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ANALYSIS AND MODELLING OF DRIVER DECELERATION BEHAVIOR NEAR PHYSICAL TRAFFIC CALMING MEASURES

Summary. Speed humps are widely used as an effective traffic calming measure to reduce vehicle speeds and enhance road safety. This study evaluates driver deceleration behavior when approaching commonly applied physical traffic calming measures, such as mini-roundabouts, small roundabouts, speed humps, raised pedestrian crossings and intersections, and speed cushions. Utilizing empirical speed data collected from over 120 vehicle passages per site and GPS-based monitoring, this study examines how different traffic calming designs affect drivers' deceleration patterns, braking intensities, and speed reductions. The results indicate significant variations in deceleration strategies depending on the design of the traffic calming measures and the approach speed. A two-phase braking pattern—initial mild deceleration (d_1), followed by sharp braking (d_2) near the obstacle—is commonly observed, with up to a fivefold difference between these phases for speed humps. The study further develops regression models to describe average deceleration (Dec_{avg}) as a function of distance to the obstacle, with piecewise regressions achieving R^2 values as high as 0.99. The study also provides insights into optimizing speed hump placement and design to improve traffic safety and driver comfort and to offer predictive tools for traffic behavior modeling.

1. LITERATURE REVIEW

Traffic calming measures (TCM) are physical modifications made to a road to reduce vehicle speeds and improve safety, particularly in residential or high pedestrian activity areas. These interventions are essential for creating safer environments for non-motorized road users, such as pedestrians and cyclists, and for mitigating the frequency and severity of crashes [1]. The most common devices employed include speed humps, raised pedestrian crossings, chicanes, curb extensions, and road narrowings, each of which is intended to reduce vehicle speeds in areas with high pedestrian activity. These interventions play a critical role in managing the interaction between motorized and non-motorized traffic, ensuring a balance between efficiency and safety in urban road networks [2, 3]. The primary mechanism by which physical traffic calming devices work is by introducing either vertical or horizontal deflections in the road alignment, compelling drivers to reduce their speed. The effectiveness of these devices is influenced by several factors, including their design parameters and the perception of the road users [4, 5]. Understanding how drivers decelerate when approaching these devices is vital for optimizing their design and placement and predicting their impact on traffic flow and safety.

Numerous studies have documented the positive effects of traffic calming on speed reduction and crash mitigation. Lee and Abdel-Aty [6] observed that properly designed speed humps can reduce

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vehicular speeds by up to 40%. Similarly, Chen et al. [7] reported significant reductions in approach speed at pedestrian crossings raised to the level of the sidewalk. Driver response, however, varies depending on the device geometry, placement, and driver awareness. Mullan and King [8] showed that abrupt and poorly marked traffic calming measures might lead to excessive braking or sudden steering maneuvers, creating new hazards. Furthermore, the driver's familiarity with the road environment significantly influences their deceleration profile. Finnis [9] emphasized that drivers tend to exhibit more cautious braking behavior when they are familiar with the road and aware that there are traffic calming measures ahead. In contrast, unfamiliarity with a road or unexpected traffic calming features may lead to a more abrupt deceleration. Furthermore, Karlaftis and Yannis [10, 11] highlighted the crucial role that the geometric characteristics of the measures (e.g., length, height, ramp slope) play in determining driver responses. Drivers tend to begin braking earlier and more abruptly when approaching taller or steeper devices. The researchers pointed out that the geometric design of the measure directly influences driver deceleration profiles. In particular, abrupt changes in road elevation prompt earlier and more intense deceleration.

Behavioral modeling plays a crucial role in understanding and predicting how drivers react near traffic calming devices. Car-following and psycho-physical models have been widely adopted to simulate longitudinal control behavior [12]. However, these models often require calibration to local driving conditions and may not account for sudden deceleration due to physical devices. Microsimulation platforms such as VISSIM and AIMSUN have also been combined with empirical data to reproduce traffic behavior near calming measures more realistically [13]. Calibration with trajectory and deceleration data allows simulation tools to assess complex interactions in great detail. Other studies have utilized car-following models or discrete choice frameworks to assess how environmental and driver-specific factors, such as familiarity with the road or risk perception, influence braking decisions [14].

In addition to the geometry characteristics of traffic calming devices, the road environment, including its geometry, lighting, and visual cues, has a marked effect on driver behavior. Research conducted by Ewing and Dumbaugh [1] revealed that TCMs implemented in zones with high pedestrian traffic tend to have stronger effects on driver behavior. In poor weather or low-visibility conditions, drivers tend to decelerate earlier and more cautiously. Chen and Lin [15] reported increased braking distances when there was rain and fog, particularly when road markings were degraded or absent. Furthermore, nighttime conditions are associated with more cautious responses, depending on lighting and road familiarity [16].

