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# The Best Location for Speed Bump Installation Using Taguchi and Classical Design of Experiments

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**ABSTRACT** Speed bumps as a traffic-calming technique can be a key issue in ensuring safe passage through secondary roads. Limited works in finding the best location of speed bumps prior to stop points has prompted this investigation. The objectives of this work are to explore the influence of factors in determining the bump location for obtaining the minimum speed at a stop point and to obtain a robust design by investigating the effect of environmental noise on the factors. The mathematical models effectively explain the performance indicators within the range of the factors, and the vehicle speed is the most significant factor.

**KEYWORDS** speed bump location, classical design of experiments (DOE), Taguchi method, distance–time, local optimum point

## INTRODUCTION

For the sake of speed control in residential areas, traffic-calming measures are used to decrease the vehicle speed when passing through high-risk area (Ansari Ardeh et al. 2008; Salau et al. 2004; Vrubel et al. 2008). Speed bumps or road bumps are extensively used for controlling vehicle speed and improving traffic safety on local streets (Huang et al. 2011; Khorshid and Alfares 2004; Salau et al. 2004). Various types of materials (asphalt, cement, or even rubber) are used to make speed bumps and these are directly applied on the road. Speed bumps are best suited for deployment on local streets with posted speed limits of 40 km/h or lower. These devices are intended to reduce speeds to as low as 8 km/h and therefore they are appropriate for high-risk areas that have low speed limits (Huang et al. 2011; Parkhill et al. 2007; Pedersen 1998). The above studies seem to indicate that speed bumps are effective in moderating vehicle speeds in their surrounding area.

However, some other studies over the last two decades on the deployment of speed bumps have yielded fully different outcomes. These results seem to indicate that speed bumps have limited impact on reducing traffic speed, especially when these are compared to better designed passive speed control devices, such

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as speed humps or cushions (Pau 2002; Wang et al. 2009; Zhen 2008). Pau (2002) conducted an investigation based on a case study in an Italian town that revealed that when vehicles approach speed bumps they generally avoid the vibration and undulation experienced when passing over the speed control devices. This requires drivers to perform maneuvers or slow down suddenly, which causes unexpected accidents. Bumps and humps are two different types of protuberances that need to be distinguished. Bumps are narrow and humps are wide. Guidelines for their design are moderately different, so they have different effects on drivers and vehicle performance when passing over them (Chadda and Cross 1985). When the bumps are installed properly, it is anticipated that the bumps slow down the flow of traffic in the critical area before the stop point and help drivers to decrease their speed smoothly. The vibration experience when going over speed bumps would make drivers pass through the critical areas such as road junctions and entry gates at a suitable speed. There are various factors that may have an influence on the position of speed bumps, and these include vehicle speed, vehicle weight, road inclination, distance from the bump to the stop point, road friction, vehicle braking capability, climate situation, and so on.

There are policies and engineering guidelines for the design and application of speed control devices, published by Institutes of Transportation Engineers, and most engineers follow them (Ernish et al. 1998; Ewing 1999; Parkhill et al. 2007). However, there is no existing research or regulations on determining the best location for the installation of these devices before stop points using practical statistical methodologies. Therefore, this study aims to examine the influence of some design variables or factors in determining the best location for installing a speed bump by optimizing the distance of the bump to stop point using the classical and Taguchi design of experiments (DOE).

Classical DOE is an efficient statistical technique whereby experiments designed are performed under controllable conditions to appraise which design factors have a significant effect on the process response in order to quickly optimize performance of systems (Uy and Telford 2009). Hambli et al. (2003) found that DOE is an efficient and cost-effective way to model and analyze the interactions that indicate process variations. The application of experimental design techniques has proved to be very effective in improving

process yield, reducing variability in the process, and ensuring conformance to objective requirements of reduced design and progression time and reduced cost of operation. By applying designed experiments, engineers can ascertain which subset of the process variables has the greatest influence on the performance of the process (Antony and Capon 1998).

Analysis of variance (ANOVA) is a highly effective technique to analyze experimental data that involves quantitative measurements. It is especially suitable in factorial experiments where numerous independent sources of variation may be presented (Montgomery and Runger 2011).

The Taguchi DOE focuses on product or process robustness against uncontrollable influences, or noise. The method is designed to reduce variability and optimize function or performance. It is a modification of the classical DOE concept (Antony 2006; Peace 1993). The method applies two arrays, an inner array for the control factors and an outer array for noise factors. This is in place of a single array in classical DOE. The strategy is to quantify the signal-to-noise interaction between the control and noise factors, just as factor-to-factor interactions are quantified in classical DOE (Peace 1993).

Once the experiments are performed, the results are summarized by computing the mean and the signal-to-noise ratio (SNR). SNR is a performance statistic that is applied by Taguchi to measure the process robustness (Taguchi et al. 2007). Therefore, the Taguchi method makes the process performance insensitive to the variations of uncontrollable noise factors (Liu et al. 2010). It is evident that both classical and Taguchi DOE have their similarities and differences. This study will also compare the findings obtained as a result of using the different methods.

