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Comparative Performance Analysis of Bumps and Humps In Terms of Ride Speed Calming

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Abstract: The study evaluated speed control undulations (SCUs), as one of the crucial speed management tools in urban areas, performance in reducing passenger car speeds. The evaluations investigated two narrow-type SCU (Bump) and two wide-type SCU (Hump) with 5 cm and 10 cm height. The performance of SCUs in reducing vehicle speeds has been examined by reading speed values from video records. Vehicle speeds have been determined at a distance from the SCUs that does not affect the speed of the drivers (approx. 125-150 m) and also at a distance of -60 m, -40 m, -20 m, 0 m (passing over), +20 m, +40 m and +60 m according to the SCU. All speed measurements were made in two different traffic flow regimes, free flow (FF) and oversaturated flow (OSF). Between the measured vehicle speeds and speed reduction rates, statistical evaluations were made for each SCU at different measurement points and the exact measurement points between different SCUs. It was seen that the 10 cm high humps would be the right choice for reducing passenger car type vehicles speeds.

Keywords: Bump, hump, traffic calming, speed management

Dar ve Geniş Hız Kesici Tümseklerin Sürüş Hızını Sakinleştirme Açısından Karşılaştırmalı Performans Analizi

Öz: Çalışmada, kentsel alanlarda çok önemli hız yönetimi araçlarından biri olan Hız Kesici Tümseklerin (HKT'ler), binek araç hızlarını azaltmadaki performansları değerlendirilmiştir. Değerlendirmelerde, 5 cm ve 10 cm yüksekliklerdeki iki adet dar tip HKT (Bump) ve iki adet geniş tip HKT (Hump) incelenmiştir. HKT'lerin taşıt hızlarını azaltma konusundaki performansları kamera görüntülerinden hız değerleri okunarak incelenmiştir. HKT'lerin sürücüleri hızlarını azaltma konusunda etkilemediği bir mesafede (yaklaşık 125-150m) ve ayrıca HKT'ye göre -60 m, -40 m, -20 m, 0 m (üzerinden geçişte), +20 m, +40 m ve +60 m mesafelerdeki taşıt hızları belirlenmiştir. Tüm hız ölçümleri serbest akım ve doygun akım olmak üzere iki farklı trafik akım rejiminde ayrı ayrı yapılmıştır. Ölçülen taşıt hızları ve hız azaltma oranları arasında gerek her bir HKT için farklı ölçüm noktalarında gerekse farklı HKT'ler arasındaki aynı ölçüm noktalarında istatistiksel değerlendirmeler yapılmıştır. Değerlendirmelerde binek otomobil türündeki taşıtların hızlarını azaltma konusunda 10 cm yüksekliğindeki geniş tip HKT'nin en doğru tercih olacağı görülmüştür.

Anahtar Kelimeler: Dar hız kesici tümsek, geniş hız kesici tümsek, trafik sakinleştirme, hız yönetimi

1. Introduction

Traffic engineers have developed various methods to reduce the undesirable consequences of speed for vulnerable road users, especially on urban roads. Traffic control with electronic detectors, speed restrictions, warning and stop signs, lane channelization, diagonal diverters, road chokers, rumble strips and speed control undulations (SCU) are some of these methods. As a result of being easy to implement and economical, the SCUs are frequently preferred throughout the world for traffic

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calming purposes. SCUs developed to fulfil multiple tasks to regulate the traffic are named speed bumps (B), speed humps (H), speed tables (ST) and speed cushions (SC) according to their dimensions and cross-section geometries. Bs and Hs, which are frequently preferred worldwide for calming the traffic, are applied in constantly fixed sections as the platform width of the road. Bs are narrow and somewhat abrupt (0.30 - 1 m base width), whereas Hs are wide and relatively gradual (over 1 m base width), with their heights varying, are designed with a sinusoidal, circular, or parabolic vertical profile in the direction of movement [1-3].

Research shows that at least half of the drivers use their vehicles above the speed limit from time to time. Also, drivers often exceed the speed limit at speeds below 20 km/h. [4]. Besides, it has been determined that in accidents involving pedestrian collision, the probability of death at 50 km/h is 5 to 8 times higher than the same at 30 km/h [5]. Therefore, further reducing the relatively low speed of traffic operation in urban road networks is crucial in eliminating accidents in the frequently encountered form of a pedestrian collision.

SCUs are known to be used for the first time in 1970 in Delft for traffic calming [3]. Studies involving before-after evaluations in which different speed averages (arithmetic mean, 50th and 85th percentile speed) were used as components to assess the efficiency of SCUs are included in the literature [6-8]. Antić et al. investigated the effects of Bs at different heights on speed reduction [8]. In their study, the effects of Bs at the height of 3, 5 and 7 cm, with 96 cm width, were evaluated. In the same traffic lane, two Bs of the same height were established at 50 m intervals. The speed values of the vehicles passing were read at the midpoint of two Bs in three different periods, before being manufactured, one day after and 30 days after. Also, arithmetic means, 50th and 85th percentile speed values were calculated. It has been concluded that the Bs of 5 cm and 7 cm high contribution to the safety of vulnerable road users, especially to the protection of pedestrians. At 50th percentile speeds of 5 cm height of approximately 30%, 7 cm height of roughly 35% reduction was found. Cottrell et al. compared H and ST at 9 cm height in their studies [3]. It was determined that speed reductions varying from 13.8 km/h to 5.4 km/h are achieved in 15 of the 18 points evaluated at 85th percentile speeds. In the study, it was determined that the Hs were more successful than the STs in reducing the speed according to the situation of the terrain on where the road passes. Pau and Angius [9] investigated the efficiency of 3 cm high Bs in terms of speed reduction. They concluded that traffic lane shrinkage is much more effective than a 3 cm high Bs in terms of speed reduction. They also observed that the Bs placed before the pedestrian crossings were not very effective. In the Ewing study [10], it has been determined that 3.65 m wide Hs decreases the average speed by 22%, and 4.25 m wide Hs decreases the average speed by 23% (heights were not specified). In addition, in the study conducted with approximately 400 data in 10 different speed calming applications, it has been reported that Hs performance varies according to location. In Evans study [11], it was determined that Hs with 8.5 cm height reduced the average speed by about 28% and Hs with 7.5 cm height by approximately 25%. In general, studies show that as the height increases, the efficiency of traffic calming increases. Especially at heights over 5 cm, it was found that the speed decreased by 30% and above. Kırbaş and İskender [12] evaluated SCU performances at heights of 5, 10, and 15 cm in reducing speed on a minibus, midibus, and bus type vehicles, which are frequently used in public passenger transportation activities. It was emphasized that the effects of SCUs on speed reduction did not change in different traffic flows as the size of the vehicles increased. Kiran et al. [13] analysed speed humps and bumps on various accounts such as travel time delays, mileage reductions, exhaust emissions and propose a new traffic calming device, which can retain the positive impacts of speed humps and also reduce the disadvantages associated with them. They evaluated the geometrical limits of the new design, called Curved Speed Hump, in practice. Yeo et al. [14] investigated the speed reduction effects of speed humps on roads in different service classes. The study determined that speed humps reduced the velocity of the flow by 18.4% in local roads and 24.0% in major roads, and the speed reduction effect was influential in the 30 m range (± 30 m) before and after the hump. In the study of Shahdah and Azam [15], it was determined that the intersection average delay increases in the range of 109–448%

in the case of using hump in a three-leg intersection area. In addition, there are studies in the literature that evaluate SCUs in terms of fuel consumption and environmental effects [16, 17], the convenience of location selection and their distribution in urban areas [18], and the comfort or discomfort it provides to drivers [19-21], besides reducing the speed of traffic flow.