Bokare and Maurya [17] analyzed the acceleration/deceleration behavior of various types of vehicles in Wardha Town, India. Using a limited number of test vehicles and a GPS data logger, they evaluated and modelled the intensity of drivers' maneuvers along a 1.5-km stretch of a two-lane national road to simulate drivers' behavior at signalized intersections and congested traffic conditions. They developed various regression models of deceleration based on speeds in relation to different types of vehicles. The observed deceleration rates for two wheelers, three wheelers, cars, and trucks ranged from 0.88 to 1.71 m/s^2. Similar extended research was conducted by Ramireddy et al. [18], who analyzed deceleration on approach sections to 24 signalized intersections. Besides developed models, they pointed out that more aggressive driver behavior resulted in higher deceleration values regardless of the type of vehicle. Empirical studies have assessed the impact of various design parameters on speed reduction. Other research was carried out in Italy by Zampino [19], who analyzed the deceleration behavior of drivers influenced by the presence of a lead vehicle in the area near off-ramps during diverging maneuvers. The values of decelerations remained rather low and did not exceed 0.6 m/s^2.

Few studies have analyzed the behavior of drivers in the vicinity of physical traffic calming measures. Therefore, the aim of this article is to fill this gap in the literature and to estimate the effects of commonly used traffic calming measures on the intensity of braking maneuvers.

2. RESEARCH AREA AND METHODOLOGY

2.1. Selection of study segments

This study examined the most widely applied types of physical traffic calming measures, including mini-roundabouts (MR), small roundabouts (SR), speed humps (SH), raised pedestrian crossings (RPC), raised intersections (RI), and speed cushions (SC). Fig. 1 presents examples of these physical traffic calming measures in areas where speed measurements were conducted.

The speed measurements were taken on roads with a posted speed limit of 50 km/h, located in both low- and high-density residential areas comprising single- and multi-family developments. An exception was made for the study sites involving mini-roundabouts, which were situated within traffic-calmed zones with a reduced speed limit of 30 km/h. In urban traffic conditions, particularly on local and access roads with good pavement quality, the primary factors influencing drivers' speed selection were traffic volume, cross-sectional road design, and the presence of traffic calming measures. The influence of physical obstacles installed within the roadway (which introduced vertical deflections) on vehicle speed and driver behavior dynamics was assessed under controlled conditions by minimizing external factors. Free-flow traffic conditions, characterized by low traffic volumes or isolated vehicle movements, were established to ensure that driver responses were not affected by surrounding traffic. Straight road sections with a longitudinal slope not exceeding ±2% were considered. The research was conducted under free-flow traffic conditions on roads with lane widths ranging from 2.75–3.25 m. The selected length of the straight section preceding the location of the installed traffic calming measure ensured that drivers could reach the characteristic speed for an inter-connector section where no traffic disruptions affecting speed choice are present [20, 21].

2.2. Speed measurements

Speed measurements were taken under free-flow traffic conditions, defined by the time or distance intervals between consecutive vehicles. According to HCM2000, free-flow speed is the average speed of vehicles measured when traffic density is low, which allows drivers to travel at their preferred speed without being restricted by traffic control measures. The minimum time gap necessary to maintain free-flow traffic is five seconds. Research in this area has further established that the time gap ranges from 5–12 seconds [24-26]. Due to the absence of universally accepted standards, it was assumed that a vehicle was operating under free-flow conditions if the time gap between the preceding vehicle and the following vehicle was no less than seven seconds, which corresponds to a minimum distance of 100 m between vehicles.

The objective of the speed measurements was to develop individual speed profiles for vehicle passages through areas featuring traffic calming measures. The measurements, conducted over several years, involved the use of a variety of commonly encountered passenger vehicles, including the Opel Corsa, Renault Laguna, Seat Ibiza, Audi A3, Volkswagen Golf, and Mazda 6. Given the level of traffic composition during the measurements, only passenger cars were considered, as they represent the predominant vehicle category. A GPS data logger was installed in the test vehicle to record the speed data. This device captured data on the vehicle's position and instantaneous speed, which were subsequently utilized to analyze speed profiles along mid-block sections and at traffic calming installations. The data recording frequency was set at one second, with the instantaneous speed of vehicles recorded with an accuracy of 0.1 m/s. Drivers were trained to operate their vehicles using their natural driving technique while adhering to the posted speed limits. The sample size for each trial (number of vehicle passages) was determined individually for each traffic calming measure. The minimum sample size was established based on preliminary measurements of speed distribution, assuming a 90% confidence level that the allowable error in estimating the mean value would not exceed μ = 5% [27]. As a result, the minimum sample size was determined to range between 80 and 100 passages. For the analyses, only samples exceeding the calculated minimum values were considered, and the number of individual vehicle passages within the influence area of each analyzed traffic calming measure was no less than 120. An example of a collective graph illustrating a group of speed profiles recorded on a section with a speed hump is presented in Fig. 2.

