarize the ANOVA results for the models (Y_1 and Y_2). The coefficient of determination was used in the ANOVA analysis to assess the model's quality (R^2). According to the results of the ANOVA analysis, the R^2 for each empirical equation (Eqs. 1-2) was between 0.95 and 0.96 for responses Y_1 and Y_2. The standard deviations for each model were 51.61 and 0.013, respectively. Each model had a significantly high R^2 value. Thus, each empirical model's total variability percentages were 95% (Y_1) and 96% (Y_2), respectively.

Table 4: Analysis of variance (ANOVA) of quadratic model for maximum Von Mises stress (Y_1).

Source	Sum of squares	DF	Mean square	F value	Prob > F
Model (Y1)	5.139E+005	9	57097.32	21.44	< 0.0001
A	2.138E+005	1	2.138E+005	80.28	< 0.0001
B	99068.18	1	99068.18	37.20	0.0001
C	10039.39	1	10039.39	3.77	0.0809
A2	18521.76	1	18521.76	6.95	0.0249
B2	2383.98	1	2383.98	0.90	0.3664
C2	4000.98	1	4000.98	1.50	0.2484
AB	1.049E+005	1	1.049E+005	39.39	< 0.0001
AC	44.89	1	44.89	0.017	0.8993
BC	696.20	1	696.20	0.26	0.6203
Residual	26633.20	10	2663.32		
Lack of Fit	26633.20	5	5326.64		
Pure Error	0.000	5	0.000		
Std. Dev.	51.61		R-Squared	0.9507	
Mean	181.29		Adj R-Squared	0.9064	
C.V.	28.47		Pred R-Squared	0.8035	
PRESS	2.143E+005		Adeq Precision	16.442	

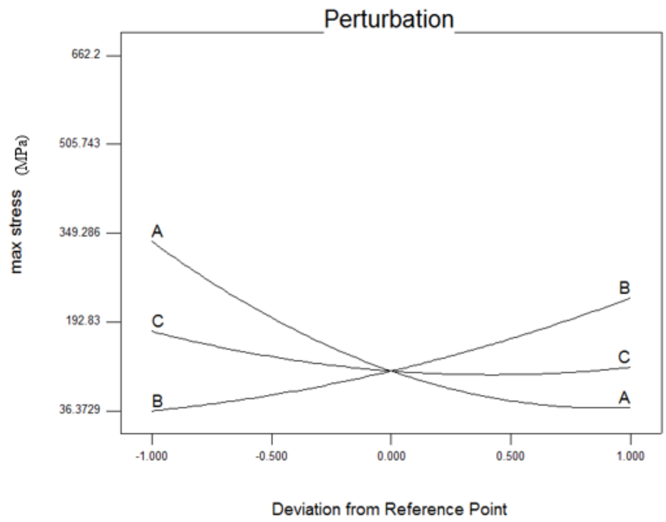
Table 5: Analysis of variance (ANOVA) of quadratic model for maximum displacement (Y_2).

Source	Sum of squares	DF	Mean square	F value	Prob > F
Model (Y2)	0.043	9	4.796E-003	26.68	< 0.0001
A	0.020	1	0.020	113.27	< 0.0001
B	7.994E-003	1	7.994E-003	44.48	< 0.0001
C	1.447E-003	1	1.447E-003	8.05	0.0176
A2	1.267E-003	1	1.267E-003	7.05	0.0241
B2	2.032E-004	1	2.032E-004	1.13	0.3127
C2	3.367E-004	1	3.367E-004	1.87	0.2011
AB	6.961E-003	1	6.961E-003	38.73	< 0.0001
AC	6.588E-006	1	6.588E-006	0.037	0.8520
BC	5.184E-006	1	5.184E-006	0.029	0.8685
Residual	1.797E-003	10	1.797E-004		
Lack of Fit	1.797E-003	5	3.595E-004		
Pure Error	0.000	5	0.000		
Std. Dev.	0.013		R-Squared	0.9600	
Mean	0.066		Adj R-Squared	0.9240	
C.V.	20.25		Pred R-Squared	0.8922	
PRESS	0.014		Adeq Precision	18.967	

