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Evaluating the Effect of Main Factors in Determining Speed Bump Location Based on Taguchi Design of Experiments

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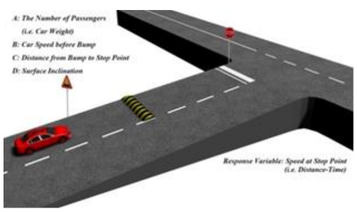
Graphical abstract



Abstract

Use of speed bumps as a traffic-calming technique is a key issue to a safe and smooth traffic flow. Lack of consideration on finding the best location for speed bump installation before stop points, such as traffic junctions, has provided the motivation to conduct this study. This paper investigates the influence of some main factors on determining bump location and to optimize the distance from bump to stop point in order to obtain the minimum speed at this point. A robust design was used whereby the effect of environmental noises on the parameters was investigated using the Taguchi design of experiments. A 2-level L8 inner array and an L4 outer array design is used to evaluate and analyze the results. The results suggested that the linear models effectively explain the performance indicators within the ranges of the factors. It can be concluded that the optimum setting suggested is at the most influential levels of the design parameters which yields a robust and insensitive design for speed bump installation after considering the effect of environmental noises. The car speed before bump has the greatest influence and also the most robust factor in terms of signal-to-noise ratio and mean analysis.

Keywords: Speed bump location; Taguchi design of experiments; local optimum point plant

1.0 INTRODUCTION

Traffic-calming measures are used to decrease vehicle speeds when passing through a high-risk area such as a residential estate[1-3]. Speed or road bumps are extensively used for controlling vehicle speeds and improving traffic safety on local streets[3-5]. The use of speed bumps is controversial even though they are effective as a speed deterrent device. Various kinds of material are used to make the speed bumps such as asphalt, cement or even rubber, which are directly applied on the road. Speed bumps are best suited for deployment on local streets with a posted speed limit of 40 km/h or lower[4-7]. These devices are intended to reduce speeds to be as low as 8 km/h and therefore are appropriate for high-risk areas that have low speed limits[4-7].

Bumps and humps are two unlike types of protuberances, which are essential to be distinguished; bumps are narrow while humps are wide protuberances. Guidelines for their designs are moderately different; so, they have different effects on drivers and vehicle performance when passing through them[8]. The existing literatures indicate that the reduction of vehicle speeds is statistically significant and speed bumps are effective in moderating vehicle speeds in their surrounding area. Whilst, a large number of researches have been performed over the last two decades indicate that speed bumps have just a limited impact on reducing traffic speed, especially when they are compared to the better designed passive speed control devices, such as speed humps or cushions[9-11]. Pau (2002)[9], conducted an investigation based on a case study in an Italian town which reveals that, while vehicles approaching the speed bumps, generally avoid perceiving the vibration and undulation through passing the speed control devices; therefore, it induces drivers to perform man oeuvres or slow down their speed suddenly, which causes unexpected accidents[9].

There are only national regulations and enforcements in designing and applying of speed bumps, which are published by institutes of transportation and most of the engineers follow them[6, 12-16]. However, there are no existing researches that study on determining the best location of bump installation before a stop point using a practical statistical methodology. Therefore, this study experimentally examines the source of variation using Taguchi design of experiments based on the effects of some important design variables to find the best location for installing a speed bump and to optimize the distance from a bump to stop point in order to reach the minimum speed at that point. When the bumps are installed properly, it is anticipated that the bumps will slow down the flow of traffic in the critical area before stop point and help drivers to decrease their speed smoothly. The vibration of speed bumps would force drivers to pass through the critical areas such as an entry gate, with suitable speed. There are various kinds of factors that have tangible or intangible effects on the process that can allude to the car speed, the car weight, the road degree, the distance from bump to stop point, the road fraction, the car brake capability, the climate situation and so on.

Taguchi's approach to design of experiment (DOE) is to find the source of variation in the process and appraise which process inputs have a significant effect on the process result in order to quickly optimize performance of systems with known input variables. By applying designed experiments, engineers can ascertain which subset of the process variables has the greatest influence on the process performance[17-20]. Taguchi approach estimates the best arrangement of parameters, which are controlled throughout the normal situation and minimize the effect of environmental noise, which makes variability in process execution in a timely manner by reducing the total number of experiments regardless of the interaction terms[17-20].