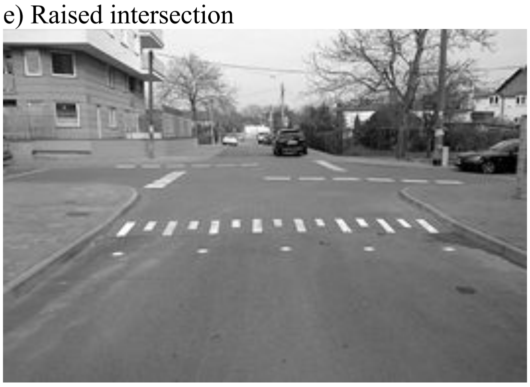
a) Mini-roundabout

b) Small roundabout

c) Speed hump

d) Raised pedestrian crossing

e) Raised intersection



f) Speed table

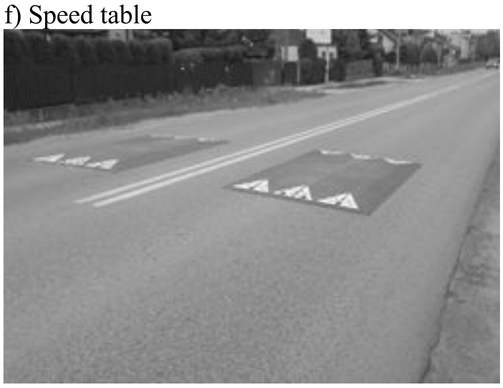
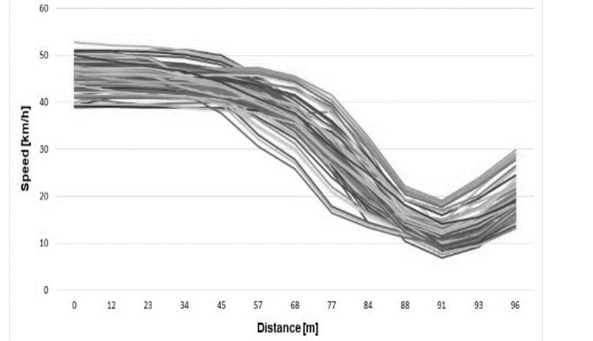


Fig. 1. Examples of analyzed traffic calming measures

a)



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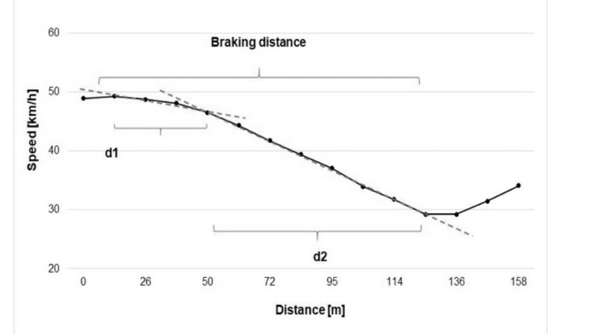

Fig. 2. (a) Individual and (b) averaged speed profiles in the area of a small roundabout, with indicated zones of braking intensity

Based on the aggregated data, an averaged speed profile was constructed (Fig. 2b), which served as the basis for determining the braking distance. Using the averaged speed profile, the intensity of braking maneuvers, expressed by the deceleration value "d," was determined. Due to the observed variation in braking intensity along the braking path, two distinct levels of deceleration dynamics were identified, denoted as "d_1" and "d_2." Additionally, for the entire braking section, the average deceleration value, "davg," was determined. Considering that speed was recorded at one-second intervals, the deceleration at the i-th second was calculated as the difference between two consecutive speed values (V_0, V_1, ..., V_n) according to the following formula:

$$d_{t1} = \frac{v_1 - v_0}{t_1 - t_0} \quad (1)$$

where, d_{t1} is the deceleration at time t_1, and $v1$ and $v0$ are the average speeds at time t_1 and t_0, respectively.

The beginning of the braking distance was the point at which the deceleration value, calculated according to Equation (1), was greater than or equal to 0.1 m/s² for three consecutive seconds [28]. The end of the braking distance was defined at the location of the given traffic calming measure (e.g., speed table, speed cushion, raised pedestrian crossing) at the beginning of the device (for raised intersections) or at the point where the vehicle entered the roundabout.

3. ANALYSIS AND DISCUSSION OF THE RESULTS

3.1. Evaluation of speed changes

The impacts of selected traffic calming measures on speed changes were evaluated based on fundamental speed parameters, the data for which are presented in Table 1 and Fig. 3.

Table 1

Descriptive statistics of vehicle speeds in areas with physical traffic calming measures

Mini-roundabout							
Measurement point	V_{avg}	σ	V_{15}	V_{85}	V_{85}-V_{15}	V_{min}/V_{max}	P_{dop}
	[km/h]	[km/h]	[km/h]	[km/h]	[km/h]	[km/h]	[%]
Mid-block segment	31.2	2.1	29.1	33.1	4.0	26.1/36.72	37
Roundabout	15,6	4,8	11.0	19.3	8.3	7.3/24.2	0
Small roundabout							
	[km/h]	[km/h]	[km/h]	[km/h]	[km/h]	[km/h]	[%]
Mid-block segment	45.9	6.2	39.5	52.2	12.7	36.7/64.4	23.7
Roundabout	25.5	4.1	21.4	29.9	8.6	17.0/35.1	0
Speed hump							
	[km/h]	[km/h]	[km/h]	[km/h]	[km/h]	[km/h]	[%]
Mid-block segment	45.3	3.2	41.9	48.4	6.5	37.9/52.9	9,0
Speed hump	11.7	3.0	8.9	14.5	5.6	6.0/21.9	0
Raised intersection							
Mid-block segment	49.0	2.1	46.8	51.3	4.5	43.8/54.9	31.8
Raised intersection	13.5	2.2	11.4	15.5	4.1	4.6/14.1	0
Raised pedestrian crossing							
	[km/h]	[km/h]	[km/h]	[km/h]	[km/h]	[km/h]	[%]
Mid-block segment	44.9	3.3	41.4	48.2	6.8	38.0/55.2	8.5
Raised pedestrian	12.2	3.1	8.7	15.6	6.9	6.3/19.8	0
Speed cushion							
	[km/h]	[km/h]	[km/h]	[km/h]	[km/h]	[km/h]	[%]
Mid-block segment	48.9	4.2	44.7	53.7	9.0	39.2/61.0	39.5
Speed cushion	29.2	3.7	25.2	33.2	8.0	20.7/38.6	0

The data show that the average travel speeds on the mid-block sections of streets located within speed-restricted zones (Vlim = 30 km/h) with mini-roundabouts are significantly lower compared to the speeds on other street sections located outside such zones. This highlights the effectiveness of traffic calming zones in regulating drivers' travel speeds.