There are limited studies in the literature comparing SCUs in terms of both comfort and efficiency in reducing speed. In the study of Mak [6], firstly, the SCUs compared as speed control devices and the ride (driving) speed was reduced by approximately 24% of Hs and 44% of Bs. Then, SCUs were compared in terms of comfort and, it was determined that vehicles are exposed to vibrations about twice as much vibration in B passages than in H passages. In the study, Bs and Hs with equal heights were not compared. As a result, the author has suggested that the use of Hs instead of Bs for speed management is more appropriate.

Speed management is defined as all methods that reduce adverse effects caused by over speed. Also referred to as “sleeping policemen”, SCUs, are one of the most economical and efficient ways to reduce vehicle speeds and thus reduce accidents. In this study, for passenger car type vehicles, Bs and Hs at 5 cm and 10 cm heights were evaluated comparatively in terms of their performances on speed reduction. The performances of the SCUs in reducing the vehicle speeds were determined by reading the distance average speed values of the vehicles via video records. The vehicle speeds (speed unaffected, SU) were primarily determined at a distance where the drivers did not reduce their speed from the SCU. To determine the speed reduction performances, for each SCU, the speed of the passing vehicles at -60 m, -40 m, -20 m, 0 m (crossing over), +20 m, +40 m and +60 m were determined. All speed measurements were carried out separately in two different traffic flow regimes, free flow (FF) and oversaturated flow (OSF). The measured vehicle speed data and the rate of deceleration (RoD) values at each point relative to the SU were visualized using graphics to compare the results. Besides, statistical evaluations were made between measured vehicle speeds and RoD values at different measurement points for each SCU and the same measurement points between different SCUs. In this study, unlike other studies in the literature, the evaluations were evaluated in two different flow regimes (FF and OSF). Also, as highlighted in the title, bumps and humps were compared in terms of speed reduction performance. Hence, a contribution has been made to existing literature where there are only a limited number of research studies.

2. Materials and Methods

2.1. SCU Profiles

The SCUs are the local elevation differences created by increasing the pavement up to 15 cm from the upper level. It is thought that the most critical factors affecting ride comfort in an SCU are peak accelerations, cognitive stimuli and rate of change of acceleration [22]. Despite the increase in the SCU height and speed and the increase in vertical vibration too much, the drivers cannot perceive much at altitudes above 76 mm, so it has been seen that this height is a significant distinction [22]. In light of this information, 5 and 10 cm heights were chosen for the measurements to remain above and below this value. All cross-sections of the Bs and Hs used in this study are a segment of a circle.

Table 1. Geometric descriptions of SCUs used in the study

SCU	Width (cm)	Height (cm)	H/W Ratio
B1	40	5	0.125
B2	75	10	0.133
H1	210	5	0.024
H2	400	10	0.025

Depending on this geometry, the widths of the SCUs used are different. Some agencies consider the SCUs as part of the road section, using the same material as pavement, while others use the additional elements on the pavement such as composite, rubber, plastic, the concrete. In the study, the SCUs were manufactured as B1 plastic, B2 and H2 asphalt and H1 concrete, and the surface roughness was negligible. Geometric descriptions and photos of examined SCU profiles are shown in Table 1 and Figure 1.

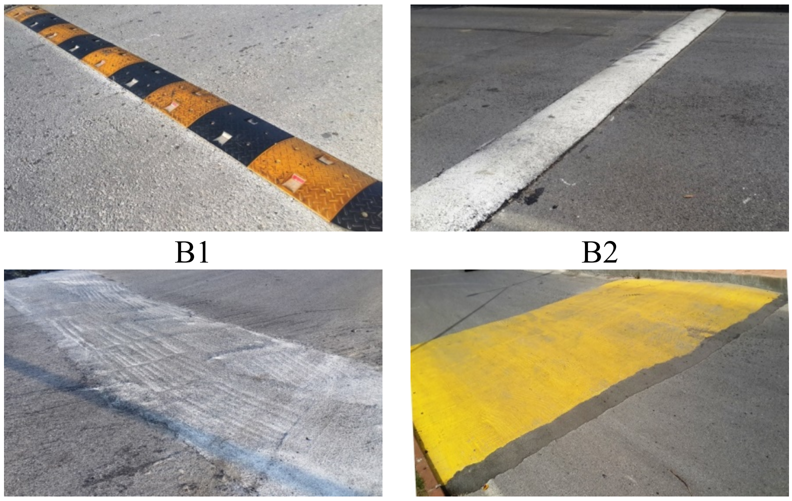

Figure 1. Photos of SCUs used in the study [20].

Apart from the devices applied for the traffic calming of the speeds of the vehicles in the traffic circulation, it is known that vehicle speeds are forced to decrease due to road geometry, traffic volume, driving habits. The examined SCUs were selected at distances as far as possible from intersections and at road sections not exceeding ± 3% longitudinal slope, mainly to avoid road geometry and traffic volume.

2.2. Vehicle Speed Measurement and Evaluation

The performance of SCUs as traffic calming devices was determined. The speeds of the vehicles were obtained by reading distance-average speed values via video records. Distance-averaged speed values were obtained by measuring the actual distance between two points determined in the field before and after the point where the average speed is desired to be determined and by using the data obtained by reading the transition times of vehicles between those points in video images, in Newton's speed model. In other words, the distances of some points on the roadside (electric pole, signage, etc.) that can be seen in the camera recordings to each other and the SCU were measured. The transit times of the vehicles between these points were determined from the camera recordings. The speed was found by dividing the distance between the points by the time travelled by the vehicle. Approximately 364 hours of images were analysed in compiling the data, and 4296 car speed readings were done. All speed measurements were made on days with no precipitation and clear visibility to minimize the effect of weather conditions on traffic. Firstly, SU values were determined for each SCU at a distance where vehicle drivers were not affected by the SCUs in reducing their speed to assess their speed reduction performance. When the literature is examined, it is understood from the studies that the drivers do not reduce their speeds very much due to SCUs at distances up to about 125 - 150 m [6, 23]. Hence, the SU measurements were made approximately 125-150 m ahead of the SCU. Then, the speeds of the vehicles passing through each SCU are determined at -60 m, -40 m, -20 m, 0 m (crossing over), +20 m, +40 m and +60 m in the direction of traffic flow. The speed measurement method described is shown schematically in Figure 2.