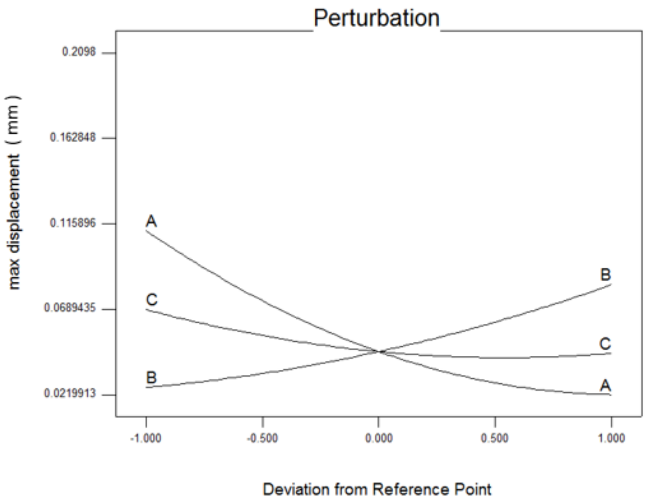
3.2 Effect of factors on the response

The perturbation plots obtained from the software were used to determine each factor's sensitivity to the responses of maximum stress (Y_1) and displacement (Y_2). Figure 2 presents the perturbation plots for (a) maximum Von Mises stress and (b) maximum displacement. The result was obtained by diverting one factor while the other remained consistent. The correlation of the factors (A, B, and C) to the model response Y_1 is shown in Figure 2(a). Maximum Von Mises stress (Y_1) was mainly influenced by factors A and B, compared to factor C. Factors A and B demonstrate a crucial change from the coded value -1 to +1 compared to factor C.

Figure 2(b) illustrates the perturbation plot of model response Y_2 (maximum displacement). The existence of each variable A, B, and C in the perturbation plots demonstrate the impact of maximum displacement (Y_2). However, factors A and B most significantly influenced the changes in maximum displacement. The maximum displacement considerably changed from a coded value of -1 to +1 for factors A and B compared to factor C. The perturbation plots demonstrate that factor C changed only minimally for both model responses, Y_1 and Y_2, which indicates less sensitivity to both model responses (Y_1 and Y_2) compared with factors A and B. This result indicates that the outer diameter and pinhole diameter design significantly affect the maximum Von Mises stress (Y_1) and maximum displacement (Y_2).



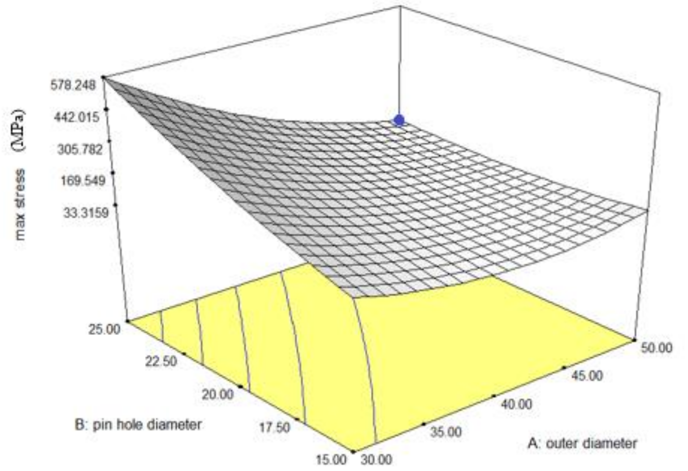
(a)



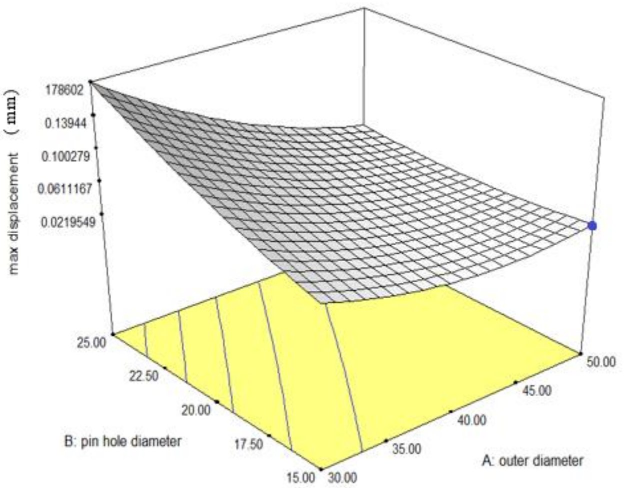
(b)

Figure 2: Perturbation plot for (a) maximum Von Mises stress and (b) maximum displacement.

Figure 3 depicts the 3D response surface and contour plots of the quadratic model for Y_1 and Y_2, which were plotted to study the interactive relationship between each factor and response. The two most important factors, which were chosen based on the sensitivity level to the responses as plotted in perturbation plots, were plotted in the 3D response surface. On the 3D response surface plots, a blue dot indicates the response's minimum value. In Figure 3, the minimum Von Mises stress was observed at an outer diameter of 50 mm and a pinhole diameter of 25 mm. Minimum displacement of the bar was achieved with the application of outer diameter at 50.00mm and pinhole diameter at 15 mm.



(a)



(b)

Figure 3: 3D response surface for (a) max Von Mises stress and (b) maximum displacement.

