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Optimum design of speed hump based on empirical data

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Traffic calming techniques are extensively used as safety tools to reduce the speed of motorised vehicles along any type of paved road. The objective of this study is to evaluate the efficacy of isolated speed humps on urban roads in India and to suggest an optimised geometry of speed humps for the desired level of speed reduction. For this, five different urban road sections were identified in Delhi and video graphic data were collected at each study section. The median speed of vehicles at each grid is estimated and speed profiles were developed for each category of vehicle approaching the speed hump. The speed behaviour of the vehicles approaching a circular or parabolic shape of isolated speed hump are examined and compared. This study developed speed profile models using regression techniques for an individual vehicle and also for the combined data. The observed speed of the vehicle was considered as a response variable and the physical properties of the speed humps were considered as explanatory variables. Further, the combined linear equation was considered for determining the optimum height and entry radius of the speed hump for the desired speed by using the simplex method.

Notation

a_0	model constant
a_1, a_2, a_3	coefficients of the model parameters
D_s	distance of vehicle from speed hump
H_s	height of speed hump
R^2	coefficient of determination
R_s	entry radius of speed hump
r	correlation coefficient
V_{Ds}	speed of vehicle at distance D_s

1. Introduction

Most of the fatal accidents in India occur due to speeding of motorised vehicles. The accident statistics of 2016 showed that speeding of vehicles was responsible for 56% of the total road accidents (MoRTH, 2016). A vehicle moving at high speed will have greater impact during an accident and hence will cause more injuries. On urban roads, the causes of road accidents and deaths are mainly the speed of the vehicle, chaotic behaviour of drivers and the vulnerability of some road users (Huang and Cynecki, 2000). Mixing of non-motorised traffic with motorised vehicular traffic increases the risk of road accidents. The severity of road accidents can be reduced by reducing the speed of vehicles (Watts, 1973; Zainuddin *et al.*, 2012). Traffic calming techniques have emerged primarily through society's requirement for safety (IRC, 2018). These techniques have played an important role in enhancing road safety by ensuring the lowering of driving speeds.

A speed hump (SH) is a vertical traffic calming measure used as a tool in many countries to control the speeds of motorised vehicles on different types of roads on urban and rural road networks (Silva *et al.*, 2014). The speed characteristics of

vehicles when approaching traffic calming measures change considerably. Various researchers have studied the reduction of vehicle speed due to traffic calming measures on different categories of urban roads (Amir *et al.*, 2012; Pan *et al.*, 2011; Vasudevan, 2018). The reduction will depend on the type of vehicle, speed limit on the road and the shape and size of the SH. These humps, when not designed properly, become very dangerous to small vehicles like motorised two-wheelers.

The main objective of this study is to evaluate the effect of SHs on the speed of different types of vehicles on an urban road and thereby to develop a speed model for a vehicle approaching an SH on urban roads in India. Field data resulting from collecting the speeds of vehicles while traversing an SH have been statistically analysed to achieve this objective. Five isolated SHs (circular and parabolic) were identified on arterial, sub-arterial and collector streets in the city of New Delhi, India. The study evaluates the efficacy of the isolated SH. Real data were collected using a video graphic technique and the speed of an individual vehicle approaching the SH was monitored for a certain distance before the hump. The speed profile model is developed using a regression analysis technique. Finally, an attempt is made to obtain the most appropriate shape of hump for a given speed limit using linear programming problems (LPPs).

2. Literature review

Traffic calming measures involve physically altering the road layout or appearance to slow down or reduce the speed of motor-vehicle traffic, as well as to improve safety for pedestrians and cyclists (Hass-Klau and Nold, 1993). The goal of traffic calming measures is to reduce vehicle speeds, improving safety and enhancing the quality of life. Traffic calming

measures are mainly classified into horizontal and vertical measures. The horizontal traffic calming measures include traffic circles, roundabouts, chicanes and so on; they are less effective than vertical traffic calming measures, such as SHs, speed tables, speed cushions, rumble strips and so on. SHs are raised mounts that can reduce speeds to a certain limit based on the height and length of the hump. A hump is often designed as a circular, parabolic, trapezoidal or sinusoidal curve. SHs can be designed for different target speeds, and are not limited to low-traffic streets. Ideally, SHs will enable vehicles to travel at a target speed consistently along a road, rather than slowing down and speeding up before and after each hump (IRC, 2017). Tester *et al.* (2004) studied the protective effectiveness of SHs in reducing child pedestrian injuries in residential neighbourhoods. They identified 100 individuals who had been victims in the emergency department during the study period and used multivariate logistic regression models for analysis. Their study suggested that SHs can make children's lives safer.