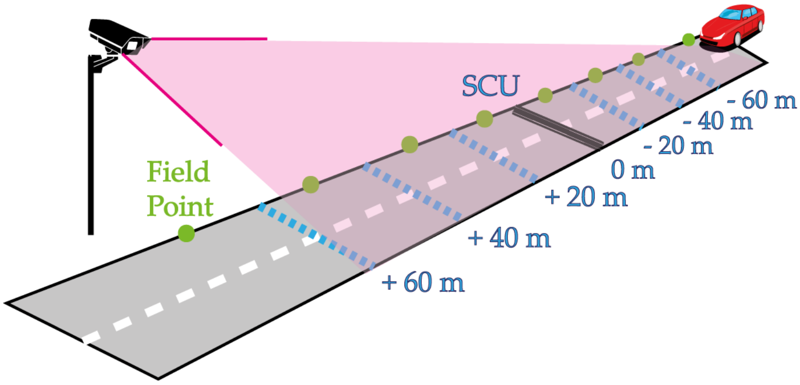

Figure 2. Schematic representation of distance-averaged speed measurement method.

The relative change of speed, volume and density parameters, derived variables of traffic, determines the current characteristics of the traffic, or in other words, the traffic flow regime. Highway capacity manual (HCM) explains the theoretical relationship between speed and flow (expressed as flow rate or volume), as shown in Figure 3 [24].

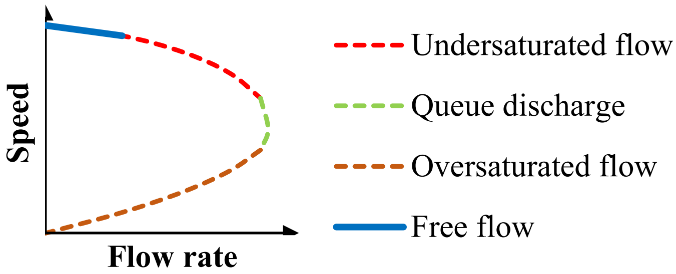

Figure 3. The theoretical relationship between speed and flow [24].

As shown in Figure 2, the speed is highest in the place where the traffic flow rate is the lowest. This situation continues until a particular flow rate value. This traffic flow, on the other hand, describes the level of service (LOS) A as the service level, and the speed formed here is called the free-flow speed (FFS) [24]. In this traffic flow regime, it is assumed that vehicles do not affect each other in any way during movement in terms of speed reduction. HCM considers the traffic flow regime in three categories. Undersaturated flow (USF) regime is considered the stage of the regime in which vehicles begin to affect each other to reduce each other's speed after the FFS has been maintained up to a specific flow rate. Queue discharge (QD) is known to regulate the FFS of vehicles after the bottleneck regime (downstream), but vehicles tend to slow each other down before the bottleneck (upstream). Oversaturated flow (OSF) regime refers to the conditions in which vehicles tend to reduce the speed of each other either upstream or downstream [24]. In this study, speed readings were carried out in two different traffic regimes to determine the performance of the SCUs in these different traffic regimes, which significantly affect the speed of the vehicles. These are the FF under the USF regime and also the OSF regimes. It is impossible to determine these flow regimes without conducting traffic analysis studies in the field. Hence, in the examined speed measurements, it is accepted that the traffic flow is in the FF regime of the vehicles in single passes from SCUs and that the traffic flow is in the OSF regime of the vehicles in numerous and mutually influencing passes from SCUs. In light of this acceptance, speed measurements have been completed. It should also be recognized that some vehicles in the QD regime during the measurements may also be counted in the OSF regime, as it is not possible to distinguish the traffic flow regimes by nature. Therefore, the study should consider the results by assuming that vehicle speeds measured in the OSF regime intentionally cover both OSF and QD traffic regimes. Sample images showing flow conditions in the FF and OSF traffic regime in this study are shown in Figure 4.

Figure 4. Sample images showing flow conditions in the (a) FF traffic regime and (b) OSF traffic regime in this study

3. Results

In this study, SCU in four different sections, two of B and two of H, were evaluated for their traffic calming performance in decreasing vehicle speeds. The results of the measurements made in this section are explained with the aid of graphs. The successes of reducing the speed of vehicles passing through SCUs have been examined. It is understood that speed was examined using three different components, 85th percentile, 50th percentile, and arithmetic mean speed, in many studies on the evaluation of vehicle speeds [1, 6, 8, 9, 25, 26]. The 85th percentile speed refers to the speed threshold not exceeding 85% of the vehicles, and the 50th percentile speed refers to the speed threshold not exceeding 50% of the vehicles. Vehicle speeds for FF and OSF traffic regimes were determined at SU, -60, -40, -20, 0, +20, +40 and +60 points for each SCU and the speed changes are shown in Figures 5 and 6. At the same time, standard deviation variations are also shown in the figures.