A marked reduction in vehicle speed upon entry to the mini-roundabout carriageway is particularly notable. Although the average travel speed on the mid-block segment was relatively low (31.2 km/h), drivers further decreased their speed to 15.6 km/h when entering the roundabout, corresponding to a 56% reduction. This significant deceleration is primarily attributable to the roundabout's geometric design—specifically, the small diameter of the central island combined with the narrow circulating carriageway, which effectively constrains higher travel speeds. Additionally, the physical construction of the central island plays a critical role. When the island is designed as non-traversable and is bordered by a raised curb, it compels drivers to navigate a clearly defined curved trajectory around it. In contrast, control studies conducted at an intersection where the central island was delineated solely by pavement markings revealed that drivers frequently crossed the island directly, resulting in elevated speeds and reduced braking intensity.

For the study sections involving roads with a speed limit of Vlim = 50 km/h, the average travel speeds were notably higher, consistently ranging from 44.9–49.0 km/h (Fig. 3a). Although the variation in mean values was relatively small, an analysis of variance (ANOVA) indicated that the differences were statistically significant at the $p < 0.000$ level. The significance of these differences is primarily attributable to the substantially higher speeds recorded in the presence of raised intersections and speed cushions (Fig. 3c).

Moreover, the average speed data recorded at the location of TCMs (Fig. 3b) reveal considerably greater differences between individual traffic calming measures. The gap between the lowest (PL) and highest (PW) average speed was 17.5 km/h (149.6%). Moreover, in this case, the variance analysis confirmed the statistical significance of the differences ($p < 0.000$).

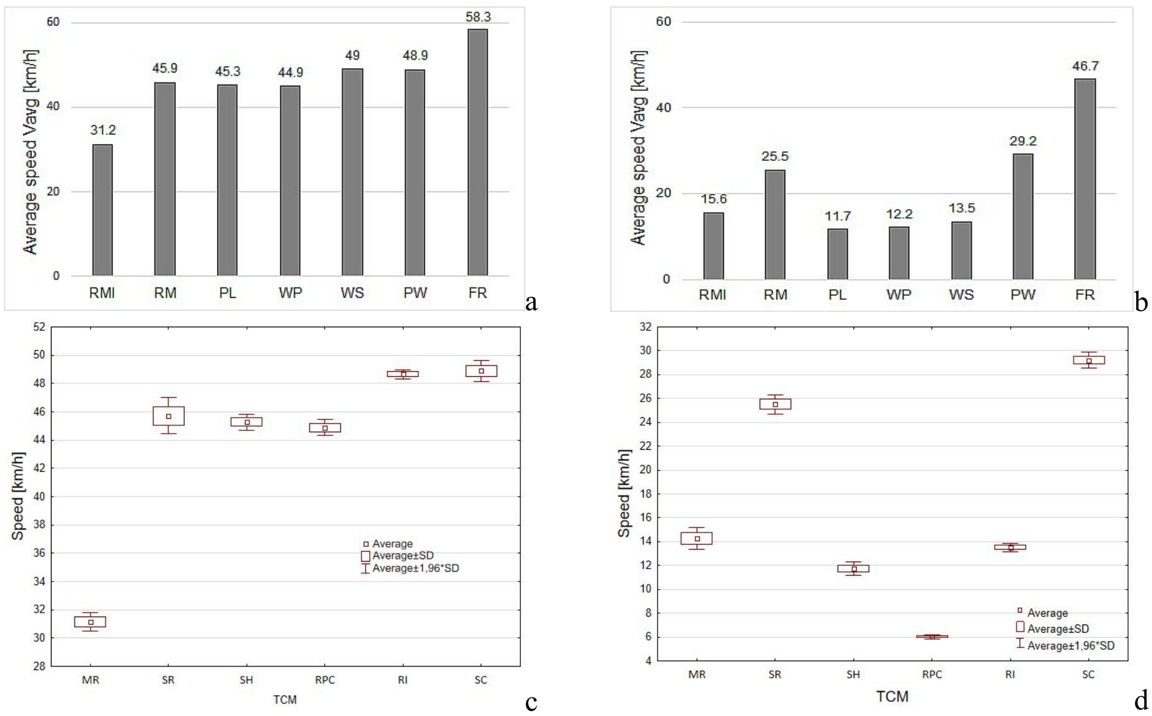

Fig. 3. Average vehicle speeds (a) for mid-block segments before the initiation of braking, (b) at the TCM location after the completion of braking, along with box-and-whisker plots for average speeds (c) on mid-block segments and (d) at the TCM location

One of the main objectives of implementing traffic calming measures is to improve speed homogeneity. When isolated calming measures were applied, a wide dispersion between the minimum and maximum recorded speeds was observed both on mid-block segments and at the location of the calming feature itself. When using the difference between the 85th percentile speed (V85) and the 15th percentile speed (V15) as a measure of speed homogeneity (Table 1) [29], the most favorable results were recorded in the areas featuring mini-roundabouts—that is, in zone-based traffic calming areas (Vdop=30 km/h). On the mid-block segments in these zones, the difference between V85 and V15 was the smallest (4.0 km/h). A slightly higher value (4.5 km/h) was observed on approach sections leading to raised intersections.