Taguchi's designs consist of crossed arrays wherein the controllable variables are allocated to an inner array, and the noise variables are allocated to an outer array which makes orthogonal array (OA). Taguchi's orthogonal arrays are not randomly generated as they are based on judgmental sampling. Once the experiments are performed, the results are summarized in the mean and the Signal-to-noise (S/N) ratio. S/N ratio is a performance statistic that is applied by Taguchi to measure the process robustness[19-21]. Therefore, the Taguchi method makes the process performance insensitive to the variations of uncontrollable noise factors[19-21].

2.0 EXPERIMENTAL DETAILS

The aim of this experimental design is to apply Taguchi method to examine the best location for the installation a speed bump before a stop point (e.g. before an entry gate) in a cost-effective and timely manner. The Taguchi design method attempts 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. Robust parameter design identifies appropriate levels of controllable variables to identify the best location for the installation of a speed bump before a stop point.

The experiment was performed using the above encoded design matrix. Each trial condition was replicated once to capture variation due to noise parameters, which were difficult or expensive to control during the experiment, but have significant impact on the product's functional performance variability.

After planning the experiment, the experiment is actually performed by utilizing a '*Proton Saga Iswara 1.3S Sedan*' and finding two roads with totally homogeneous situations of asphalt type and speed bump's shape and type but the conditions of these roads are difference in terms of surface inclination (0% and 7%). Other equipment such as chronometer, clinometer and tape measure are used when performing the experiment. While the experiment is performed, to simplify the mathematical design inquiry, the driving force in the following equations is totally set aside. To ignore the driving force on the car speed after passing the bump, driver put the vehicle gear in the normal/free position. The following equations are the mathematical design inquiries (Equations (1), (2) and (3)).

$$\sum F = ma \tag{1}$$

$$f_s = N\mu_s\ ;\ 0 < \mu_s < 1 \tag{2}$$

$$\mu_s(\text{Dry Asphalt}) = 0.75, \mu_s(\text{Wet Asphalt}) = 0.5$$

$$N = mg\cos\theta;\ g = 9.81\ m/s^2 \tag{3}$$

$$\text{If } \theta \neq 0\ ;\ -mg\sin\theta - f_s + (\text{Driving Force}) = ma \Rightarrow$$

$$-mg\sin\theta - (mg\cos\theta \times \mu_s) + (\text{Driving Force}) = ma$$

$$\text{If } \theta = 0\ ;\ -f_s + (\text{Driving Force}) = ma \Rightarrow$$

$$-mg\mu_s + (\text{Driving Force}) = ma$$

In order to clarify the process, it is obliged to allude the four controllable affecting factors and three uncontrollable factors, namely; the number of passengers (the car weight), the speed of car before bump, the surface inclination and the distance from bump to stop point as controllable factors, and asphalt situation, drivers and time takers are considered as noise variables.

In this experiment, speed at stop point is treated as the response to determine the effect of bump location on the convenient stop at aforementioned point and optimize the distance from bump to this point in order to obtain the minimum speed at stop point. Because of a paucity of required instruments for speed measurement at the stop point, it is decided to measure the response factor through the time. The time considered is the distance-time between starting point after bump to the stop point, and the minimum speed at stop point is changed to maximization of this time.

Although noise variables are difficult or impossible to control during the process, their levels can be controlled for experimental purposes. Thus, selection the levels of controllable variables focus on minimizing process variability caused by the noise variables and simultaneously reaching some desired means response. In this example, to find the best location for speed bump, the desired mean response is the maximum time between bump to stop point. The following objectives are set in the experiment:

- Which design parameters have major influence on 'mean distance-time'?
- Which design parameters affect variability in 'distance-time'?
- Determine the best settings to achieve a larger value of time for 'distance-time'.

It was decided to study four design parameters at two levels. The degrees of freedom (DF) required for studying four main effects were four. Thus, the most appropriate OA design to meet this requirement was an 8-trial experiment (L8 OA). Table 1 illustrates the list of design parameters and their ranges chosen in the experiment.

Table 1 Controllable factors and noise factors

No.	Factor	Type	Low Level (Level 1)	High Level (Level 2)
1	Number of passengers (A)	Controllable	1 person	5 people
2	Car speed before bump (B)	Controllable	10 km/hr	30 km/hr
3	Distance from bump to stop point (C)	Controllable	10 m	20 m
4	Surface inclination (D)	Controllable	0%	7%
5	Driver (E)	Noise	Driver 1	Driver 2
6	Time taker (F)	Noise	Time Taker 1	Time taker 2
7	Asphalt situation (G)	Noise	Dry	Wet

$$\text{If}\begin{cases}\text{The car is in the gear position} \rightarrow \text{Driving force is negative}\\ \text{The car is in the normal position} \rightarrow \text{Driving force is equal to zero}\\ \text{The car is in the accelarating position} \rightarrow \text{Driving force is positive}\end{cases}$$