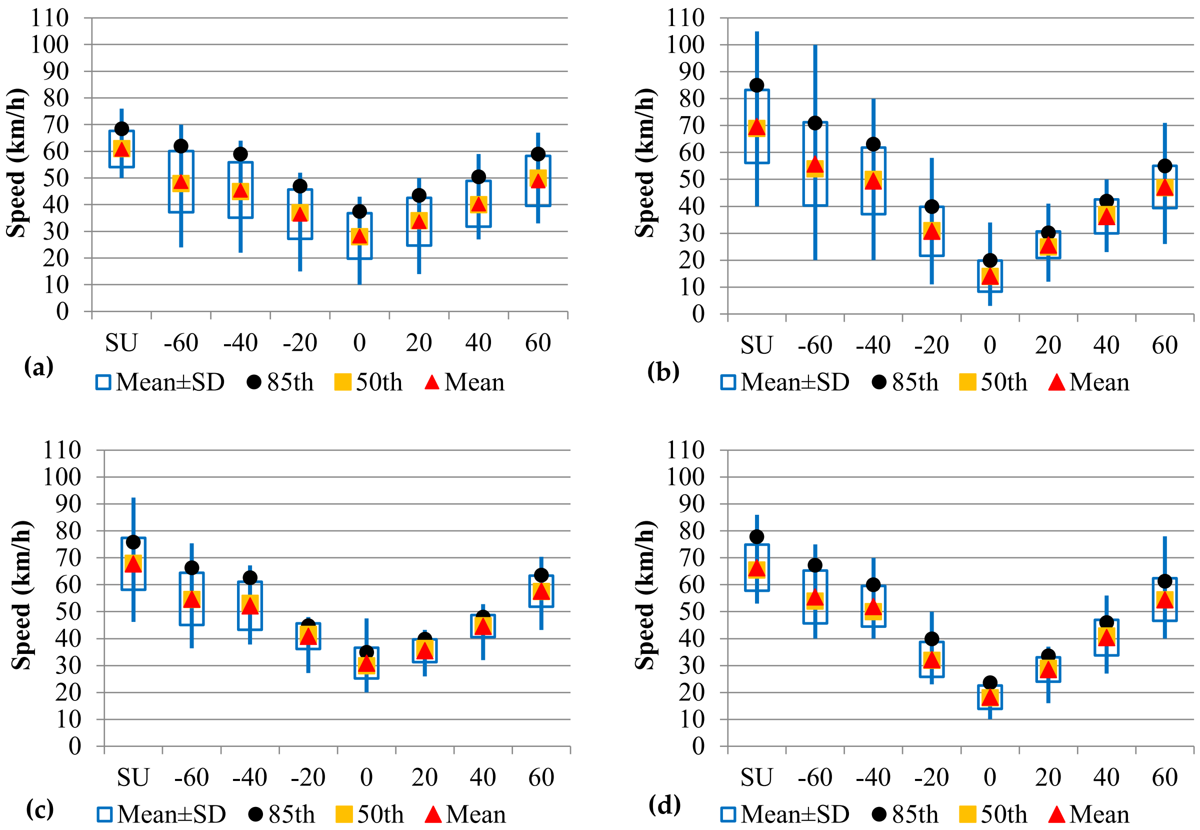

Figure 5. Changes of speeds measured in FF traffic regime; (a) B1 (b) B2 (c) H1 (d) H2

In general, it is seen that vehicle speeds are higher at all points in the FF regime than in the OSF. It is understood that the ability of SCUs on reducing the speed of vehicles also depends on the flow regime in which they are in traffic. Besides, in the FF traffic regime, it is seen that the speed change interval in each measured point is much broader than the OSF. In other words, in the OSF regime, vehicles travel at similar speeds. In the FF regime, the speed values read when the vehicles pass over the SCU are 36.5, 14.1, 30.8 and 18.2 km/h for B1, B2, H1 and H2, respectively. These values in the OSF regime are 17.8, 8.5, 23.2 and 12.6 km/h in the same order. When the SCUs were evaluated according to their heights, B at 5 cm height reduced average vehicle speed by 61% compared to 10 cm height, and H at 5 cm height decreased by 41% less than 10 cm height in the FF regime. This is 52% for Bs and 46% for Hs in the OSF regime.

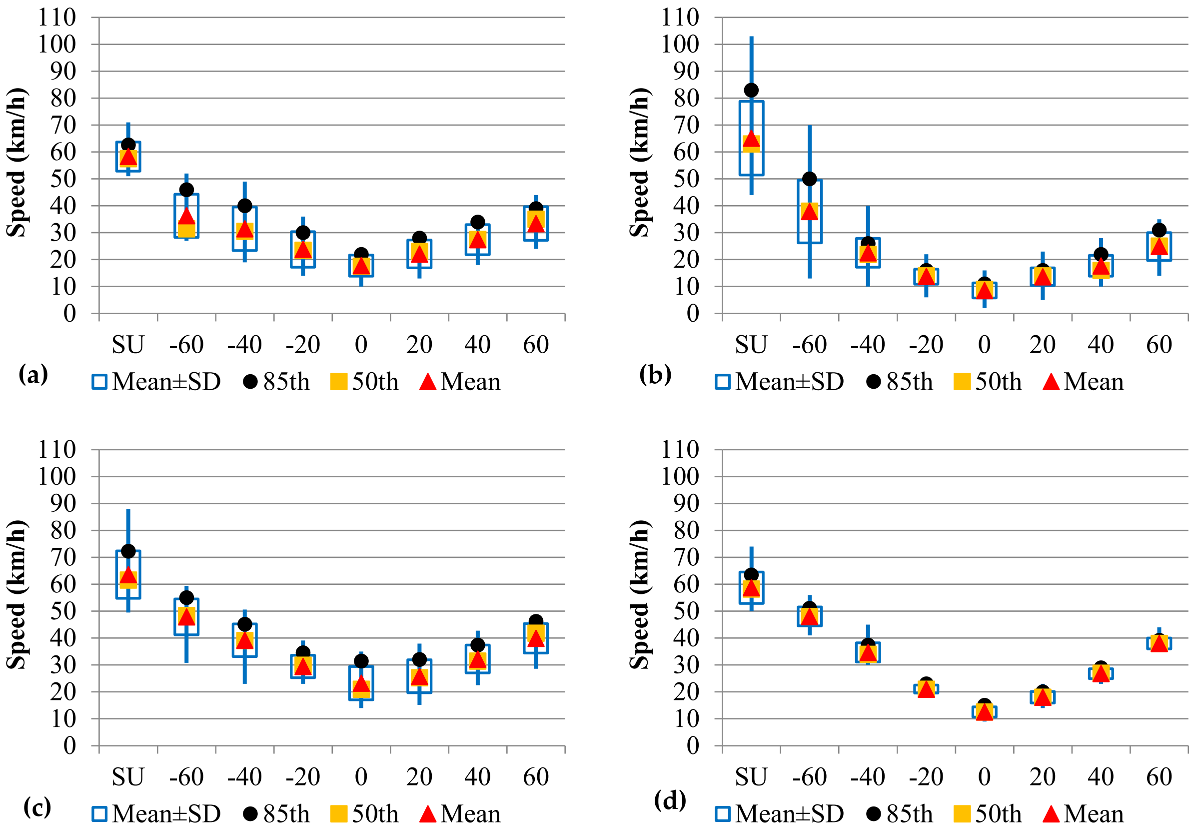

Figure 6. Changes of speeds measured in OSF traffic regime; (a) B1 (b) B2 (c) H1 (d) H2

When the height difference is taken into consideration, the evaluation shows that the efficiency of Bs in the FF regime increases as the height increases and that Hs increase in the efficiency of the OSF regime. In addition, it is seen that in the FF regime, the speeds are close to each other at -60 m and -40 m points in all SCUs; that is, the vehicles tend to decrease their speed after more than -40 m. Also, in the FF regime, it is seen that speeds are reached in +40m and +60m after passing through the SCUs at -40 m and -60 m speeds. Hence, it is understood that in the OSF regime, the same vehicle speed cannot be obtained at the same measuring points (such as -60 m and +60 m) in the road sections after the SCU passes.

In the study, vehicle speeds before and after SCUs were determined and compared according to different parameters. However, although the traffic characteristics are similar in all SCU speed measurements, the SU values cannot be measured the same. For this reason, the performance of SCUs in reducing vehicle speeds has been re-evaluated with the rate of deceleration (RoD) values according to the SU at each point of measurement. This evaluation shows the changes of 85th percentile speed, 50th percentile speed, and arithmetic mean speed for FF and OSF regimes in Figures 7, 8 and 9, respectively.