An analysis of the vehicle speeds directly at the location of the calming measures revealed that lower crossing speeds over PL, WS, and WP features also promote a more homogeneous traffic flow (V85–V15 = 4.1–6.9 km/h). In contrast, for other solutions (RMI, MR, PW), traffic exhibited greater speed variability (V85–V15 = 8.0–8.3 km/h).

3.2. Assessment of braking maneuver dynamics

Driver behavior, expressed by the dynamics of the deceleration maneuver, depends on the type of obstacle and the distance at which the driver is located from the obstacle. Based on the developed speed profiles as a function of distance, the intensity of the maneuvers and the braking distance were determined. The calculated parameters characterizing the braking maneuver are presented in Table 2, and the speed profiles reflecting the average and maximum braking maneuvers are shown in Fig. 4.

Table 2

Parameters characterizing braking maneuvers in the zone of influence of physical traffic calming measures

Mini-roundabout							
Deceleration during braking [m/s^2]				Breaking distance [m]			
d_1	d_2	$d_{śr}$	d_{max}	Average	σ	Min.	Max.
-0.24	-0.74	-0.60	-2.4	61.0	11.4	17.0	75.0
Small roundabout							
Deceleration during braking [m/s^2]				Breaking distance [m]			
d_1	d_2	$d_{śr}$	d_{max}	Average	σ	Min.	Max.
-0.20	-0.94	-0.57	-3.15	108.7	24.3	35.0	133.0
Speed hump							
Deceleration during braking [m/s^2]				Breaking distance [m]			
d_1	d_2	$d_{śr}$	d_{max}	Average	σ	Min.	Max.
-0.4	-2.0	-1.2	-4.3	88.3	17.2	34.0	102.0
Raised intersection							
Deceleration during braking [m/s^2]				Breaking distance [m]			
d_1	d_2	$d_{śr}$	d_{max}	Average	σ	Min.	Max.
-0.57	-2.04	-1.24	-3.25	85.5	12.2	54.0	117.0
Raised pedestrian crossing							
Deceleration during braking [m/s^2]				Breaking distance [m]			
d_1	d_2	$d_{śr}$	d_{max}	Average	σ	Min.	Max.
-0.22	-1.64	-1.14	-3.6	70.1	11.6	37.0	89.0
Speed cushion							
Deceleration during braking [m/s^2]				Breaking distance [m]			
d_1	d_2	$d_{śr}$	d_{max}	Average	σ	Min.	Max.
-0.16	-0.69	-0.56	-1.99	83.9	15.8	46.0	118.0

The behavior of a driver approaching an obstacle is highly influenced by the distance at which the driver is located from the obstacle. As drivers approach an obstacle and become aware of the need to reduce their speed, they tend to delay the onset of braking as much as possible in order to minimize the loss of speed during their approach on the mid-block segment. This behavior results in a gradual initiation of braking at the beginning of the maneuver (d_1). Only as the vehicle approaches the obstacle and the need to adjust the speed for safe passage becomes evident do drivers increase the intensity of braking (d_2). The initial deceleration values range from d_1 = 0.16 to 0.57 m/s², with the smallest value observed in the area of speed humps. As drivers approach the obstacle, the braking intensity increases, particularly as the vehicle approaches raised crossings and raised pedestrian crossings. Here, the final deceleration (d_2) is up to 7.4 times greater than the initial deceleration (d_1). Large differences are also observed when approaching speed humps, as a fivefold difference between deceleration intensity d_1 and d_2 is observed. In both of these cases, the highest values of instantaneous deceleration were recorded at d_2 = -3.6 m/s² for the raised pedestrian crossing and d_2 = -4.3 m/s² for the speed hump. Considering the average deceleration (Dec_{avg}) throughout the entire braking distance as the vehicle approaches the obstacle, the smoothest braking occurred when approaching speed humps (Dec_{avg} = -0.56 m/s²). Likewise, at roundabout locations, the average deceleration was at a comparable level, with davg = -0.57 m/s² and Dec_{avg} = -0.60 m/s² for small and mini-roundabouts, respectively. The average deceleration was approximately twice as high for other solutions.