## EXPERIMENTAL DETAILS

### Classical DOE Method Experimental Details

Determining the best location for the installation of a speed bump before a convenient stop point (e.g., before an entry gate or a road junction) by the use of classical DOE method involved a full-factorial design and environmental noise blocking technique. Three facets of the procedure were examined: *factors*, or inputs to the process that can be categorized as either

controllable or uncontrollable variables; *levels*, or settings of each factor; and *response* or output of the experiment (Montgomery 2008). In order to clarify the process, four controllable factors, namely, the speed of the car before the bump, the number of passengers, the road surface inclination, and the distance from the bump to the stop point, are examined. In this experimental design, the road friction, which depends on the type of material used when making the road; the climate situation; and the vehicle braking capability are the uncontrollable or intervening variables and are totally ignored in this experiment. To investigate the effects of the four controllable factors, according to the aforementioned explanations, the factors were divided into various levels as follows:

- The number of passengers (A), which encompasses two levels: 1 passenger and 5 passengers.
- The speed of the car before the bump (B), which includes two levels: 10 km/h and 30 km/h.
- The distance between the bump and the stop point (C), consists of two levels: 10 m and 20 m.
- The road surface inclination (D), which encompasses two levels: a flat surface (0%) and 7% road surface inclination.

In the current study, the speed at the designated stop point was treated as a response and it is desirable to have a minimum speed at this stop point; therefore, the distance from the bump to this point should be correctly determined. Because speed is a function of time and distance, measurement of time would simplify the data collection step. The time taker measures the time taken to travel from the starting point after the bump to the stop point; therefore, the requirement to minimize speed at the stop point was changed to the maximization of this time. Upon obtaining the model describing the relationship between the significant factors and the response, the optimum setting for the factors can be determined. Additionally, adjustments of these critical variables can be explored to determine their effect on the response.

Based on the full-factorial design and according to the aforementioned levels, there are  $2^4$  potential treatment combinations. Three replicates of each treatment combination were considered, which means that there were  $2^4 \times 3$  experimental trials or runs to be done for all combinations of factor levels. Due to the number of experiments, the trials spanned over 2 days; in order to

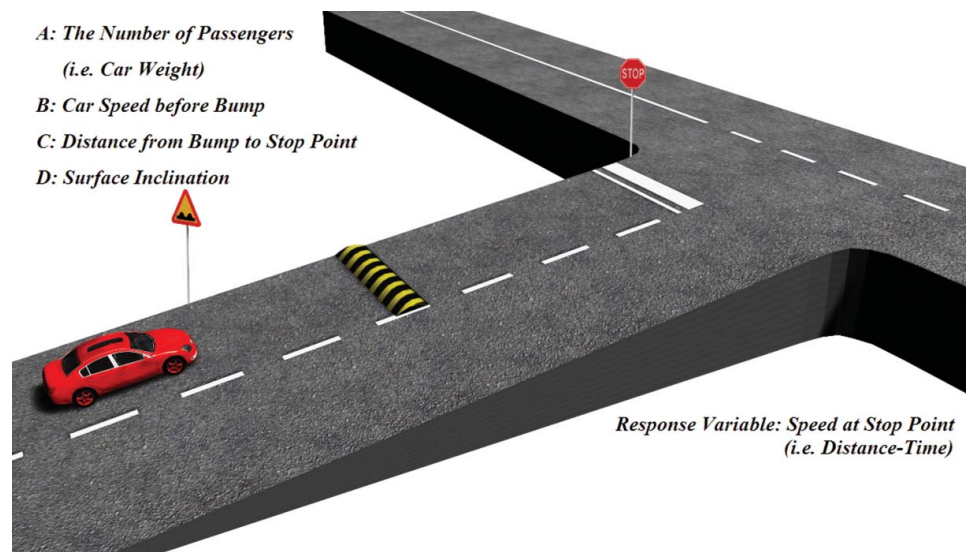
neutralize the effect of different days, each day was considered as one block. To validate the assumption that the factor effect relationships are linear, two center points (CPs) were added to each block of the design. These CPs were set at three passengers, 20 km/hr vehicle speed, 15 m distance from the bump to the stop point, and 3.5% road surface inclination. Eventually, the experimental design involved  $(2^4 \times 3) + 2 + 2$  or 52 runs.

After planning the factorial experiment, the experiments were performed by utilizing a Proton Saga Iswara 1.3S Sedan on three roads with totally homogeneous situations of asphalt type and speed bump shape and type but with different road surface inclinations (0%, 3.5%, and 7%). The driver remained the same throughout the experimental trials. Other equipment such as chronometer, clinometer, and tape measure were used when performing the experiment. While the experiment was performed, in order to ignore the effect of driving force on the vehicle speed after passing the bump, the driver put the vehicle gear in the freewheel state. In Figure 1, the experimental independent variables as input factors and dependent variable as an output or response factor are depicted.

Table 1 shows the experimental design used in this study. Table 2 vividly shows the treatment combinations that need to be performed on day 1 and day 2 as two blocks were considered in the experimental design. The selection is based on the ABCD factorial effects. The results of the actual experiments are also presented in Table 1.