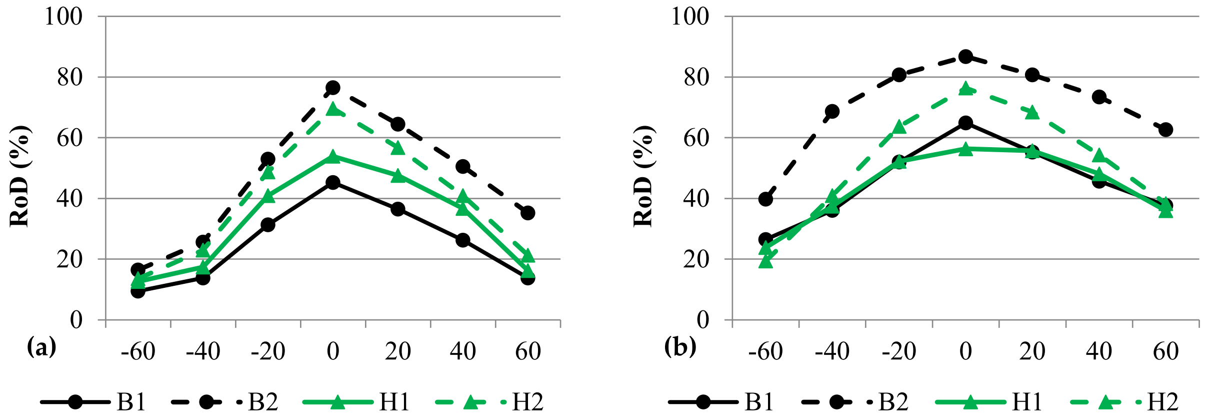

Figure 7. RoD values for 85th percentile speed in (a) FF and (b) OSF traffic regime

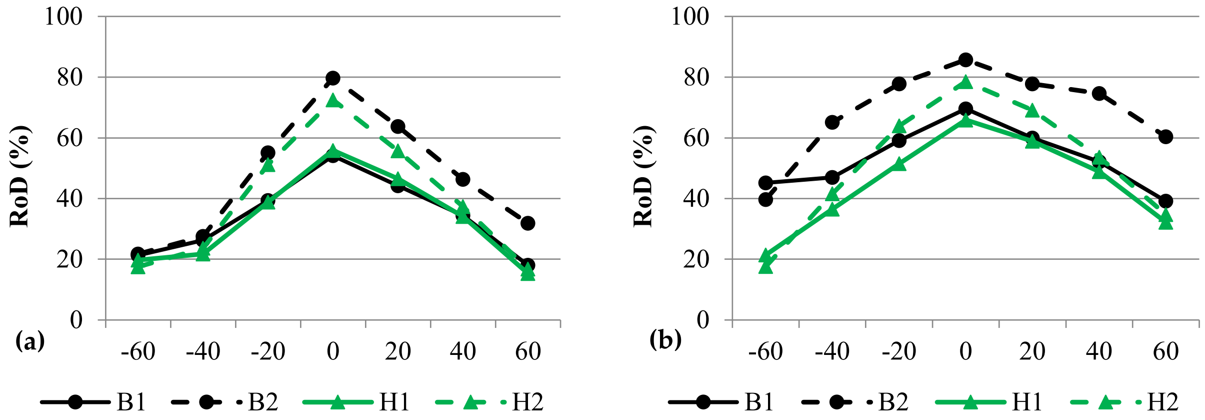

Figure 8. RoD values for 50th percentile speed in (a) FF and (b) OSF traffic regime

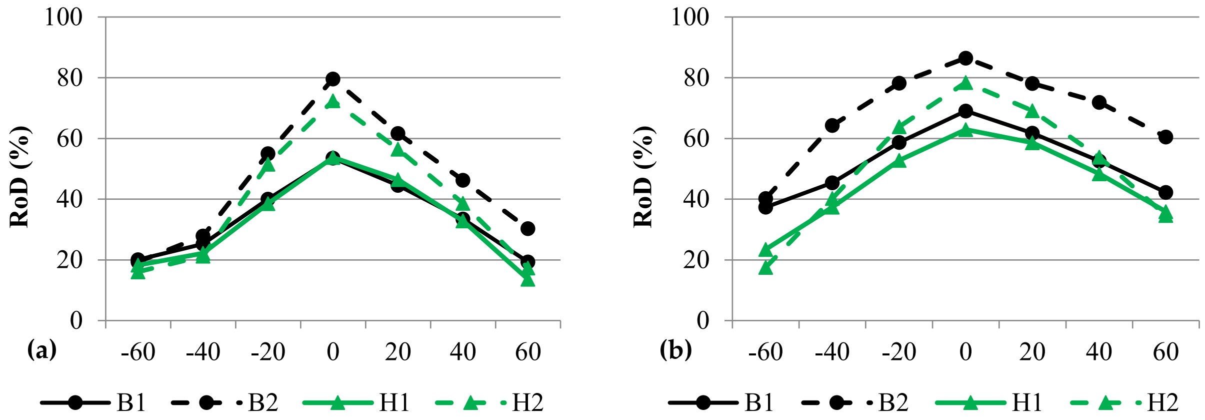

Figure 9. RoD values for arithmetic mean speed in (a) FF and (b) OSF traffic regime

At the 85th percentile, the 50th percentile, and mean speed evaluations reveal that the most successful SCU type to reduce the speed of vehicles is B2, followed immediately by H2. It is seen that B1 and H1 are very close to each other in reducing vehicle speeds, and B1 is slightly better than H1. Only in the 85th percentile speed evaluation is it observed that H1 is better than B1 in the FF regime. It is seen that 50th percentile speed and arithmetic mean speed evaluations have very similar results in both traffic flow regimes. In the 85th percentile speed evaluation, the vehicle speeds are reduced by

76.5%, 69.6%, 53.9%, and 45.3% for B2, H2, H1 and B1, respectively, while vehicles pass over the SCUs in the FF regime. It was determined that these rates were 86.7%, 76.4%, 64.9% and 56.4% for B2, H2, B1 and H1 in the OSF regime, respectively. In the 50th percentile speed evaluation, the vehicle speeds are reduced by 79.7%, 72.5%, 55.9%, and 54.1% for B2, H2, H1 and B1, respectively, while vehicles pass over the SCUs in the FF regime. It was determined that these rates were 77.8%, 63.9%, 59.1% and 51.5% for B2, H2, B1 and H1 in the OSF regime, respectively. In the FF traffic regime, it is seen that while the vehicles pass over the SCUs, the vehicle speeds are decreased by 79.6%, 72.4%, 53.8% and 53.5% for B2, H2, H1 and B1, respectively in the evaluation of the arithmetical mean speed. These rates were 86.5%, 78.5%, 69.1% and 62.9% for B2, H2, B1 and H1 respectively in OSF regime.

The fact that the RoD values are higher than similar studies in the literature can be explained by the widespread habit of not complying with the speed limits of the vehicles in the speed measurement region. Particularly in the FF traffic regime, 85th percentile speed threshold values are relatively lower than 50th percentile and mean speed threshold values. As a result, it is thought that the 85th percentile speed limit can be used to stay on the safe side in speed studies in FF traffic regimes. Other evaluations show similar results. The results clearly show that B1 is more successful in the OSF regime than the FF regime.