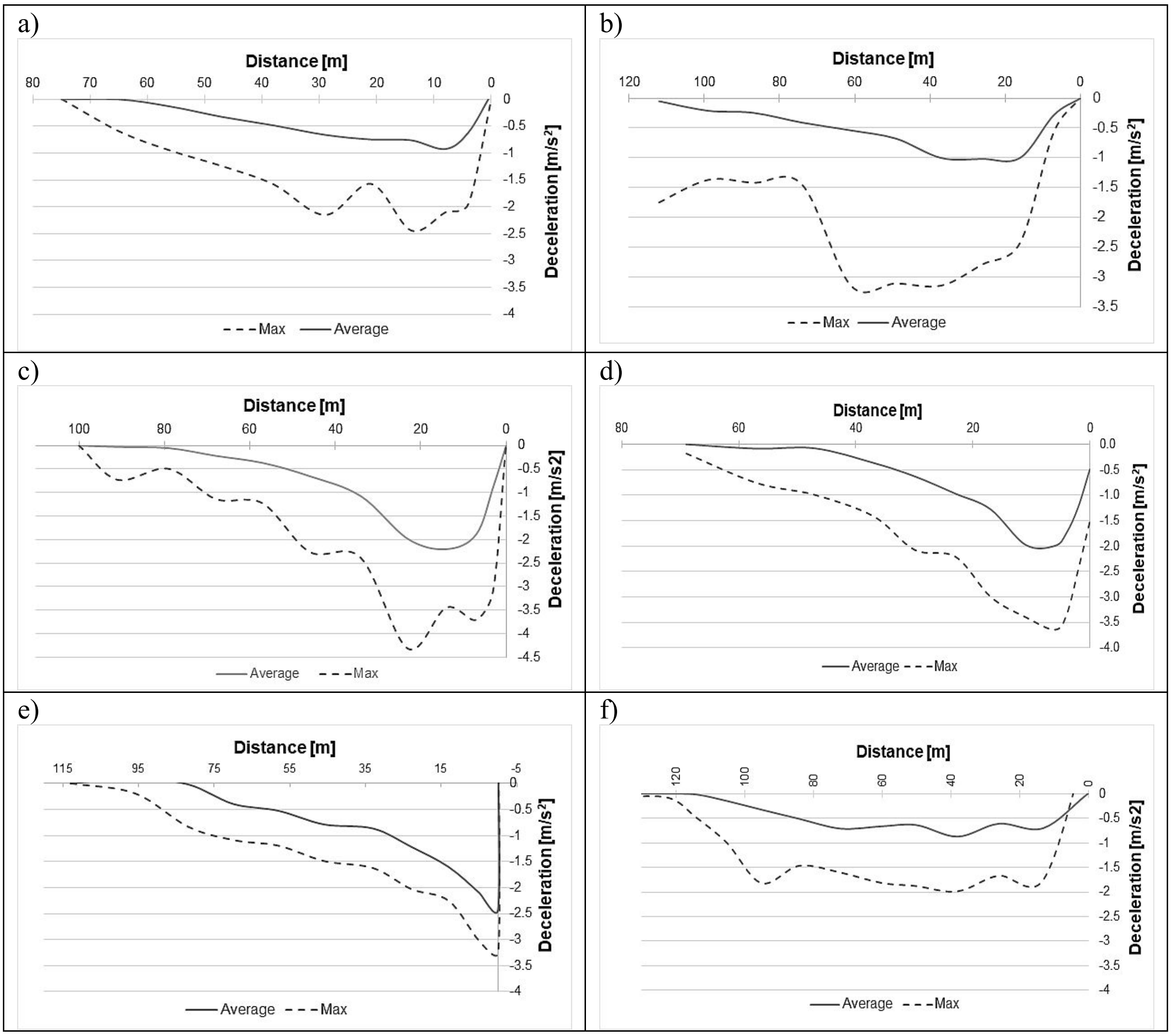

Fig. 4. Average and maximum deceleration profiles in the influence zone: (a) mini-roundabout, (b) small roundabout, (c) speed hump, (d) raised pedestrian crossing, (e) raised intersection, and (f) speed cushion

The data suggest that braking dynamics (i.e., the average deceleration) increase as the travel speed decreases in the vicinity of the traffic calming measure. Notably, the presence of speed humps (PLs, WPs, and WSs) required drivers to reduce their speed significantly more than the presence of other traffic calming measures (RMIs, MRs, and PWs). However, the low travel speed through mini-roundabouts did not result in greater braking intensity, as drivers were already traveling at relatively low speeds on the mid-block segment. This low speed on the mid-block segment also resulted in the shortest braking distance, with an average value of 61.0 m for mini-roundabouts. Drivers began adjusting their speed the earliest when approaching a small roundabout, with speed adjustments commencing at a distance of over 108 m. This contradicts the findings of Bennet and Dunn [30], who stated that most vehicles slow down over the same distance irrespective of the initial speed. In the case of circular intersections, the greatest variation in braking distance was observed between the shortest and longest braking distances. This significant variation can be explained by the type and geometry of the roundabout (3-arm, 4-arm, and the angle of the approach road to the circulatory roadway), as well as the direction of travel. This was particularly evident in 3-arm roundabouts, where traveling straight ahead under good visibility and with a moderate approach speed did not require drivers to reduce their speed significantly, so they could adjust it to the conditions shortly before entering the intersection.