3.3 Optimization of design parameters

Von Mises stress and displacement on the car support jack bar were analyzed in the optimization study. More investigations are carried out to obtain the idealized parameter using the RSM tool on the car support jack bar. Throughout this study, the design parameter was focused on the outer diameter, pinhole diameter, and bar thickness. In order to minimize the responses, the optimization software suggested the optimized factors of the design. The suggested solution is A = 49.79 mm, B = 21.70 mm, and C = 5.85 mm, with the minimum Y_1 (43.48 MPa) and Y_2 (0.024 mm).

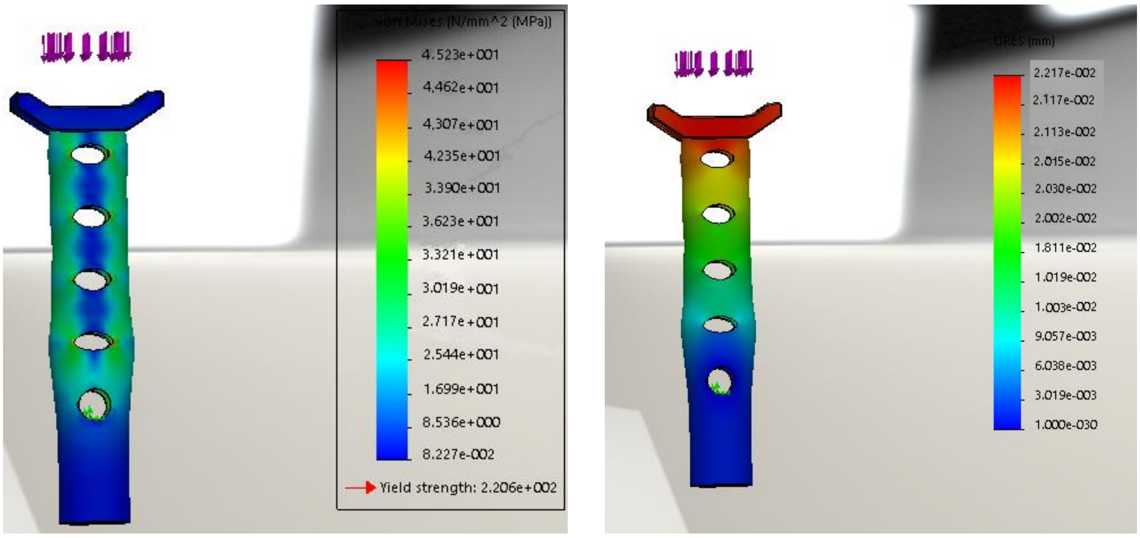
3.4 Validation of simulation results

The reliability of the car stand could be improved by minimum stress and displacement. The minimum responses (Y_1 and Y_2) in this optimization study are significant. The optimization software suggested the idealized design factors (A = 49.79 mm, B = 21.70 mm, and C = 5.85 mm) that yield minimum Von Mises stress and displacement. The suggested idealized factors were confirmed through simulation Xpress. The comparison between model response and simulation is listed in Table 6. The discrepancy in results varied within the range of 3.86% to 8.33%. This finding shows that the suggested model responses could achieve a reliable prediction.

Table 6: The validation of model response for optimized factors (A = 49.79 mm, B = 21.70 mm, C = 5.85 mm).

	Responses (Y)	
	Y_1	Y_2
	Von Mises stress (MPa)	Displacement (mm)
Model response	43.48	0.024
Simulation	45.23	0.022
Error (%)	4.03	8.33
Standard deviation	1.2374	0.0014

Figure 4 shows the Von Mises stress and displacement after RSM optimization. The highest displacement was centered at the top of the bar. In comparison, Von Mises stress was found focused at the second pinhole from below part of the car jack bar. The optimum value of each factor was successfully determined using the response surface methodology. Besides, other decision-making tools, such as the analytical hierarchy process (AHP) [16,17], can also be integrated into car jack bars' manufacturing process selection.



(a) (b)

Figure 4: Simulation results for (a) Von Mises stress (MPa) and (b) displacement (mm).

4. CONCLUSION

This RSM optimization on the car support jack bar via finite element analysis simulation was successfully conducted. The influence of three factors (A = outer diameter, B = pinhole diameter, and C = bar thickness) was modeled and optimized to minimize the von Mises stress (Y_1) and maximum displacement (Y_2). A quadratic model was used to fit each model response. The software's recommended optimal values for factors A, B, and C were 49.79 mm, 21.70 mm, and 5.85 mm. The responses Y_1 and Y_2 were examined through simulation Xpress, which resulted in 45.23 MPa and 0.022 mm, respectively. The results discrepancy of model reactions and simulation came out within the extent of 4.03% to 8.33%. Overall, the outer diameter, pinhole diameter, and bar thickness considerably minimized the Von Mises stress and displacement. The results revealed that the outer and pinhole diameter crucially influenced the von Mises stress and displacement. This study provides a better understanding of each factor's interactive relationships and the optimization of the car support jack bar using RSM.

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