Ullah *et al.* (2016) reviewed the time line work on the impact of SHs on vehicles. They discussed various types of retarders used to calm vehicle speeds, such as speed breakers, which are installed for the safety of users. They evaluated the speed of vehicles at SHs, accident rate and traffic volume and found that the accident rate is reduced after the installation of SHs. Their study suggested the need to design SHs in a better way to control the accident rate in Pakistan.

Satiennam *et al.* (2014) studied the influence of speed bumps and humps on the speed of free-flowing motorcycles and passenger cars. This study considered two groups, namely, speed bumps and humps. The height of the speed bumps was 50 to 70 mm and the length varied from 0.35 m to 1.5 m. Motorcyclists crossed with a speed ranging between 15 and 18 km/h. The other category of the SH had a height of 130 to 180 mm and length of 5.3 to 10.3 m. A motorcyclist's crossing speed ranges between 29 and 31 km/h at this SH, yielding a speed reduction of 13–39%.

Silva *et al.* (2014) studied the speed profile of vehicles on an isolated SH. They developed a speed profile model using an hierarchical multiple linear regression technique. This model can predict a vehicle's speed in the vicinity of an SH.

Vasquez-Sanchez and Obregon-Biosca (2017) observed that the efficiency of SHs depends on the physical dimensions of the devices. They analysed two different geometries, namely, circular and trapezoidal, and noted that the speed of vehicles passing over these devices is dependent on the geometry of the hump. They recommended that the height of a trapezoidal hump should be in the range of 15–18 cm and the slope in the range of 9–14%. The circular hump design with a height from 11 to 15 cm and width from 125 to 140 cm can effectively reduce the speed by up to 55–75%.

Bassani *et al.* (2011) also studied the effects of trapezoidal speed humps (TSHs) on the kinematic performances of vehicles. Their study highlighted the main factors influencing TSHs and their effect on the operating speed of a vehicle. They developed a relationship between the operating speed and spacing of the TSHs using a linear regression model.

Most of the studies reported above have evaluated the efficiency of the speed breakers with respect to the reduction in speed of a vehicle. Authors have used linear regression analysis to develop the relationships between the speed of the vehicle and the geometry of the SH. The benefits of various SHs and speed bumps as reported in these studies are summarised in Table 1.

As may be seen from Table 1, the effect of a traffic calming measure is different in different countries. India holds the very dubious distinction of having the highest number of fatalities in road crashes (MoRTH, 2016). Almost 40% of road crash deaths occur on urban roads (Nikhil, 2015). Although the Indian Roads Congress (IRC) has given some guidelines for the design of speed calming measures (IRC, 2018), local civic agencies erect different types of SHs on urban streets under the pressure of local residents. The present study sets out to

Table 1. Yielded benefits of SHs observed in previous studies

Study no.	Author	Study location	Objective of the study	Type of SH	Benefits
1	Silva <i>et al.</i> (2014)	Portugal	Speed profile model for SHs	Circular and trapezoidal	Speed reduction of 40 to 60%
2	Tester <i>et al.</i> (2004)	Oakland, California, USA	Effectiveness of SHs in reducing child pedestrian injuries	Speed humps (not stated)	Child pedestrian injuries and deaths reduced to 53–60%
3	Satiennam <i>et al.</i> (2014)	Northeastern Thailand	Effects of speed bumps and humps on speed profiles of motorcycles	Circular and parabolic	Speed reduction is 43–47% for circular and 13–39% for parabolic
4	Vasquez-Sanchez and Obregon-Biosca (2017)	Geoplazas, Queretaro, Mexico	To study the effectiveness of humps on traffic flow	Circular and trapezoidal	Circular humps decrease the vehicle speed 50–75%, trapezoidal hump reduces the speed by 60 to 75%
5	Pardon and Average (2013)	Masvingo, Zimbabwe	To study the effectiveness of traffic calming measures	Speed humps	Reduction of speed 70%

determine the efficacy of different types of speed breakers (humps) on urban roads in India and to suggest the most appropriate shape and size of the hump depending upon the speed limit on a road.