4. Discussion

Since many authorities widely use it globally, this technique is thought to be a 'panacea' that can be used to solve any problem caused by speed [9]. SCU, which is applied without considering the traffic characteristics, driving habits and road geometry of the region, should not be excluded from the mind that brings with it wrong and unnecessary usage with it. For example, it is recommended that Bs are only used on private roads and parking lots where traffic is under control [2, 27]. In contrast, it is also used frequently in calming urban traffic, especially in developing countries.

When considering the 85th percentile speed values concerning the discomfort, B2 reduces the vehicle speed by 76.5% in the FF regime, while it reduces vehicle speed by 86.7% in the OSF regime. These ratios show the most successful performance in speed reduction when compared to other SCUs. However, it seems that H2 is the second most successful SCU type to reduce vehicle speeds. In the evaluation of 85th percentile speed, it reduces the speed of the vehicles by 69.6% in the FF regime while decreasing the speed of the vehicles in the OSF regime by 76.4% in passing over. Concerning this, H1 reduces the speed of vehicles by 53.9%, while B1 reduces by 45.3% in the FF traffic regime. However, in the OSF regime, the opposite of B1 reduces vehicle speeds by 64.9%, while H1 reduces by 56.4%. In SCU with relative comfort levels such as B1 and H1, it is understood that drivers can only show their preferences for speed reduction in the FF traffic regime. H2 is very advantageous in terms of slowing vehicles in both FF and OSF regimes.

In addition, statistical similarities were investigated between different measuring points that speed measured for each SCU evaluated in the study and between different SCUs for each speed measurement point. The assessments were made separately for FF and OSF regimes. ANOVA test was used in statistical evaluations between vehicle speed measurement points. In this context, first of all, the vehicle data and RoD data were tested for Kolmogorov-Smirnov significance, confirming the normal distribution of the data. Multiple sample hypothesis test evaluation approaches have been used to evaluate all data together. For mutual correlation of the data by checking the condition of ensuring the uniform variance assumption, if an equal variance is provided, the comparisons' significance values were calculated using the Tukey test from Post-Hoc tests. If an equal variance is not offered, they were calculated by using Tamhane's T2 test. For each SCU, the significance values in the FF regime are summarized in Table 2, and the significance values in the OSF regime are summarized in Table 3 at different speed measurement points. Filled cells in the tables show the differences are significant (indicates that it is different) between the speed measurement points in the horizontal and vertical columns, statistically.

Table 2. Statistical significance values of speed between measurement points in FF regime for each SCU

B1

	-60m	-40m	-20m	0m	+20m	+40m	+60m
SU	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-60m		0.894	0.000	0.000	0.000	0.014	1.000
-40m			0.005	0.000	0.000	0.379	0.848
-20m				0.017	0.942	0.729	0.000
0 m					0.323	0.000	0.000
+20m						0.101	0.000
+40m							0.010

B2

	-60m	-40m	-20m	0m	+20m	+40m	+60m
SU	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-60m		0.071	0.000	0.000	0.000	0.000	0.000
-40m			0.000	0.000	0.000	0.000	0.988
-20m				0.000	0.000	0.000	0.000
0 m					0.000	0.000	0.000
+20m						0.000	0.000
+40m							0.000

H1

	-60m	-40m	-20m	0m	+20m	+40m	+60m
SU	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-60m		0.993	0.000	0.000	0.000	0.000	0.830
-40m			0.000	0.000	0.000	0.000	0.008
-20m				0.000	0.000	0.001	0.000
0 m					0.000	0.000	0.000
+20m						0.000	0.000
+40m							0.000

H2

	-60m	-40m	-20m	0m	+20m	+40m	+60m
SU	0.001	0.000	0.000	0.000	0.000	0.000	0.000
-60m		0.980	0.000	0.000	0.000	0.000	1.000
-40m			0.000	0.000	0.000	0.000	0.999
-20m				0.000	0.320	0.000	0.000
0 m					0.000	0.000	0.000
+20m						0.000	0.000
+40m							0.000

Table 3. Statistical significance values of speed between measurement points in OSF regime for each SCU

B1

	-60m	-40m	-20m	0m	+20m	+40m	+60m
SU	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-60m		0.885	0.000	0.000	0.000	0.010	0.999
-40m			0.074	0.000	0.005	0.895	1.000
-20m				0.050	1.000	0.894	0.001
0 m					0.168	0.000	0.000
+20m						0.113	0.000
+40m							0.090

B2

	-60m	-40m	-20m	0m	+20m	+40m	+60m
SU	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-60m		0.000	0.000	0.000	0.000	0.000	0.000
-40m			0.000	0.000	0.000	0.000	0.045
-20m				0.000	1.000	0.000	0.000
0 m					0.000	0.000	0.000
+20m						0.000	0.000
+40m							0.000

H1

	-60m	-40m	-20m	0m	+20m	+40m	+60m
SU	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-60m		0.000	0.000	0.000	0.000	0.000	0.000
-40m			0.000	0.000	0.000	0.000	1.000
-20m				0.000	0.023	0.107	0.000
0m					0.687	0.000	0.000
+20m						0.000	0.000
+40m							0.000

H2

	-60m	-40m	-20m	0m	+20m	+40m	+60m
SU	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-60m		0.000	0.000	0.000	0.000	0.000	0.000
-40m			0.000	0.000	0.000	0.000	0.044
-20m				0.000	0.000	0.000	0.000
0m					0.000	0.000	0.000
+20m						0.000	0.000
+40m							0.000

There is no similarity between speeds measured in SU and other points in all SCUs in the FF regime. It is also noteworthy that all SCUs have similarities between speeds measured at -60 m and -40 m. However, there is a similarity between the speeds measured at -60 m and the speeds measured at +60

m at B1, H1 and H2. In other words, it is understood that vehicles in the FF regime have completed speed changes between -60 m and +60 m in pass through the SCUs except for B2.
Since the OSF regime is forcing the traffic at the speed of the vehicles, quite different results are obtained from the FF regime. There is no similarity in the speed measurement point in the passage of vehicles from H2. In B2, there is a similarity between only in -20 m and +20 m points. On the other hand, there are more similarities in SCU types with a height of 5 cm. It is noteworthy that B1 has similarities, especially at -20 m before and after +20 m. However, similarities are observed to decrease in H1 when compared with B1. This situation brings to mind that the excess width in low SCUs causes instability on drivers about vehicle speeds.

Similarly, statistical evaluations were made according to the RoD values obtained by comparing the speed values at each measurement point with the SU values. The statistical significance results are shown in Tables 4 and Table 5.

Table 4. Statistical significance values of RoD between measurement points in FF regime for each SCU.