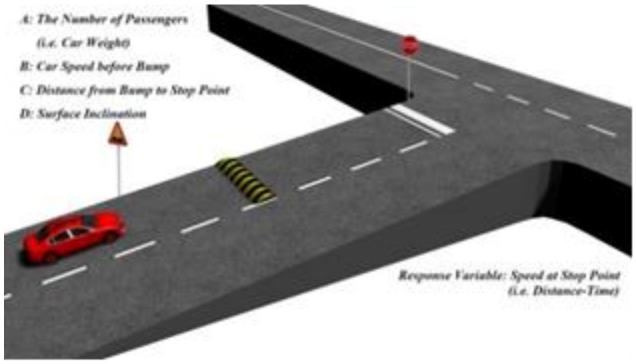


Figure 1 Graphical experimental design dependent and independent variables

Table 2 Controllable factors and noise factors

	Inner control factor array / Factor					Outer noise array / Response (Time (Sec.))					
					E: Driver	1	2	2	1		
					F: Time Taker	1	2	1	2		
					G: Asphalt Situation	1	1	2	2		
Run	**A: No. of Passengers**	**B: Car Speed (km/hr)**	**C: Distance (m)**	**D: Surface Inclination (%)**		**N_1**	**N_2**	**N_3**	**N_4**	**Mean (Y)**	**S/N (Z)**
1	1	1	1	1		2.18	3.26	4.90	3.30	3.41	9.61
2	1	1	2	2		6.59	5.71	8.33	8.15	7.20	16.82
3	1	2	1	2		1.65	1.66	1.85	1.96	1.78	4.94
4	1	2	2	1		3.08	3.05	3.26	3.29	3.17	10.01
5	2	1	1	2		3.53	3.82	4.27	3.87	3.87	11.70
6	2	1	2	1		6.44	6.69	7.81	7.13	7.02	16.86
7	2	2	1	1		1.26	1.30	1.36	1.71	1.41	2.79
8	2	2	2	2		3.20	3.21	3.24	3.42	3.27	10.27
										$\bar{\bar{Y}}$	$\bar{\bar{Z}}$
										3.89	**10.37**

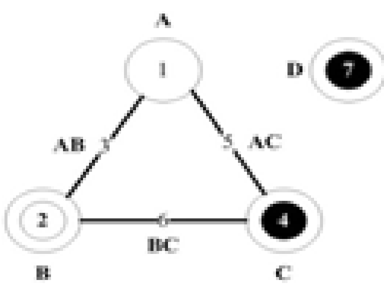


Figure 2 Linear graph

Figure 1 shows the experimental independent variables as input factors and the dependent variable as an output or response factor. Table 2 represents the data gathered based on the orthogonal arrays associated with a linear graph shown in Figure 2 where an L8 inner array and an L4 outer array are used. In this particular case, the response is longer the better and the average of S/N ( ) and the average of mean ( ) with value of 10.37 and 3.89 was gained, respectively.

3.0 TAGUCHI ANALYSIS

As mentioned in previous section, this study aims to identify the influence of factors that have an effect on the time between the starting points after the bump to stop point. Factors are divided into two subgroups: controllable factors and noise factors. The factors and their corresponding levels are shown in Table 1.

The results are used to determine whether the factors are significantly related to the response data and each factor's relative importance in the model. The order of the coefficients by absolute value indicates the relative importance of each factor to the response; the factor with the biggest coefficient has the greatest impact. The sequential and adjusted sums of squares in the analysis of variance table also indicate the relative importance of each factor; the factor with the biggest sum of squares has the greatest impact. These results mirror the factor ranks in the response table (Table 7). In this study, for S/N ratios (Table 3, and Table 4), car speed (p=0.001) and distance (p=0.002) and for means (Table 5, and Table 6), again car speed (p=0.012) and distance (p=0.018) were significant because their p-values are less than 0.10.

3.1 Linear Model Analysis for S/N Ratios & Means

Each linear model was analyzed by utilizing the MINITAB® release 16 software which provides the model coefficients for each factor, their p-values and an analysis of variance table.
The response table (Table 7) shows the average of each response characteristic (S/N ratios, means) for each level of each factor. The tables include ranks based on Delta statistics, which compare the relative magnitude of effects. The Delta statistic is the highest minus the lowest average for each factor. Minitab assigns ranks based on Delta values; rank one to the highest Delta value, rank two to the second highest, and so on. Use the level averages in the response tables to determine which level of each factor provides the best result. Based on this Table, the main effects' plots are constructed and illustrated in Figures 3 and 4.