## Taguchi DOE Method Experimental Details

For Taguchi's DOE, the same factors were considered; that is, the number of passengers, the speed of the vehicle before the bump, the surface inclination, and the distance from the bump to the stop point were considered as controllable variables; asphalt situation, drivers, and time takers (two different individuals) were the noise variables considered. Although noise variables were difficult or impossible to control during the process, their levels could be controlled for experimental purposes. Thus, selection of the levels of controllable variables focused on minimizing process variability caused by the noise variables and simultaneously reaching some desired mean response. In the above-mentioned example, to



**FIGURE 1** Graphical experimental design—dependent and independent variables.

find the best location for a speed bump, the desired mean response was the maximum time between the bump and the stop point.

We decided to study the four design parameters at two levels in order to facilitate the comparison to be made with the classical DOE method. The degrees of freedom (dof) required for studying four main effects

were four and one dof is required for the average, resulting in a total of 5 dof. Thus, a minimum of five treatment combinations was required; therefore, the most appropriate orthogonal array design to meet this requirement was an eight-trial experiment (L8 orthogonal array). Table 3 illustrates the list of design parameters and their ranges chosen for the experiment.

**TABLE 1** Response Factors Measured when Performing the Actual Experiment Design

Std. order	Treatment combination	ABCD factorial effect	Factors				No. of replicates (time, s)			Total	Average	SD
			A: No. of passengers	B: Vehicle speed (km/h)	C: Distance (m)	D: Surface inclination (%)	R <sub>1</sub>	R <sub>2</sub>	R <sub>3</sub>			
1	(1)	+	1	10	10	0	2.18	4.90	3.26	10.34	3.45	1.37
2	a	-	5	10	10	0	3.05	3.69	3.35	10.09	3.36	0.32
3	b	-	1	30	10	0	1.20	1.35	1.68	4.23	1.41	0.24
4	ab	+	5	30	10	0	1.36	1.26	1.71	4.33	1.44	0.24
5	c	-	1	10	20	0	4.31	7.76	6.56	18.63	6.21	1.75
6	ac	+	5	10	20	0	4.41	7.95	7.72	20.08	6.69	1.98
7	bc	+	1	30	20	0	3.08	3.05	3.29	9.42	3.14	0.13
8	abc	-	5	30	20	0	3.13	3.16	3.37	9.66	3.22	0.13
9	d	-	1	10	10	7	4.34	2.79	3.91	11.04	3.68	0.80
10	ad	+	5	10	10	7	3.53	4.27	3.87	11.67	3.89	0.37
11	bd	+	1	30	10	7	1.65	1.66	1.96	5.27	1.76	0.17
12	abd	-	5	30	10	7	1.70	1.58	2.14	5.42	1.81	0.30
13	cd	+	1	10	20	7	8.12	8.42	8.64	25.18	8.39	0.26
14	acd	-	5	10	20	7	5.71	8.93	10.28	24.92	8.31	2.35
15	bcd	-	1	30	20	7	3.45	3.18	3.05	9.67	3.22	0.20
16	abcd	+	5	30	20	7	3.20	3.24	3.46	9.90	3.30	0.14
17	CP	0	3	20	15	3.5	2.79	3.41	3.44	9.64	3.21	0.37
18	CP	0	3	20	15	3.5	3.46	5.13	4.29	12.88	4.29	0.84
19	CP	0	3	20	15	3.5	3.05	3.41	3.14	9.59	3.20	0.19
20	CP	0	3	20	15	3.5	4.53	3.41	2.96	10.89	3.63	0.81



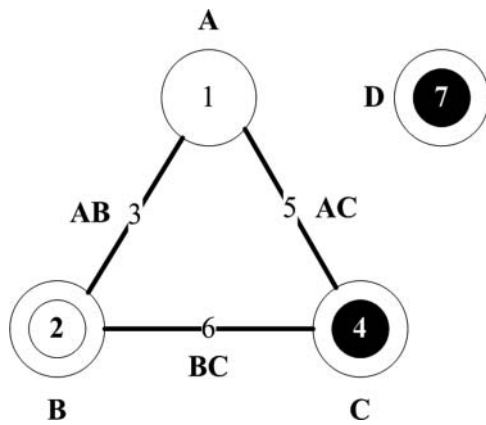


FIGURE 2 Linear graph.

allow all main effects and two-factor interactions to be considered for the model. No interaction terms were ignored in the model. Due to the asymmetry in the Box-Cox plot, inverse square with  $-0.5$  lambda was selected as a type of the model transformation to transform response data. Then, a half-normal plot of effects was selected to find significant estimated effects of the model. The main effects of B, C, and D and the BC interaction terms were selected in order to enter the ANOVA model as significant main and two-factor interaction effects (Figure 3). An ANOVA table was used to confirm statistically significant effects and to summarize the test (Table 6).