3. Method

The method adopted for this research consisted of: identification of study sections; collection of primary data using video graphics; processing of the video data and their analysis; and evaluation of traffic calming measures. Various categories of urban roads – namely, arterial, sub-arterial and collector streets – were considered for identification of the study sections. The study is limited to vertical traffic SHs only. Five SHs were identified on different roads in Delhi. A trap 60 m long was marked in the approaching direction of the vehicle and it was divided into six small sections of 10 m each to observe the speed profile of approaching vehicles. Video data recorded in the field were screened on a computer screen in the laboratory to extract the speed of the individual vehicle at different intervals before the SH. The relationship between approaching speed of the vehicle and the physical features of the SH – namely, height, width and slope (radius) – was developed using multiple linear regression analysis. The optimum shape of the SH for the desired reduction in speed is estimated through a linear programming technique.

4. Data collection and extraction

Five study sections were identified in Delhi and the traffic data at all these locations were collected for 2 h on a normal weekday, during the day. A simple surveying method was adopted in the field to measure the vertical height of the SH at regular intervals with reference to the plane surface and these details were plotted in the Auto CAD software to obtain the complete vertical shape of the hump. A parabola is a curve where any point is at an equal distance from a fixed straight line (directrix). Therefore, in this study, the vertical height from a fixed straight line formed using string was measured (the string line was fixed at both ends to form a directrix). The location of each SH and its main physical features, such as height, width and entry radius, were measured and are presented in Figure 1. The radius of a circular hump is a well-defined parameter and describes the complete shape of the curved surface. In the case of a parabolic hump, the radius of the curve changes with the distance from the entry point and therefore there is no single radius that can describe the complete shape of the curve. To ensure the similarity of the parameters on circular and parabolic shapes of an SH, the entry radius is considered for the analysis in this paper. A video graphic technique was used to record the traffic flow characteristics, including volume, speed and traffic composition, using a camera with a frame speed of 25 per second. In this study, spot speed data before the SHs are also collected using laser guns and these speeds were compared with the speeds estimated from video data. The accuracy of the estimated speed by video method was $\pm 2\text{--}3$ km/h. In the literature

most of the studies used 25–30 frames/s for the speed estimation of vehicles. Temiz *et al.* (2012) compared the speed estimated by video analysis and global positioning system (GPS) techniques and they observed that the accuracy of the speed data is approximately $\pm 1\text{--}2$ km/h. The video data captured in this study was in the format of MPEG Transport Stream (MTS) and this video was further converted into Audio Video Interleaved (AVI) format. The AVI format video was run through Kinovea software to develop grids in the video film, as shown in Figure 2. The reference points marked during videography were used to draw this grid. Traffic cones were initially placed to clearly mark the trap length of the study section. A few minutes later, the cones were removed from the location. The entire 60 m trap length is divided into six equal grids and this video with grid was played into K-Lite media player classic. The current time and current frame number of the video displayed on screen were noted for each individual vehicle at the entry and exit points of the grid lines. This procedure was continued until the vehicle under observation reached the crown of the SH. With the help of the frame numbers and time stamp at each grid line, the speed was estimated at every 10 m distance before the SH. Six categories of vehicles – namely, cars, motorised two-wheelers, three-wheelers, light commercial vehicles (LCVs), buses and heavy commercial vehicles (HCVs) – were considered and a minimum sample size of 30 was taken for each category of vehicle for the development of the speed profile of each vehicle type. These profiles are examined in the next section.