Deceleration values recorded near some of the installations (raised intersections, raised pedestrian crossings, small roundabouts, and speed humps) were higher than those found in a study conducted by Bokre [17] and mostly higher than those reported by Najm et al. [31]. He exerted normal and hard braking to cause deceleration rates of 1.47, 2.74, and 3.83 m/s^2 in a normal driving situation. Other studies showed that the deceleration values of cars approaching intersections with traffic lights depend on the speed limit [32, 33]. The deceleration rates they found are comparable to those in the vicinity of the traffic calming measures observed here. They found that drivers decelerated between 2.59 and 2.98 m/s^2 on streets with low (< 64.3 km/h) speed limits, while they decelerated between 3.07 and 3.62 m/s^2 on streets with high (> 64.3 km/h) speed limits.

3.3. Modeling average deceleration changes as a function of distance

The scatter plots of average deceleration in the influence zone of the analyzed traffic calming measures (Fig. 3.3) were used as the basis for developing the functional relationships for changes in average deceleration along the braking distance. The presented data indicate the nonlinear nature of deceleration changes along the braking distance. Linearizable linear regression models and nonlinear estimation were used to describe these changes: quadratic function, third- and fourth-degree polynomial regression, and piecewise regression. The final selection of the model best describing the data variability was based on the maximization of the coefficient of determination (R^2). The significance of the models was verified using the Fisher-Snedecor statistic at the significance level of $\alpha = 0.05$. The significance of individual model parameters and the constant term was verified using the t-test.

Considering the potential significant impact of the location of mini-roundabouts (situated in areas with different speed limits) on the final form of the function, two scenarios were analyzed during the development of the statistical model:

a) A model that includes data from all analyzed research polygons, referred to as "All."

b) A model excluding data on mini-roundabouts (referred to as "Without MR"), which includes the analyzed traffic calming measures located in areas with a speed limit of Vdop = 50 km/h.

The development of functional relationships for changes in average deceleration, "Dec_{avg}," as a function of distance resulted in the creation of eight regression models. The results regarding the obtained coefficient of determination R^2 for the analyzed models and scenarios are presented in Table 3. Models based on aggregated data from all analyzed traffic calming measures exhibit R^2 values from 0.67–0.76. Excluding the research polygons involving mini-roundabouts from the analyzed data group practically did not affect the quality of the resulting models, regardless of the type of regression function used.

Considering the obtained values of the coefficient of determination, R^2, for the developed models, we analyzed the possibility of developing functions that better reflect the variability of deceleration as a function of distance. Therefore, the dynamics of braking were analyzed separately for each of the analyzed traffic calming measures. The results (presented in Table 4) show that these more detailed models describe the changes much better, with R^2 values ranging from 0.56–0.99.

Table 3
Regression functions with fit metrics for describing changes in average deceleration as a function of distance

All	R^2	Without MR	R^2
Type of function		Type of function	
Quadratic	0.67	Quadratic	0.64
Cubic polynomial	-	Cubic polynomial	-
Quartic polynomial	0.76*	Quartic polynomial	0.77
Piecewise regression	0.76	Piecewise regression	0.74

Table 4
Regression functions with fit metrics for describing changes in average deceleration as a function of distance for individual traffic calming measures

MR	R^2	SM	R^2	SH	R^2
Type of function		Type of function		Type of function	
Quadratic	0.58*	Quadratic	0.56*	Quadratic	-
Cubic polynomial	0.80*	Cubic polynomial	0.88*	Cubic polynomial	0.77
Quartic polynomial	0.90*	Quartic polynomial	0.95*	Quartic polynomial	0.95*
Piecewise regression	0.99	Piecewise regression	0.98	Piecewise regression	0.96
RPI	R^2	RI	R^2	SC	R^2
Type of function		Type of function		Type of function	
Quadratic	0.94	Quadratic	0.97	Quadratic	0.91*
Cubic polynomial	0.95*	Cubic polynomial	0.99	Cubic polynomial	0.92*
Quartic polynomial	0.98*	Quartic polynomial	0.99*	Quartic polynomial	-
Piecewise regression	0.99	Piecewise regression	0.99	Piecewise regression	0.96

* The model contains statistically insignificant parameters (independent variables, intercept).
- A statistically significant model could not be achieved.

Some of the obtained functions have a coefficient of determination, R^2, close to 1, indicating very good fit. As the final form for describing the variability of the distribution of average deceleration as a function of distance, piecewise regression models were chosen ($R^2 = 0.96–0.99$), taking into account the breakpoint near the achieved maximum value of the deceleration distribution. The functions describing deceleration changes on the approach sections of the individual research polygons are as follows:

- mini-roundabout (MR):

$$Dec_{avg} = \begin{cases} -0.15S & \text{for S } \leq 6 \\ -1.06 + 0{,}016S & \text{for S } > 6 \end{cases} \quad (2)$$

- small roundabout (SR):

$$Dec_{avg} = \begin{cases} -0.059S., & \text{for S } \leq 18 \\ -1.31 + 0{,}011S & \text{for S } > 18 \end{cases} \quad (3)$$

- speed hump (SH):

$$Dec_{avg} = \begin{cases} -0.27S & \text{for S} \leq 8.2 \\ -2.35 + 0{,}029S & \text{for S} > 8.2 \end{cases} \quad (4)$$

- raised pedestrian crossing (RPI):

$$Dec_{avg} = \begin{cases} -0.51 - 0{,}057S & \text{for S } \leq 30 \\ -4.00 + 0.058S & \text{for S } > 30 \end{cases} \quad (5)$$

- raised intersection (RI):

$$Dec_{avg} = \begin{cases} -2.37 + 0.052S & \text{for } S \leq 25 \\ -1.50 + 0.171S & \text{for } S > 25 \end{cases} \quad (6)$$

- speed cushion (SC):

$$Dec_{avg} = \begin{cases} -0.69S & \text{for } S \leq 49 \\ -1.46 + 0.015S & \text{for } S > 49 \end{cases} \quad (7)$$

where Dec_{avg} is an average deceleration [m/s^2], and S is the braking distance [m].