In the ANOVA table, the model F-value of 118.03 indicates that the model is significant and there is only a 0.01% possibility that a model F-value this large could occur due to noise. In this case B, C, D, and BC are significant model terms; center points and, consequently, the model curvature are not significant. The lack of fit F-value of 0.44 specifies that the lack of fit is not significant related to the pure error. There is a 92.60% probability that a lack of fit F-value this large could occur due to noise. The predicted  $R^2$  of 0.8840 is in reliable conformance with the adjusted  $R^2$  of 0.9015 due to the less than approximately 0.2 difference from each other. Adequate precision of 28.174 indicates an adequate signal

TABLE 5 Column Information Sheet

Name	Units	Type	Low (-1)	High (+1)	Mean	SD
A: No. of passengers	(No.)	Factor (numeric)	1	5	3	—
B: Vehicle speed	(km/h)	Factor (numeric)	10	30	20	—
C: Distance	(m)	Factor (numeric)	10	20	15	—
D: Surface inclination	(%)	Factor (numeric)	0	7	3.5	—
Time	(s)	Response (numeric)	1.2	10.28	3.93	2.26

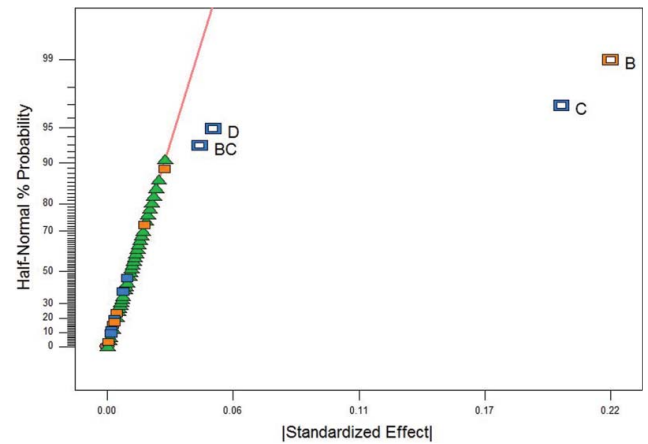


FIGURE 3 Half-normal probability plot.

and ratios greater than 4 imply adequate model distinction (Anonymous 2007; Anderson and Whitcomb 2007). In this case, the value is ideally above 4. In the post ANOVA (Table 7), the high and low 95% confidence interval (CI) indicates that the factors have a statistically significant effect on the response.

The predictive models are listed in both actual and coded terms. These equations are used for prediction. With these equations, adjustments to the factor levels can be explored to see their effect on the response. The following equations are the final empirical models in terms of coded factors (Eq. [1]) and actual factors (Eq. [2]) for time (the experiment response):

$$\frac{1}{\text{Sqrt}(\text{Time})} = +0.56 + 0.11 * B - 0.100 * C - 0.023 * D - 0.020 * B * C \quad [1]$$

$$\frac{1}{\text{Sqrt}(\text{Time})} = +0.54379 + 0.017176 * \text{Car Speed} - 0.011835 * \text{Distance} - 3.10876E - 003 * \text{Surface Inclination} - 4.07165E - 004 * \text{Car Speed} * \text{Distance} \quad [2]$$

**TABLE 6** ANOVA Table (Partial Sum of Squares, Type III)

Source	Sum of squares	df	Mean square	F value	p-Value (Prob. > F)	
Block	5.37E-05	1	5.368E-05			
Model	1.11	4	0.28	118.03	<0.0001	Significant
B: Vehicle speed	0.59	1	0.59	249.45	<0.0001	Significant
C: Distance	0.48	1	0.48	203.16	<0.0001	Significant
D: Surface inclination	0.026	1	0.026	11.07	0.0018	Significant
BC	0.020	1	0.020	8.44	0.0057	Significant
Curvature	4.768E-03	1	4.77E-03	2.02	0.1619	Not significant
Residual	0.11	45	2.36E-03			
Lack of fit	0.013	11	1.20E-03	0.44	0.9260	Not significant
Pure error	0.093	34	2.73E-03			
Cor. total	1.22	51				
SD	0.049	$R^2$	0.9094			
Mean	0.56	Adj. $R^2$	0.9015			
Coefficient of variation (%)	8.70	Pred. $R^2$	0.8840			
PRESS	0.14	Adeq. precision	28.174			

The next step in the progression was to proceed with the diagnostic plots. The normal probability plot of the residuals and the Box-Cox plot are shown in Figure 4. From a holistic view of Figure 4a it can be seen that the residuals generally fall on a straight line, indicating that the errors are distributed normally. Figure 4b vividly shows the 95% CI around the lambda; therefore, there is no need for a new specific transformation to be made. The Box-Cox plot of the transformed responses is found to be in symmetry. Thus, the model statistics and diagnostic plots seem to be acceptable and the analysis section can be finalized.