Table 3 Estimated model coefficients for S/N ratios

Term	Coefficient	SE Coefficient	T-value	p-value
Constant	10.3742	0.2908	35.671	0.000
A: No. of Passengers	-0.0309	0.2908	-0.106	0.922
B: Car Speed (km/hr)	3.3715	0.2908	11.593	0.001
C: Distance (m)	-3.1153	0.2908	-10.712	0.002
D: Surface Inclination (%)	-0.5599	0.2908	-1.925	0.150
S = 0.8226		**R-Sq. = 98.8%**		**R-Sq.(adj.) = 97.3%**

Table 4 Analysis of variance for S/N ratios

Source	DF	Seq. SS	Adj. SS	Adj. MS	F-value	p-value	
A: No. of Passengers	1	0.008	0.0076	0.0076	0.01	0.922	***not significant***
B: Car Speed (km/hr)	1	90.938	90.9377	90.9377	134.40	0.001	significant
C: Distance (m)	1	77.640	77.6396	77.6396	114.74	0.002	significant
D: Surface Inclination (%)	1	2.508	2.5076	2.5076	3.71	0.150	***not significant***
Residual Error	3	2.030	2.0299	0.6766			
Total	7	173.123					

Table 5 Estimated model coefficients for means

Term	Coefficient	SE Coefficient	T-value	p-value
Constant	3.89000	0.2689	14.465	0.001
A: No. of Passengers	-0.00125	0.2689	-0.005	0.997
B: Car Speed (km/hr)	1.48375	0.2689	5.517	0.012
C: Distance (m)	-1.27250	0.2689	-4.732	0.018
D: Surface Inclination (%)	-0.13875	0.2689	-0.516	0.642
S = 0.7606		**R-Sq. = 94.7%**		**R-Sq.(adj.) = 87.5%**

Table 6 Analysis of variance for means

Source	DF	Seq. SS	Adj. SS	Adj. MS	F-value	p-value	
A: No. of Passengers	1	0.0000	0.0000	0.0000	0.00	0.997	***not significant***
B: Car Speed (km/hr)	1	17.6121	17.6121	17.6121	30.44	0.012	significant
C: Distance (m)	1	12.9541	12.9541	12.9541	22.39	0.018	significant
D: Surface Inclination (%)	1	0.1540	0.1540	0.1540	0.27	0.642	***not significant***
Residual Error	3	1.7356	1.7356	0.5785			
Total	7	32.4558					

Table 7 Response table for S/N ratios & for means (rank and optimum setting of the controllable factors)

Controllable Factor	Signal to Noise (S/N) Ratios Analysis				Mean Analysis				Optimum Setting
	1	2	Effect (Δ)	Rank	1	2	Effect (Δ)	Rank	
A	10.34	***10.41***	0.06	4	3.89	***3.89***	0.003	4	**2**
B	***13.75***	7.00	-6.74	1	***5.37***	2.41	-2.97	1	**1**
C	7.26	***13.49***	6.23	2	2.62	***5.16***	2.55	2	**2**
D	9.81	***10.93***	1.12	3	3.75	***4.03***	0.28	3	**2**