Figs. 5 and 6 show example plots of the developed piecewise function and the agreement of the calculation results according to Equation (2) with the empirical data. The mini-roundabout data is used in these examples.

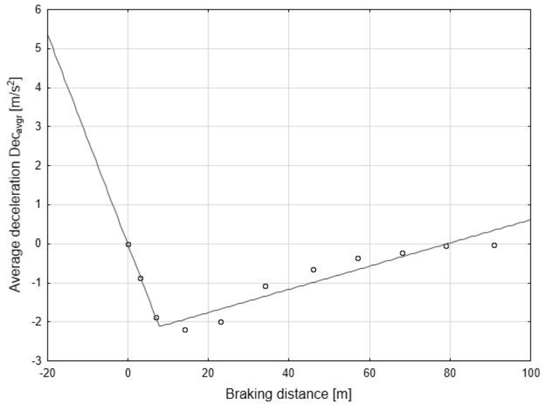

Fig. 5. Piecewise function of deceleration distribution as a function of distance before the mini-roundabout

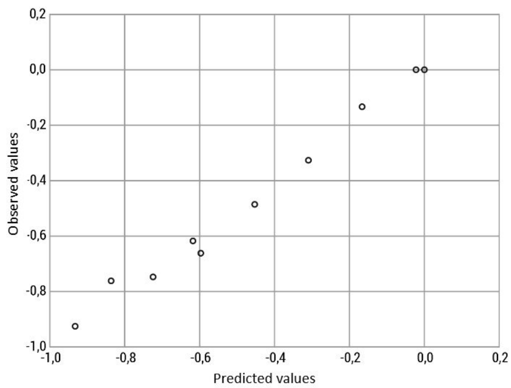

Fig. 6. Agreement of predicted data with empirical data for the mini-roundabout

Based on the regression relationships and fit coefficients, when developing functional dependencies, data should be limited to individual groups of distinct physical traffic calming measures. This approach allowed for the development of piecewise functions with a much better fit (R^2 = 0.96–0.99) compared to functions based on aggregated data (R^2 = 0.64–0.76).

4. CONCLUSIONS

The conducted studies and analyses aimed at recognizing and assessing the behavior of drivers in areas where various physical traffic calming measures were implemented to regulate speed. The analysis focused on the most commonly used solutions, including mini-roundabouts, small roundabouts, speed humps, raised pedestrian crossings, raised intersections, and speed cushions.

The results indicate the high effectiveness of the applied measures. All analyzed physical traffic calming solutions significantly reduced vehicle speeds, with the most substantial effectiveness in speed reduction demonstrated by raised pedestrian crossings and speed humps (average reductions of 73% and 74%, respectively). Mini-roundabouts, despite relatively low approach speeds, also impose a considerable speed reduction (50%), confirming their effectiveness in areas with a speed limit of 30 km/h. Areas with this speed limit, such as those with mini-roundabouts, are characterized by greater speed uniformity and smaller variation in V15–V85 values, indicating the effective regulation of driver behavior while highlighting the impact of local conditions.

In light of the practical aspects of the results, when designing traffic calming measures, it is important to consider not only speed reduction but also braking dynamics to improve safety and driving comfort. Maximizing the effectiveness of individual solutions also requires the range of their impact to be considered. Using functional relationships describing braking dynamics can assist in this process.

Drivers approaching obstacles tend to delay braking, resulting in varying intensities of braking depending on their distance from the obstacle. In addition to the two distinct zones of differing intensity in the braking area, a momentary and very abrupt braking maneuver occurs in the area closest to the obstacle, reflected by significantly high instantaneous deceleration values. The highest values of instantaneous deceleration (up to -4.3 m/s²) were recorded at speed cushions, while raised pedestrian crossings showed deceleration values of -3.6 m/s². The substantial speed reduction when approaching obstacles placed across the entire width of the road (e.g., speed cushions, raised pedestrian crossings, and raised intersections) leads to a much higher intensity of braking. The intensity of average deceleration in these zones is twice as high as in other cases. Conversely, the presence of island speed humps and roundabouts results in a gentler and smoother deceleration maneuver.

The relationship between deceleration and braking distance is nonlinear, with piecewise functions being the most accurate way to describe it. The fit models for each traffic calming measure, individually, achieved very high coefficients of determination (R^2 = 0.96–0.99), indicating high-quality predictions of driver behavior.

Considering the practical implications of the findings, it is evident that, when designing traffic calming measures, it is essential to incorporate not only speed reduction but also braking dynamics to enhance safety and comfort. Moreover, the range of these solutions' impact must also be taken into account to maximize their effectiveness. Functional relationships describing braking dynamics can be an essential tool in this process.

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