B1	-40m	-20m	0m	+20m	+40m	+60m
-60m	0.785	0.000	0.000	0.000	0.005	1.000
-40m		0.001	0.000	0.000	0.261	0.667
-20m			0.005	0.870	0.536	0.000
0m				0.180	0.000	0.000
+20m					0.038	0.000
+40m						0.002

B2	-40m	-20m	0m	+20m	+40m	+60m
-60m	0.024	0.000	0.000	0.000	0.000	0.000
-40m		0.000	0.000	0.000	0.000	0.999
-20m			0.000	0.004	0.000	0.000
0m				0.000	0.000	0.000
+20m					0.000	0.000
+40m						0.000

H1	-40m	-20m	0m	+20m	+40m	+60m
-60m	0.934	0.000	0.000	0.000	0.000	0.774
-40m		0.000	0.000	0.000	0.000	0.007
-20m			0.000	0.002	0.110	0.000
0m				0.004	0.000	0.000
+20m					0.000	0.000
+40m						0.000

H2	-40m	-20m	0m	+20m	+40m	+60m
-60m	0.788	0.000	0.000	0.000	0.000	1.000
-40m		0.000	0.000	0.000	0.000	0.966
-20m			0.000	0.207	0.000	0.000
0m				0.000	0.000	0.000
+20m					0.000	0.000
+40m						0.000

In the evaluations performed with RoD values, very close results were obtained with speed data. Evaluations using both speed data and RoD data have shown that the vehicles use similar speeds at similar distances during passing from low SCUs. It is noteworthy that the similarities for speeds or RoD values are considerably reduced with the effect of discomfort in passages from high SCUs.

Another assessment was carried out by investigating the similarities between SCUs for RoD values at each measurement point. Since the SU values of the vehicles are different for each SCU, this evaluation was not carried out using the speed data. In both traffic regimes, the ANOVA test was performed between the RoD values and Tamhane's T2 test was conducted from Post-Hoc tests to compare the results. The statistical significance values found in the study are shown in Table 6. It can be seen from the results that there is a similarity between all RoD values in the FF regime at -60 m and -40 m speeds. In other words, the presence of SCUs seems to be much more effective than the SCU type in reducing vehicle speeds up to -40 m in the FF regime. On the other hand, in B1 and H1 type SCUs, it is understood that the traffic speeds are similar to each other at all measurement points. It was seen that there are similarities at points +40 m and +60 m for B1 and H1, at -20 m for B2 and H2, and at +40 m and +60 m for H1 and H2. In the FF regime, it is understood that RoD values are similar in examined SCUs except for B2. When this assessment was made for the OSF regime, it was impossible to achieve apparent results as traffic was a forced characteristic. It is noted that there is no difference between B1 and H1 in terms of RoD at other measurement points except -60 m. RoD values are similar between B1 and H2 at points -40 m, -20m, +40 m and +60 m, and between H1 and H2 at points -60 m, -40m and +60.

Table 5. Statistical significance values of RoD between measurement points in OSF regime for each SCU.

B1

	-40m	-20m	0m	+20m	+40m	+60m
-60m	0.396	0.000	0.000	0.000	0.003	0.878
-40m		0.019	0.000	0.001	0.548	0.985
-20m			0.129	0.987	0.727	0.001
0m				0.526	0.001	0.000
+20m					0.247	0.000
+40m						0.133

B2

	-40m	-20m	0m	+20m	+40m	+60m
-60m	0.000	0.000	0.000	0.000	0.000	0.000
-40m		0.000	0.000	0.000	0.000	0.022
-20m			0.000	1.000	0.000	0.000
0m				0.000	0.000	0.000
+20m					0.000	0.000
+40m						0.000

H1

	-40m	-20m	0m	+20m	+40m	+60m
-60m	0.000	0.000	0.000	0.000	0.000	0.000
-40m		0.000	0.000	0.000	0.000	1.000
-20m			0.000	0.158	0.488	0.000
0m				0.714	0.000	0.000
+20m					0.000	0.000
+40m						0.000

H2

	-40m	-20m	0m	+20m	+40m	+60m
-60m	0.000	0.000	0.000	0.000	0.000	0.000
-40m		0.000	0.000	0.000	0.000	0.009
-20m			0.000	0.046	0.000	0.000
0m				0.000	0.000	0.000
+20m					0.000	0.000
+40m						0.000

Table 6. Statistical significance of RoD values between speed measurement points for each SCU

Comparison		F Val.	Sig.	Post Hoc Analysis Significance Values (Tamhane's T2)					
				B1 to B2	B1 to H1	B1 to H2	B2 to H1	B2 to H2	H1 to H2
FF regime	on -60m	0.398	0.754	1.000	0.997	0.880	0.999	0.822	0.974
	on -40m	2.479	0.062	0.959	0.924	0.779	0.125	0.059	0.999
	on -20m	27.768	0.000	0.000	0.996	0.001	0.000	0.280	0.000
	on 0 m	122.559	0.000	0.000	1.000	0.000	0.000	0.000	0.000
	on +20m	33.978	0.000	0.000	0.986	0.001	0.000	0.036	0.000
	on +40m	17.513	0.000	0.000	1.000	0.427	0.000	0.011	0.104
	on +60m	20.480	0.000	0.003	0.314	0.989	0.000	0.000	0.639
OSF regime	on -60m	16.948	0.000	0.977	0.008	0.000	0.000	0.000	0.168
	on -40m	73.507	0.000	0.000	0.283	0.774	0.000	0.000	0.881
	on -20m	133.791	0.000	0.000	0.390	0.476	0.000	0.000	0.000
	on 0 m	130.190	0.000	0.000	0.077	0.000	0.000	0.000	0.000
	on +20m	63.535	0.000	0.000	0.839	0.039	0.000	0.000	0.000
	on +40m	91.848	0.000	0.000	0.630	0.998	0.000	0.000	0.046
	on +60m	97.650	0.000	0.000	0.312	0.134	0.000	0.000	0.996

5. Conclusions

Although many devices have been developed for traffic calming by the authorities responsible for the operation of the roads, it is known that one of the most efficient methods is an undulation in the vertical direction of the road. That is why it is understood that the SCUs will continue to be used to reduce speed in urban road networks as they are economical. In developing countries, it is known that SCUs are used mainly by researchers without determining their in-situ suitability. The study examined the Bs frequently used in urban roads in developing countries and the Hs recommended by internationally recognized standards to help some of the departments responsible for traffic management. For this purpose, the performance of two B and H units of 5 and 10 cm high were evaluated comparatively in reducing the speed of the passenger cars. The following findings were obtained in the light of these evaluations.