From two-factor BC interaction plot (Figure 5) it is clear that the large positive effect of distance occurs primarily when the vehicle speed is at the low level to provide maximum time and, consequently, minimum speed at the stop point. The number of passengers does not have any effect on this plot and to gain the

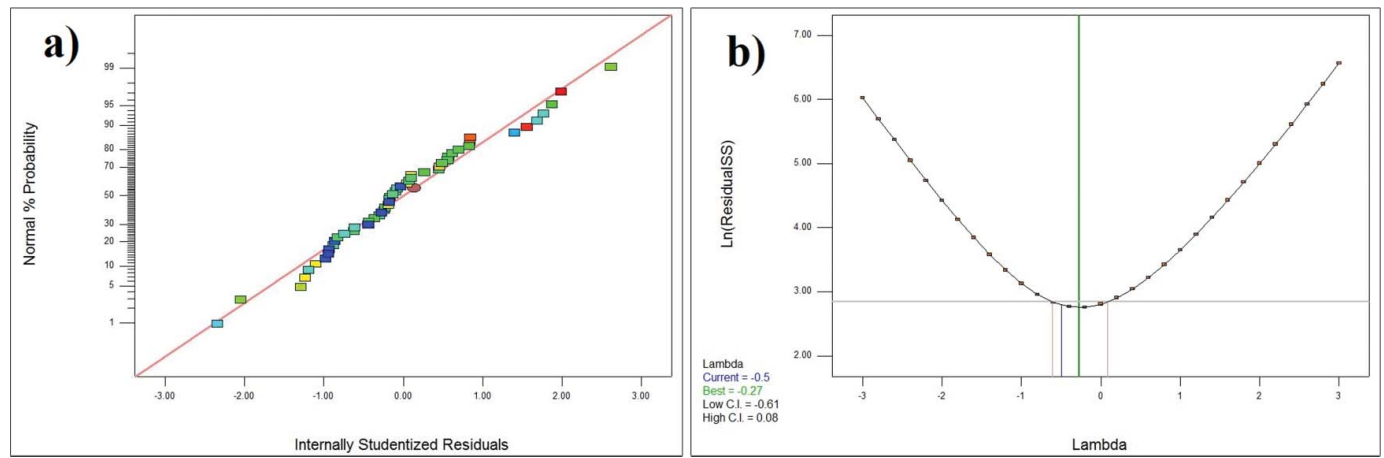
maximum response, the plot is set at the highest level of the surface inclination (7%).

Additionally, a 3D surface plot demonstrates this object using a 3D figure. At the highest level of the surface inclination (7 %) in Figure 6, the maximum time is achieved at the lowest vehicle speed (10 km/hr) and the highest distance (20 m) based on the time contours trend. In this plot, the maximum time occurs at the peak of the curvature.

Eventually, after analyzing the experimental model, the optimum point within the range of the model with the value of 8.12629 s is gained at the  $B^-$ ,  $C^+$ , and  $D^+$  corner of the cube plot (Figure 7). This value is the maximum time between the starting point after the speed bump and the stop point. According to the aim of this experimental design and the local optimum point of the model, the best location for installing a speed bump occurs at 20 m prior to stop point to

**TABLE 7** Post ANOVA Table

Factor	Coefficient estimate	df	Standard error	95% CI (low)	95% CI (high)	Variance inflation factor
Intercept	0.56	1	6.81E-03	0.55	0.58	
Day 1	1.02E-03	1				
Day 2	-1.02E-03					
B: Vehicle speed	0.11	1	7.09E-03	0.10	0.12	1
C: Distance	-0.100	1	7.09E-03	-0.11	-0.086	1
D: Surface inclination	-0.023	1	7.09E-03	-0.04	-9.05E-03	1
BC	-0.020	1	7.09E-03	-0.03	-6.10E-03	1



**FIGURE 4** (a) Normal probability plot of residuals and (b) Box-Cox plot.

achieve the minimum speed and the convenient stop at the aforementioned point. The interconnectivity of the critical variables (B, C, and D) is important for achieving this aim.

### Confirmation Test for Classical DOE Method

To confirm the adequacy of the developed model, eight confirmation run experiments were performed (Tables 8 and 9). The test conditions for the first two verification run experiments were among the treatment combinations that were performed previously, and the remaining six verification run experiments were in conditions that had not been used previously but were within the range of the levels specified before (Table 8). Using the confirmation capability of the software, the time of the selected experiments was predicted with the 95% prediction interval (PI) and the size or number of trials was three in the confirmation experiment

(Table 9). The predicted value and the related PI were based on the model developed previously. The residual absolute value, which is the difference between the value of the predicted response and the actual response, and the percentage error, which is the value of the residual divided by the actual values, were calculated. All of these values are provided in Table 9. The range of the percentage errors for time is  $\sim 0.06\%$  to  $11.53\%$ .