5. Speed of vehicles approaching SHs

The speed of different types of vehicles approaching SHs is examined in this section. The categories of vehicles included in this study are car, two-wheeler, motorised two-wheeler (2W), motorised three-wheeler passenger vehicles (auto), light commercial vehicle (LCV), heavy commercial vehicle (HCV) and bus. A minimum of 30 representative samples were considered for defining the speed profile of each category of vehicle. During the data extraction, care was taken to avoid the influence of any other vehicle on the movement of a subject vehicle. For this, a minimum headway of 10 s is considered. The trap length of 60 m is divided into equal intervals of 10 m and the average speed of different vehicles at every 10 m distance is estimated. Speeds of different categories of vehicles at seven different positions – namely, between 60 and 50 m, 50 and 40 m, 40 and 30 m, 30 m and 20 m, 20 m and 10 m, 10 and 0 m and at the crown of the SH – were considered to plot the speed profiles. These speed profiles are separately presented for circular SHs (two sections) and parabolic SHs (three sections) in Figure 3. The entry radius of circular SHs is less than 12 m and that of parabolic SHs varies between 16.7 m and 22 m.

5.1 Speed variation on parabolic SHs

The average speed of vehicles at 55 m before a parabolic SH is from 27 km/h to 61 km/h and that near the SH (at 5 m distance from the foot of the SH) is from 22 km/h to 37 km/h.

Sec-1: Kali Bari Marg – arterial road
(four-lane undivided carriageway)

Sec-2: Dwaraka Link Road – arterial road
(six-lane divided carriageway)

Sec-3: Shahi Road
(intermediate lane undivided carriageway)

Sec-4: Kapeshera Road
(four-lane undivided carriageway)

Sec-5: Maulana Mohammad Ali Jauhar Marg
(four-lane divided carriageway)

Figure 1. Identified study sections and physical features of SHs

The speed at the crown of the SH varies from 13 km/h to 28 km/h. Higher speeds were observed for two-wheelers and lower speed ranges were observed for buses at 55 m before the SH. Two-wheelers had higher speed and the LCV had a lower speed near and at the crown of the hump. It was observed from the speed profiles (Figure 3) that there is no sudden drop of the speeds near the SH. This emphasises that the entry

radius of a parabolic SH is quite sufficient to accommodate the vehicles at higher speeds. Also, the speed of the approaching vehicle at 60 m before the SH depends on the type and width of the carriageway, but the speed near the hump mainly depends on the entry radius of the hump. At parabolic SHs, almost all of the vehicles reduced their speed to within the range 15–20 km/h.

Figure 2. Data extraction process using video analysis

5.2 Speed variation on circular SHs

The speed profiles of different types of vehicles on circular SHs are also drawn in Figure 3. The average speed of vehicles 55 m before the SH is between 27.9 km/h and 55.5 km/h, and near the SH (at 5 m distance from the speed bump) between 15.8 km/h and 24.2 km/h. The speed at the crown of the SH varies from 5.5 km/h to 21.0 km/h. Cars are running at higher approach speeds and two-wheelers have lower speeds near the SH. At the crown, two-wheelers have higher speeds than cars. It was observed from the speed profiles of vehicles at circular SHs that there is a sudden drop of the speeds near a circular SH. This is mainly due to the sharp entry radius forcing the drivers to reduce their speeds. When the entry radius was 5 m (Sec-3), every category of vehicle tried to reduce its speed up to 5 km/h. When the radius was 11 m (Sec-4), however, there was a variation in speed of the vehicles at the crown of the SH.

6. Results

The reduction in speed of vehicles near SHs mainly depends on the geometry of the SH. In this study the speed of vehicles at 60 m before the SH and that on crown of the SH is considered for defining the speed reduction due to SHs. The median speed of the vehicle is considered for estimation of speed reduction due to the influence of SHs. A comparison of the median speed of vehicles approaching isolated SHs is presented in Table 2. It can be observed that the speed reduction due to circular SHs with a radius of less than 11.5 m varies from 55.5 to 87.0%, whereas for parabolic SHs with radius between 17 m and 22 m, the speed reduction varies from 34 to 65.7%. It was identified from these empirical data that the entry radius of the SH plays major role, rather than the height of the SH. If the slope is gentle (higher radius), vehicles have a tendency to continue at the same speed as they were going before reaching within 10 m of the SH.