- From the evaluations, it was understood that the most successful SCU type for speed reduction from the assessments was B2, and H2 was the second one. In addition to being quite advantageous in terms of discomfort, H2 seems to be quite successful in slowing down vehicles in both FF and OSF regimes.
- It appears that B1 and H1 are very close to each other in reducing vehicle speeds, and B1 is slightly better than H1.
- In the FF regime, it was seen that the vehicle speeds are higher at all measurement points than the OSF. From this situation, it is understood that SCU's ability to reduce the speed of vehicles depends on the flow regime in which the traffic takes place.
- At each measured point, the range of change at speeds is much broader in the FF regime than in the OSF regime, which means that vehicles travel at similar speeds in the OSF regime.
- When the height difference is considered, the evaluation shows that the efficiency increases as the height increases in the FF regime of Bs, while the efficiency increases as the height increases in the OSF regime of Hs.
- In the FF regime, it is seen that the speeds are close to each other at -60 m and -40 m points in all the SCUs, meaning that the vehicles tend to decrease their speed after -40 m. However, it is noteworthy that in the OSF regime, vehicle speeds tend to decrease from -60 m due to the forced traffic flow.
- In the acceleration phase, after the vehicles pass through from SCUs, the speeds of +40 m and +60 m in the FF regime have reached the speeds of -40 m and -60 m.
- In the FF regime, there was no similarity between the speeds measured at the SU point and the speeds measured at the other points in all the SCUs. But in this regime, it is noted that there is a similarity between the speeds measured at -60 m and the speeds measured at -40 m in all SCUs.
- It is noteworthy that there are considerable reductions in similarities for speeds or RoD values between measurement points (with the effect of discomfort) during passing from high SCUs.
- Based on the statistical evaluation among the SCUs, it is seen that there is a similarity between all the RoD values at the speed points of -60 m and -40 m in the FF regime. In other words, the presence of SCUs seems to be much more effective than the SCU type in reducing vehicle speeds up to -40 m in the FF regime.
- The statistical evaluation among the SCUs shows that the RoD values are similar in SCUs except for the B2 in the FF flow regime, but this similarity decreases in the OSF regime.
- It has been understood that H2 is the most suitable SCU type to be preferred for traffic calming in urban roads.

In the next stage of the study, it is thought that similar evaluations should be repeated, especially with other types of vehicles used in public transport. This and similar studies will facilitate the decision making of the authorities that regulate urban traffic.

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Authors' Contributions

Researcher UK prepared the study.

Competing Interests

The author declare that they have no competing interests.

References

[1]. Chadda, H.S., Cross, S.E., "Speed (Road) Bumps: Issues and Opinions", Journal of Transportation Engineering, 1985, 111 (4): 410-418.
[2]. Parkhill, M., Sooklall, R., Bahar, G., "Updated guidelines for the design and application of speed humps", ITE 2007 Annual Meeting and Exhibit. Pittsburgh, USA: Institute of Transportation Engineers, (2007).
[3]. Cottrell, W.D., Kim, N., Martin, P.T., Perrin, H.J., "Effectiveness of traffic management in Salt Lake City, Utah", J Safety Res, 2006, 37 (1): 27-41.
[4]. OECD, "Speed Management. European Conference of Ministers of Transport",OECD, Paris, France, (2006).
[5]. Ashton, S.J., "Vehicle design and pedestrian injuries", Pedestrian accidents, Wiley, London, (1982).
[6]. Mak, K.K., "A further note on undulation as a speed control device", Transportation Research Record, 1986, 1069: 13-20.
[7]. Vis, A.A., Dijkstra, A., Slop, M., "Safety effects of 30 km/h zones in the Netherlands", Accident Analysis & Prevention, 1992, 24 (1): 75-86.
[8]. Antić, B., Pešić, D., Vujanić, M., Lipovac, K., "The influence of speed bumps heights to the decrease of the vehicle speed – Belgrade experience", Safety Science, 2013, 57: 303-312.
[9]. Pau, M., Angius, S., "Do speed bumps really decrease traffic speed? An Italian experience", Accident Analysis and Prevention, 2001, 33 (2001): 585-597.
[10]. Ewing, R., "Impacts of traffic calming", Transportation Quarterly, 2001, 55 (1): 33-46.
[11]. Evans, D., Traffic Calming: The First Five Years and The Oxfordshire Experience, Proceedings of the Institution of Civil Engineers - Municipal Engineer, 1994, 103 (1): 9-15.
[12]. Kırbaş, U., İskender, E., "Effects of Speed Control Undulations on Public Transport Vehicles" Journal of Balıkesir University Institute of Science and Technology, 2022, 24 (1): 197-211.
[13]. Kiran, K.R., Kumar, M., Abhinay, B., "Critical Analysis of Speed Hump and Speed Bump and Geometric Design of Curved Speed Hump", Transportation Research Procedia, 2020, 48 (2020): 1211–1226.
[14]. Yeo, J., Lee, J., Cho, J., Kim, D.K., Jang, K., "Effects of Speed Humps on Vehicle Speed and Pedestrian Crashes in South Korea", J Safety Res, 2020, 75 (2020): 78-86.
[15]. Shahdah, U.E., Azam, A., "Safety and Mobility Effects of Installing Speed Humps within Unconventional Median U-turn Intersections", Ain Shams Engineering Journal, 2021, 12 (2): 1451-1462.
[16]. Obregón-Biosca, S.A., "Speed Humps and Speed Tables: Externalities on Vehicle Speed, Pollutant Emissions and Fuel Consumption", Results in Engineering, 2020, 5 (2020), 100089.
[17]. Liang, L., Chen, S., Li, P., "The Evaluation of Vehicle Interior Impact Noise Inducing by Speed Bumps Based on Multi-Features Combination and Support Vector Machine", Applied Acoustics, 2020, 163 (2020): 107212.
[18]. Chen, Q., Ding, D., Wang, X., Liu, A.X., Zhao, J., "An Efficient Urban Localization Method Based on Speed Humps", Sustainable Computing: Informatics and Systems, 2019, 24 (2019): 100341.

[19]. Darwiche, M., Mokhiamar, O., “SVR Approach for Predicting Vehicle Velocity for Comfortable Ride While Crossing Speed Humps”, Alexandria Engineering Journal, 2022, 61 (8): 6119-6128.
[20]. Kırbaş, U., Karaşahin, M., “Comparison of Speed Control Bumps and Humps According to Whole-Body Vibration Exposure”, Journal of Transportation Engineering, Part A: Systems, 2018, 144 (9): 04018054.
[21]. Gedik, A., Bilgin, E., Lav, A.H., Artan, R., “An Investigation into the Effect of Parabolic Speed Hump Profiles on Ride Comfort and Driving Safety Under Variable Vehicle Speeds: A Campus Experience”, Sustainable Cities and Society, 2019, 45 (2019): 413-421.
[22]. Watts, G., “Road humps for the control of vehicle speeds”, Transport and Road Research Laboratory, Crowthorne, Berkshire (1973).
[23]. Agerholm, N., Knudsen, D., Variyeswaran, K., “Speed-calming measures and their effect on driving speed – Test of a new technique measuring speeds based on GNSS data”, Transportation Research Part F: Traffic Psychology and Behaviour, 2017, 46 (2017): 263-270.
[24]. HCM. “Highway capacity manual”, Transportation Reseach Board, Washington, DC, (2000).
[25]. Weber, P.A., Braaksma, J.P., “Towards a North American geometric design standard for speed humps”, Institute of Transportation Engineers ITE Journal, 2000, 70 (1): 30-34
[26]. Ess, J., Antov, D., “Unified methodology for estimating efficiency of traffic calming measures – example of Estonia”, The Baltic Journal of Road and Bridge Engineering, 2016, 11 (4): 259-265.
[27]. Pau, M., “Speed Bumps May Induce Improper Drivers’ Behavior: Case Study in Italy”, Journal of Transportation Engineering, 2002, 128 (5): 472-478.