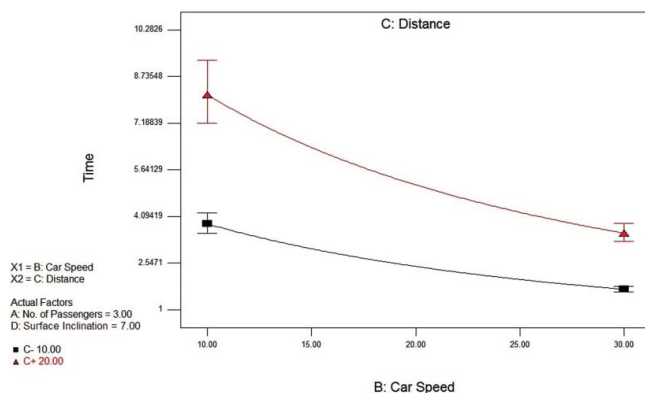
It can be concluded from the confirmation tests that the experimental model developed is reasonably accurate. All of the actual values for the confirmation runs are within the 95% PI range.

### Taguchi DOE Method Data Analysis

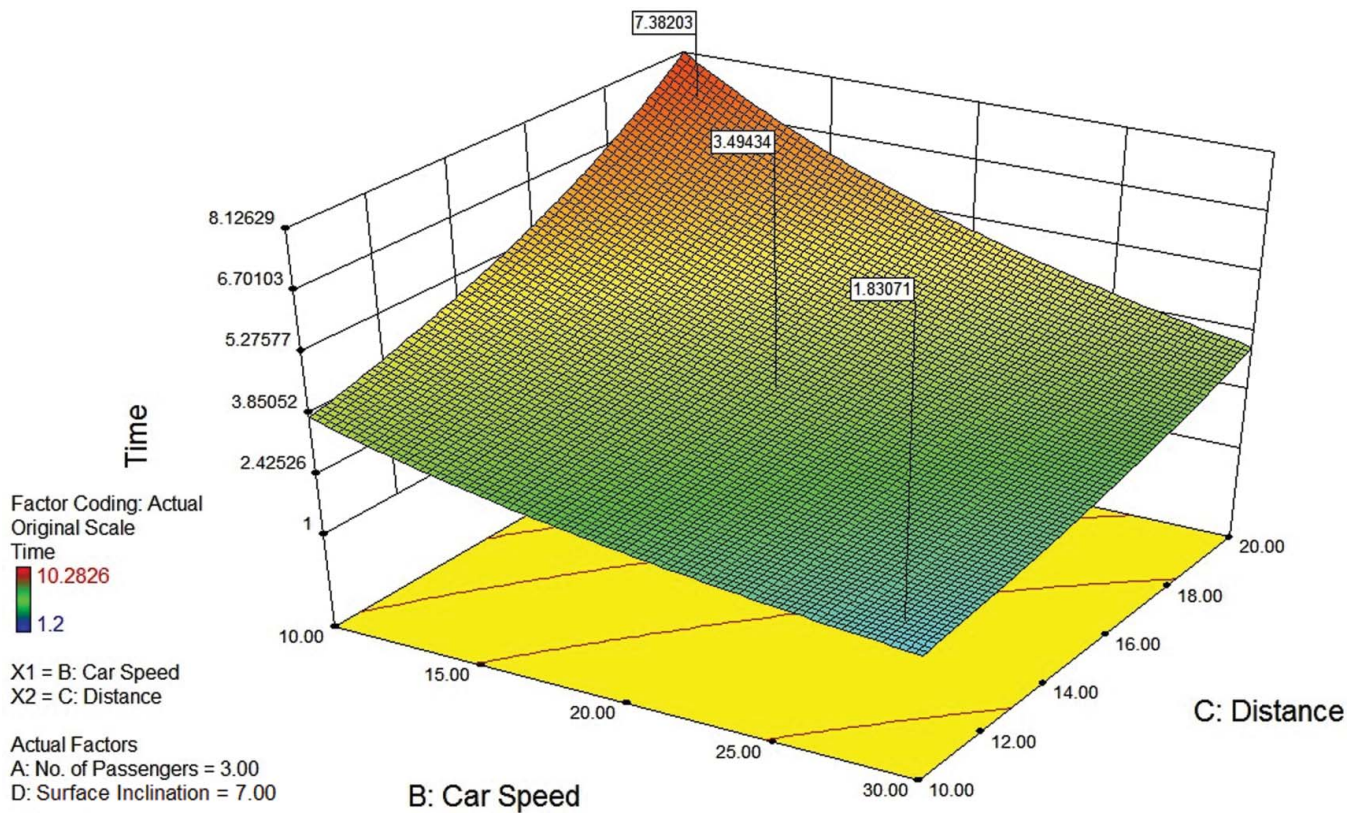
After conducting classical DOE method, a Taguchi DOE method was developed. As mentioned previously, this study aims to identify the influential factors that have an effect on the time between the starting point after the bump to the stop point. Factors were divided into two subgroups: controllable factors and noise factors. The factors and their corresponding levels are shown in Table 3.

Table 10 shows the rank and optimum setting of controllable factors. Based on this table and utilizing MINITAB release 15 software (Minitab Inc., USA), plots of the main effects are illustrated in Figures 8a and 8b.