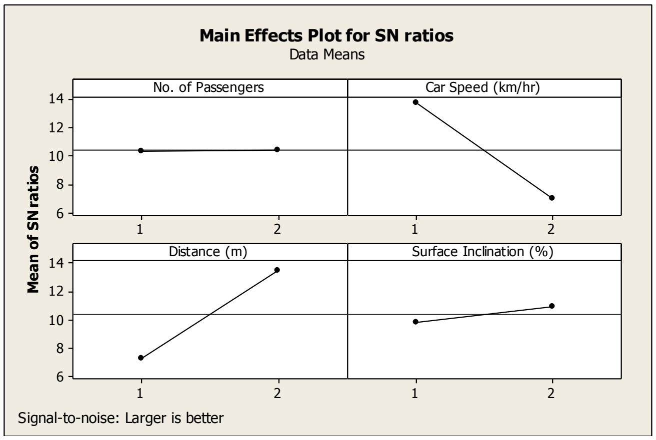


Figure 3 Main effects plot for S/N ratios

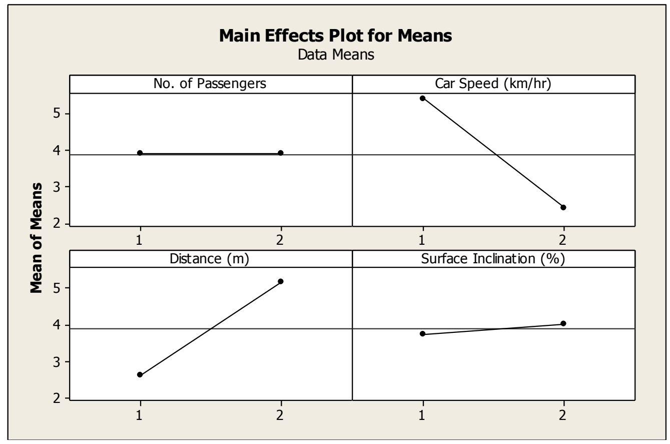


Figure 4 Main effects plot for means

In this study, the ranks indicate that, the car speed before bump (B) has the greatest influence and also the most robust factor in terms of S/N ratio and mean analysis. For both the S/N ratio and the mean, the distance from bump to stop point (C) has the next greatest influence, followed by the surface inclination (D) and No. of passengers (A). The aim of this study is to increase the distance-time between starting point after bump to the stop point. Thus, factor levels that produce the highest mean are needed. In Taguchi experiments, S/N ratio maximization is desirable. The level averages in the response table and figures show that the S/N ratios, and the means were maximized when the car speed before bump (B) was 10 km/hr, and the distance from bump to stop point (C) was 20 m. Based on these results and regarding to optimum setting, the longest response time may be achieved when factor B is set at low level and factors C is set at high level. The following section conducts confirmation experiment in order to strengthen this prediction.

4.0 CONFIRMATION TEST

Equation (4) and Equation (5) show the predicted S/N ratio $(\hat{Z})$ and the predicted mean $(\hat{Y})$ for the selected factor settings, respectively as follows:

$$\hat{Z} = \bar{Z} + (\bar{B}_1 - \bar{Z}) + (\bar{C}_2 - \bar{Z}) \tag{4}$$

$$\hat{Z} = 10.37 + (13.75 - 10.37) + (13.49 - 10.37) = 16.87$$

$$\hat{Y} = \bar{Y} + (\bar{B}_1 - \bar{Y}) + (\bar{C}_2 - \bar{Y}) \tag{5}$$

$$\hat{Y} = 3.89 + (5.37 - 3.89) + (5.16 - 3.89) = 6.64$$

To confirm the accuracy of the model, additional experiments were conducted using these factor settings. Results of the additional experiments are shown in Table 8.

Errors of 1.25% and 3.87% indicate that the S/N ratio and mean obtained from this experiment are not significantly different from predicted S/N ratio $(\hat{Z})$ and predicted mean $(\hat{Y})$, respectively. Meanwhile, the new design exposes significant improvement in terms of S/N ratio and mean with 6.5 and 2.75 values of difference between predicted value and average value, respectively. Therefore, it can be concluded that the optimum setting suggested in Table 7 offers the most influential levels of the design parameters which yields a robust and insensitive design for speed bump installation to the effect of environmental noises.

Table 8 Confirmation experiments

Optimum Setting of Factors		Response (Time (Sec.))	
B1 (km/hr)	**C2 (m)**		
10	20	7.14	
10	20	6.07	
10	20	6.53	
10	20	7.89	
S/N ratio	**16.66**	**Mean**	**6.91**
$\hat{Z}$ (Predicted)	**16.87**	**$\hat{Y}$ (Predicted)**	**6.64**
% S/N ratio Error	**1.25**	**% Mean Error**	**3.87**

5.0 CONCLUSION

The effectiveness of speed bumps to control vehicles speed and improve traffic safety on risky area lead this paper to introduce the experimental investigation of finding the effects of some controllable factors with consideration to the environmental noises on the distance-time to determine the effect of bump location on the convenient stop at stop point and to optimize the distance from bump to that point. The static Taguchi design of experiments is selected to model the controllable factors of interest in a process along with the uncontrollable or noise factors with the goal of finding settings of the controllable factors that are insensitive or robust to noise variability. In this study, the car speed before bump (B) has the greatest influence and also the most robust factor in terms of S/N ratio and mean analysis. The distance from bump to stop point (C) has the next greatest influence. The level averages in the response table and the main effects' plots show that the S/N ratios, and the means are maximized when the car speed before bump (B) is 10 km/hr, and the distance from bump to stop point (C) is 20 m. (B1, C2) is set as the robust parameters' design to identify the longest response time and the best location for the installation of a speed bump before stop point. Implementing of statistical design technique to appraise controllable factors and environmental noises of the experiment is the unique feature of this study as compared to the other studies conducted previously in this context. Hence, 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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