A greater speed reduction was observed for cars on section 3. This is mainly due to the smaller entry radius (5 m) of the SH at this location. Similarly, a smaller reduction in speed was observed at section 1, where the entry radius was large (22.6 m). The average difference of mean speed between a circular and a parabolic SH is 15 km/h. Based on the results of

this study and in view of safety considerations, it is recommended that parabolic SHs should be considered on arterial and sub-arterial roads where vehicles have higher running speeds. Circular SHs are recommended on collector and local streets where the average running speeds of vehicles are lower than those on arterial and sub-arterial roads.

6.1 Development of speed model

As discussed in the previous section, the size and shape of the speed breaker influences the desired speed at the crown of the SH. This section demonstrates the relationship between the vehicular speed and the geometry of the SH. Multiple linear regression (MLR) models are widely used in the literature to estimate the functional relationship between an exponential variable and response variables (Chandra *et al.*, 2013), and the same approach has also been used in the present study.

6.2 Multiple linear regression model

A MLR analysis was carried out to determine the relationship between the speed of the approaching vehicle and the main physical parameters of the SHs. The main assumptions of this model are: (a) the relation between the speed of a vehicle at distance (D_s) from the crown and the height of the SH and radius of the SH is linear; (b) the residuals (difference between observed and estimated speed) follow a normal distribution; and (c) the explanatory variables are not highly correlated with each other. The following form of linear functional relation is assumed for model development.

$$1. \quad V_{Ds} = a_0 + a_1 D_s + a_2 H_s + a_3 R_s$$

where V_{Ds} is the speed of the vehicle at distance D_s from the crown of the SH (m); a_0 is a model constant; and a_1 , a_2 and a_3 are coefficients of the model parameters. In this study, three explanatory variables – namely, approach speed observed from a distance D_s , height of the SH (H_s in cm) and entry radius of the SH (R_s in m) – were considered for the development of the model. The width of the SH is not considered here, because the width and radius of the SH are correlated to each other (correlation coefficient (r) = 0.95).

The MLR model coefficients for different categories of vehicles are presented in Table 3. The t -statistic value of each variable considered in the model and goodness-of-fit value in terms of the coefficient of determination (R^2) of each model are also given in Table 3. The fitted linear equation for one typical vehicle category (two-wheeler) is shown in Figure 3. It was observed that the R^2 value of a fitted linear equation for the two-wheeler category at study locations varies from 0.86 to 0.98. Therefore, the linear equation is good to explain the variation of speed of the vehicle approaching an SH. Furthermore, a model developed for the combined data is also given in the table. It can be seen that the sign of each explanatory variable is appropriate, except for the HCV. This can be attributed to

Figure 3. Vehicular speed behaviour approaching isolated SHs: (a) Sec-1: Kali Bari Marg – arterial road (four-lane undivided carriageway); (b) Sec-3: Shahi Road – collector street (intermediate lane undivided carriageway); (c) Sec-2: Dwaraka Link Road – arterial road (six-lane divided carriageway); (d) Sec-4: Kapeshera Road – collector street (four-lane undivided carriageway); (e) Sec-5: Maulana Mohammad Ali Jauhar Marg – sub-arterial road (four-lane divided carriageway)

an inadequate sample size of the HCV category of vehicle. The coefficient of height of the SH is negative, indicating that when the height of the SH increases, the speed of the vehicle while traversing the SH will reduce. The positive sign of entry radius indicates that the speed increases with the entry radius.

From this it can be concluded that the signs of the coefficients in the developed model are logical.

Analysis of variance (Anova) for each model was carried out and the goodness-of-fit (GoF) of the model in terms of