According to Table 10 and the main effects plots in Figures 8a and 8b, the vehicle speed before the bump (B) is the most significant and also the most robust factor in terms of mean and S/N analysis. The next two



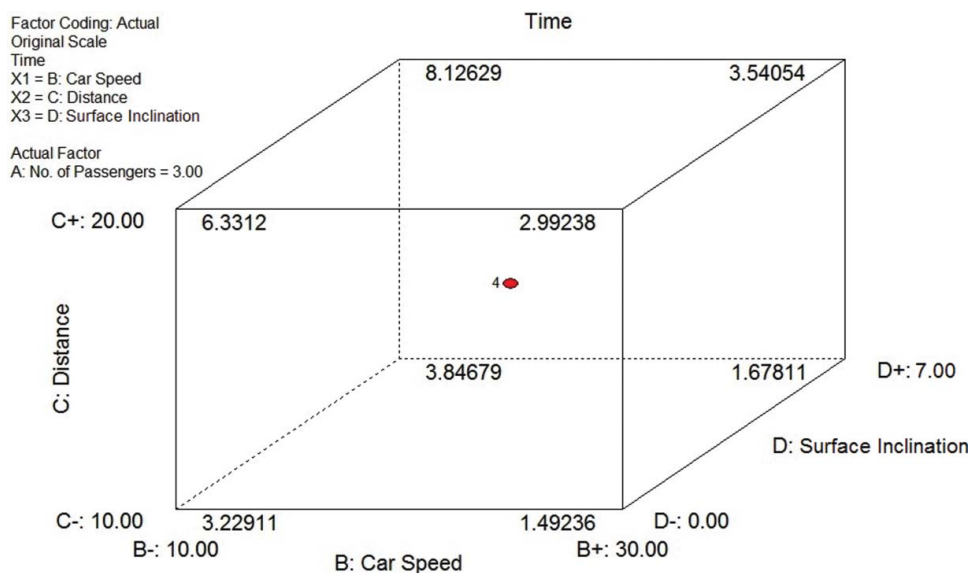
**FIGURE 5** BC interaction plot.



**FIGURE 6** 3D surface plot.

significant factors are the distance from the bump to the stop point (C) and the surface inclination (D), respectively. The figures show graphically that the number of passengers (A) does not considerably affect the response.

Regarding the optimum setting, it is indicated that the longest response time may be achieved when factor B is low and factors C and D are high level. The following section describes the confirmation experiment in order to strengthen the above-mentioned prediction.



**FIGURE 7** Cube plot.

**TABLE 8 Treatment Combinations Used for Confirmation Experiments**

Run	Factors				No. of replicates (time, s)			Total	Average
	A: No. of passengers	B: Car speed (km/h)	C: Distance (m)	D: Surface inclination (%)	R <sub>1</sub>	R <sub>2</sub>	R <sub>3</sub>		
1	5	10	20	7	5.71	8.68	9.98	24.38	8.13
2	1	10	20	7	8.42	8.54	8.15	25.11	8.37
3	5	10	15	0	4.73	4.71	4.78	14.23	4.74
4	1	10	15	0	5.00	4.76	5.14	14.90	4.97
5	5	20	10	0	1.76	2.27	2.14	6.17	2.06
6	1	20	10	0	1.95	2.00	2.19	6.14	2.05
7	1	20	20	0	4.65	3.83	4.14	12.62	4.21
8	1	30	15	0	2.13	2.29	2.20	6.62	2.21

**Confirmation Test for Taguchi DOE Method**

Equation [3] shows the predicted S/N ratio ( $\hat{Z}$ ) as follows:

$$\hat{Z} = \bar{Z} + (\bar{B}_1 - \bar{Z}) + (\bar{C}_2 - \bar{Z}) + (\bar{D}_2 - \bar{Z})$$

$$\hat{Z} = 10.37 + (13.75 - 10.37) + (13.49 - 10.37) + (10.93 - 10.37) \quad [3]$$

$$\hat{Z} = 17.43.$$

To confirm the previous experiment, additional experiments were conducted using the optimum setting proposed in Table 10. Results of the additional experiments are shown in Table 11.

An error of 3.73% indicates that the S/N ratio obtained from this experiment is not significantly different from the predicted S/N ( $\hat{Z}$ ). The new design shows significant improvement in terms of S/N with a difference of 7.06 between predicted the S/N ( $\hat{Z}$ ) and average S/N ( $\bar{Z}$ ). Therefore, it can be concluded that the optimum setting suggested in Table 10 offers the

most influential levels of the design parameters that yield a robust and insensitive design for speed bump installation to the effect of environmental noises. It is important to note that the result obtained using Taguchi’s method is relatively consistent with the result achieved using the classical design method.

**CONCLUSION**

This article describes an experimental investigation to determine the effects of some controllable factors on the distance–time between the starting point after the bump and the stop point. In order to reach the minimum speed at the stop point, the speed is treated as a response to determine the effect of bump location on the convenient stop and to optimize the distance from the bump to the stop point. A classical DOE technique is selected to find the percentage contributions of these factors on the response. ANOVA reveals that the vehicle speed is the most significant factor that

**TABLE 9 Confirmation Experiments**

Run	Factors				Average (actual time, s)	Prediction (time, s)	Residual	Error (%)	95% PI low	95% PI high
	A: No. of passengers	B: Vehicle speed (km/h)	C: Distance (m)	D: Surface inclination (%)						
1	5	10	20	7	8.13	8.12	0.00	0.06	6.26	10.96
2	1	10	20	7	8.37	8.12	0.25	2.98	5.78	12.24
3	5	10	15	0	4.74	4.39	0.35	7.35	3.68	5.34
4	1	10	15	0	4.97	4.39	0.57	11.53	3.64	5.41
5	5	20	10	0	2.06	2.11	0.06	2.91	1.85	2.44
6	1	20	10	0	2.05	2.11	0.07	3.28	1.84	2.46
7	1	20	20	0	4.21	4.20	0.01	0.12	3.56	5.04
8	1	30	15	0	2.21	2.05	0.16	7.05	1.80	2.36

**TABLE 10** Rank and Optimum Setting of Controllable Factors

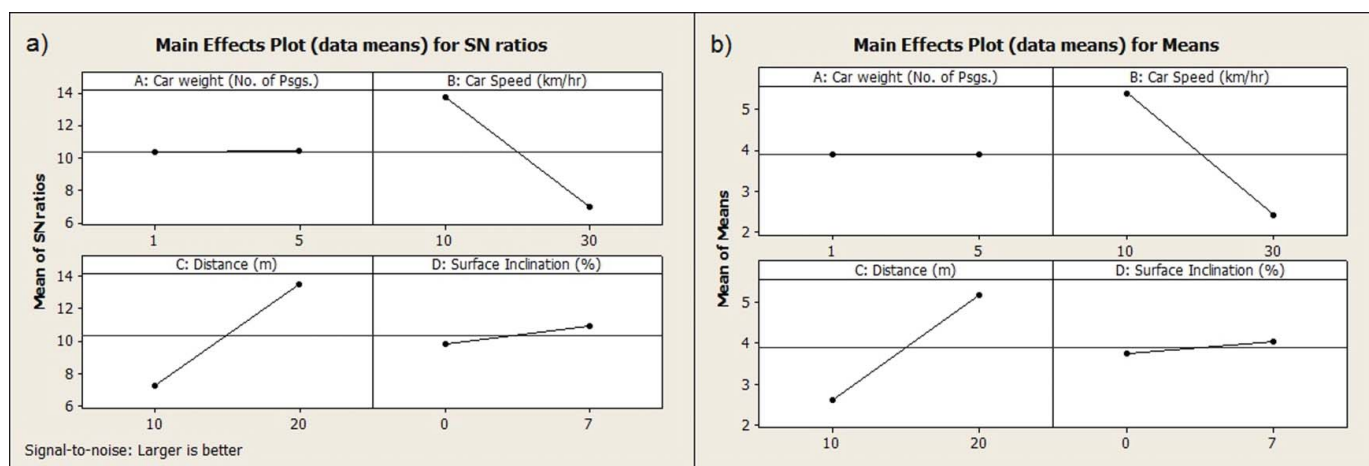
Factor	S/N analysis				Mean analysis				Optimum setting
	1	2	Effect	Rank	1	2	Effect	Rank	
A	10.34	10.40	0.06	4	3.89	3.89	0.004	4	2
B	13.75	7.00	-6.75	1	5.37	2.41	-2.97	1	1
C	7.25	13.49	6.24	2	2.62	5.16	2.55	2	2
D	9.81	10.93	1.12	3	3.75	4.03	0.279	3	2

affects the distance–time, in comparison with the other factors such as distance and surface inclination. Diagnostics case statistics reports were then used to obtain the point of the optimum response, which is the region around the current operating conditions. The experimental results indicated that the suggested mathematical model effectively explains the performance indicators within the ranges of the factors that are being examined. According to the aim of this experimental design and the local optimum point of the model, the location for installing a speed bump was investigated ( $B^-$ ,  $C^+$ , and  $D^+$ ). Taguchi's method was selected to model the controllable factors of interest in a process along with the uncontrollable or noise factors with the goal of finding the settings of the controllable factors that are insensitive or robust to noise variability. B1, C2, D2 were set as the robust parameters design to identify the best location for the installation of a speed bump before the stop point. The results of Taguchi's method are relatively consistent with the results obtained by the classical DOE method. Implementation of experimental design techniques to appraise controllable factors and environmental noise effects are

unique features of this study compared to other studies conducted previously in this context. Hence, because the current operating conditions are normally far from the optimum response, as a future study, experimenters need to move from the current operating conditions to the optimum region in the most efficient way by using the minimum number of experiments.

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**FIGURE 8** Main effects plot for (a) S/N ratios and (b) means.

**TABLE 11 Confirmation Experiments**

Optimum setting of factors			
B <sub>1</sub>	C <sub>2</sub>	D <sub>2</sub>	Response (time, s)
10	20	5	8.12
10	20	5	7.72
10	20	5	7.95
10	20	5	8.42
Mean response time			8.05
S/N experimental			18.11
Z̄ (S/N predicted)			17.43
% S/N error			3.73

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