Table 2. Summary of reduction in speed of different vehicles due to SHs

Type of vehicle	Description	Parabolic SHs			Circular speed bumps	
		Sec-1 ($R_s = 22.6$ m)	Sec-2 ($R_s = 17.71$ m)	Sec-5 ($R_s = 16.7$ m)	Sec-3 ($R_s = 5$ m)	Sec-4 ($R_s = 11.5$ m)
Two-wheelers	Speed at a distance of 60–50 m from SH: km/h	37.50	60.00	50.00	36.00	56.25
	On crown of SH: km/h	16.50	27.69	22.09	7.36	21.18
	Reduction in speed: %	56.00	53.85	55.81	79.55	62.35
Car	Speed at a distance of 60–50 m from SH: km/h	34.62	56.25	45.00	42.86	51.47
	On crown of SH: km/h	19.80	25.71	18.00	5.40	18.00
	Reduction in speed: %	42.80	54.29	60.00	87.40	65.03
Three-wheelers	Speed at a distance of 60–50 m from SH: km/h	34.62	54.60	47.37	29.06	45.00
	On crown of SH: km/h	19.42	24.00	18.00	7.36	20.00
	Reduction in speed: %	43.90	56.04	62.00	74.66	55.56
Light commercial vehicle (LCV)	Speed at a distance of 60–50 m from SH: km/h	30.00	50.00	39.13	37.50	39.20
	On crown of SH: km/h	18.69	20.00	15.19	8.10	17.14
	Reduction in speed: %	37.71	60.00	61.18	78.40	56.27
Bus	Speed at a distance of 60–50 m from SH: km/h	27.27	52.94	35.31	32.18	45.00
	On crown of SH: km/h	18.01	18.95	13.50	6.23	13.33
	Reduction in speed: %	33.98	64.21	61.76	80.64	70.37
Heavy commercial vehicle (HCV)	Speed at a distance of 60–50 m from SH: km/h	*	50.00	40.02	33.33	39.13
	On crown of SH: km/h	*	17.14	13.76	7.36	13.85
	Reduction in speed: %	*	65.71	65.62	77.91	64.62

*Not considered in analysis due to small sample size.

Table 3. Estimated model coefficients for MLR analysis

Regression model for	Constant		Distance from the SH, D_s		Height of the SH, H_s		Entry radius of the SH, R_s		Goodness of fit of the model, R^2
	Coefficient	t -statistic	Coefficient	t -statistic	Coefficient	t -statistic	Coefficient	t -statistic	
Car	60.89	8.17	0.45	9.71	−224.42	−6.16	0.13	0.91	0.811
Two-wheeler	57.49	6.04	0.46	7.81	−205.39	−4.41	0.16	0.83	0.724
Auto	41.19	5.48	0.38	8.18	−154.84	−4.21	0.52	3.51	0.762
LCV	43.35	7.26	0.39	10.62	−147.24	−5.04	0.19	1.61	0.820
Bus	31.47	6.51	0.43	14.36	−118.12	−5.32	0.51	4.44	0.919
HCV	57.81	7.50	0.37	7.14	−197.95	−5.08	−0.08	−0.30	0.765
Combined data	48.68	14.92	0.42	20.05	−176.17	−11.10	0.25	3.67	0.738

the coefficient of determination, R^2 value, was estimated. This is the ratio of explained variation to the total variation. From the results of the Anova, it was found that 73.8% of the variation is explained by the combined model. The GoF value is greater than 72% for all categories of vehicles. The coefficient of determination of about 74% for the combined model indicates a good model statistically. The scattered plot of residuals is depicted in Figure 4; this shows that the residuals form a random pattern, and this indicates that there is a good fit for a linear model. It was observed from the t -statistic values from all the models that the D_s and H_s variables in the model are significant ($p < 0.05$) at the 5% level of significance, whereas the entry radius of the SH is significant for buses and LCVs only. The t -statistic value of the entry radius for cars and

Figure 4. Scattered plot of residuals of the combined model

two-wheelers is less than 1.95 (at the 5% level of significance), which indicates that these vehicles are not reducing their speed significantly while approaching the SHs.

A combined equation was developed using the data for all categories of vehicles, as presented in Equation 2. The higher F value (181.0) was observed for the combined model as compared to the individual model. The F value is the ratio of mean squared regression (MSR) to the mean square error (MSE) and it indicates that the combined model is significant. This equation is to estimate the required height and entry radius for various desired speeds on the crown of the SH and before SHs, up to a distance of 60 m. This combined equation is considered to be an objective function for optimisation of the entry radius and height of the SH.

$$2. \quad V_{Ds}(\text{combined}) = 48.68 + 0.42D_s - 176.17H_s + 0.25R_s$$

6.3 Optimisation of height and entry radius of SH

The main physical parameters that influence the desired speed of vehicles at an SH are the height and entry radius of the SH. This study focuses on estimating the optimum values of these parameters of an SH for the desired speed on the crown of the hump. This was done by adopting a two-step approach, namely, the inverse method and the simplex method of LPPs. The process of these methods is briefly described in the following paragraphs.

The inverse method is adopted for considering three linear equations, because this study considered three explanatory variables (D_s , H_s and R_s) and one response variable (the desired speed at the SH). The method considers the inverse of the coefficient matrix. The inverse of a matrix exists precisely when its determinant is non-zero. This problem is solved in Python software to define the optimal values of the geometry of the SH. This method is used to define the height of the SH, the entry radius of the SH and the visibility distance from the SH. The outcome of these variables is considered in the simplex method, which is a linear programming technique to solve for optimal values of the decision variables, which leads to maximisation or minimisation. In this study, the simplex LPP method was considered to estimate the optimum desired speed at the crown of the SH by considering the linear constraints. The simplex method is an approach to solving linear programming models by using slack variables, tableaux and pivot variables as a means to find the optimal solution of an optimisation problem. This process was also solved by considering Python software. This syntax is used to define the linear programming optimisation to minimise a linear objective function. The objective function is taken from the equation developed in regression analysis. The result obtained from the two-step approach is presented in Table 4.

Current guidelines developed in India for traffic calming measures in urban and rural areas assume a circular hump

Table 4. Minimum height and entry radius as required for various desired speeds

Desired speed on crown of SH: km/h	Optimum height: cm	Optimum entry radius: m
15	9.0	8.0
20	12.5	10.0
25	15.5	13.0
30	19.0	15.0

with a rise of 10 cm. From the field observations it was seen that speeds are higher than the desired speed proposed by existing guidelines in India. Therefore, the outcome of the study will be extremely useful as input to revise the existing guidelines. The rate of deceleration of different vehicle types for different shapes and sizes of SHs should be investigated in future studies.

7. Conclusions

In the present study, an attempt has been made to estimate the efficacy of speed breakers of different shapes and sizes on urban roads in National Capital Territory of Delhi. Most of the urban roads in India do not have properly designed and maintained SHs. In this study, the speed behaviour of various categories of vehicles approaching an SH has been examined. The extent of reduction in speed was estimated by plotting the speed profile of vehicles for a distance of 60 m before the SH and the speed on the crown of the SH. Traffic data were collected at five locations through a video graphic technique and a minimum sample of 30 was considered for each vehicle type for the speed profile development. The effect of an isolated parabolic SH and a circular speed bump on vehicular speed at the crown of the speed breaker was estimated by considering the difference in median speed of the vehicle. From the results, it was observed that the speed at the crown of the parabolic hump varies from 13 to 28 km/h and on the circular SH varies from 5 to 21 km/h.

The relationship between desired speed and geometric parameters of the SH was also estimated for various types of vehicles. Furthermore, a single regression model was developed by combining the data for all the vehicles. From the results it was observed that the entry radius of an SH influences the speed of heavy vehicles and light commercial vehicles, whereas cars and two-wheelers do not reduce their speed before the SH, even when the height of the SH is 20 cm. Therefore, the optimum height of an SH and its entry radius were estimated through a two-step approach. Based on the objective linear function, the optimum height and radius for the desired speed was estimated by using the simplex method. However, it should be noted that the final relation presented in this paper does not fully consider the shape of the SH and is based on the radius and height only. This is because of a limited number of data points in each case and, therefore, this aspect must be studied in future works to understand better the influence of the shape of the hump on speed reduction.

Recently, the IRC published guidelines for traffic calming measures in urban and rural areas where the radius of the hump is recommended based on an assumed fixed rise of 10 cm. From the field data, it was observed that vehicular speeds are higher even at an SH height of 20 cm. This study demonstrates the existing speeds of vehicles at various SHs and the outcome of this study will be useful for designing isolated SHs for a given desired speed on the hump.

Author contribution statement

The authors confirm contribution to the paper as follows: study conception and design, Dr Satish Chandra and Dr Ch. Ravi Sekhar; data collection, Md Ruhina Begum and Dr Ch. Ravi Sekhar; analysis and interpretation of results, Md Ruhina Begum; draft manuscript preparation, Md Ruhina Begum, Dr Ch. Ravi Sekhar and Dr Satish Chandra. All authors reviewed the results and approved the final version of the manuscript.

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