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A Series of Vertical Deflections, a Promising Traffic Calming Measure: Analysis and Recommendations for Spacing

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Featured Application: This work provides a tool for determining the adequate spacing between vertical traffic calming measures as a function of the target speed in the segment.

Abstract: Traffic calming measures (TCM) are placed in urban areas to improve road safety, and among them, vertical TCMs are widely employed. Many researches are focused on the influence of the geometry of each measure on speed reduction, but it is demonstrated that drivers forget its effect and speed up after it. Therefore, placing consecutive TCMs can help to maintain a safe area. However, scarce literature can be found about the adequate spacing between them. Hence, the aim of this paper is to analyze the adequate distance between TCMs. Various streets with variable distances and different vertical TCMs were evaluated in Poland and Spain, including raised crosswalks, raised intersections, speed humps and speed cushions. The intermediate point between two TCMs was selected as the place where the maximum speed is achieved. Results showed that there was a good correlation between the speeds at intermediate points and the distance between TCMs, with a determination coefficient around 0.80. For an 85th percentile of the speed under 50 km/h, a maximum distance of 200 m between TCMs is recommended, and for a value of 40 km/h, 75 m.

Keywords: traffic calming measure; spacing; speed prediction; speed humps; raised crosswalk; raised intersection; speed cushion; road safety; urban area

1. Introduction

In spite of the important decrease recorded in the total number of fatalities in road traffic during the last decades in developed countries, road safety remains a major problem in all countries, and is even considered a public health concern [1–4]. For example, in the European Union (EU-28) the number of fatalities in highway crashes decreased by 54.7% between 2000 and 2016 (from 57,006 to 25,767) [5]. Nevertheless, the target of the EU-28 for 2010 was not achieved. A maximum number of 28,500 fatalities was aimed to achieve and a total of 31,802 deaths was registered. The objective for 2020 is to achieve a maximum value of 15,750 fatalities. Similarly, in the United States, 35,000 people die in road accidents per year [6]. However, in the EU in the period 2007–2016, in urban areas the fatality reduction (37.7%) has not been so important as in non-urban areas (41.6%), increasing its percentage of the total [7,8] and this trend was also observed in the period 2004–2013 [9].

Highway crashes are said to be a consequence of multiple factors, which are usually grouped in relation to the infrastructure (highway condition), the vehicle and the driver (human condition) [2,10–15]. However, in urban areas, but also in rural areas, one of the main problems in terms of road safety remains the excessive speed and speeding drivers [16–21]. Moreover, with higher speeds, there is higher probability of pedestrian death, and it is not proportional, as shown in Table 1 [22,23]. Consequently, aiming to improve the road safety in urban areas, traffic calming measures (TCM) are being introduced. They can be defined as the combination of mainly physical measures that reduce the negative effect of motor vehicles use, alter driver behavior and improve conditions for non-motorized streets users [24]. Moreover, speed reduction helps protect other vulnerable users like cyclists [25–27]. Additionally, it must be highlighted that the special protection of vulnerable road users (motorcyclist, cyclist, mopeds and pedestrians) became a policy orientation of the European Commission [28].

Table 1. Chance of pedestrian death if hit by a motor vehicle.

Speed of Collision (km/h)	80	65	50	32
Chance of Pedestrian Death (%)	100	80	40	5

Traffic calming schemes incorporate a wide range of measures intended to reduce speed and enhance the environment [20], although the effectiveness of them varies depending on the measures employed. Traffic calming measures are accurately defined and described in Ewing [29] and can be grouped into four categories:

- Vertical deflection: speed hump, speed bump, speed cushion, rumble strip, raised crosswalk, raised intersection, road lump and table.
- Horizontal deflection: curb-extension, chicane, gateway, raised median island, traffic circle
- Physical obstruction: semi and diagonal diverter; right-in and right-out island, raised median through intersections, street closure
- Signs and pavement markings.

In previous studies speed was mostly investigated with regard to its reduction as a consequence of various measures' influence both in field experiments [30–32] or driver simulation studies focusing on chosen infrastructural impacts on drivers' behavior [33] and on the reduction of the number of accidents and injuries. The effectiveness of TCMs depends also on their type. Many researches proved that the most effective measures in speed and fatalities reduction are vertical deflections [34,35], becoming the most employed ones [36,37]. Jateikienė et al. [38] showed 60% decrease of fatal and injury accidents and 82% decrease of killed people on roads with vertical deflection in Lithuania. In terms of the percentage accident reduction, engineering schemes incorporating vertical deflections offer the largest benefits, becoming at least twice safer than sites where cameras were used to control speeds [39–41]. Additionally, Daniels et al. [42] indicated that the installation of speed humps is one of the TCMs with a benefit-cost ratio over 1 in all the scenarios, underlining its effectiveness.

Apart from the type of the TCM, the shape characteristics of speed bumps and humps are important and influence drivers' behavior and driving comfort differently [43–46]. Lav et al. [47] conducted an experiment to determine the optimal design of speed bumps for reducing the velocity of vehicles without endangering road safety.

With regard to the environment, the most important point seems to be fuel consumption car emissions as a result of driving style. Driving pattern in urban areas is characterized by a lower average speed and higher number of stops, implying both fuel consumption and pollutant emissions many times higher per vehicle·km. Wang et al. [48] pointed that emission estimates should incorporate the acceleration instead of mean speed of vehicle and the effect of acceleration is higher at lower speed than at higher speeds.

Due to costs, it is very common that traffic calming measures operate separately instead of adopting systematic solutions. Hence, their effectiveness, especially the most commonly used TCMs, speed humps and bumps, is limited to short distances [49] and is believed to cause disturbance in traffic flow and smoothness. When applied inappropriately, i.e., the distance between devices are too short or too long, they can push drivers to an aggressive style instead of keeping them within assumed limits. Frequent deceleration and acceleration maneuvers may also lead to additional dangerous behavior due to lack of speed uniformity [31,50]. Although a number of studies have been dedicated to the assessment of the various effects of individual traffic calming measures [21,30,51], there is still a lack of information on the relative impact and effectiveness of vertical shifts implemented in sequence. The first traffic calming measures in the US were often spaced at intervals over 150 m (500 feet) and it was found that at the midpoint no speed reduction was achieved. However, if they were very near, they even became a problem. In Bellevue (US) speed humps spaced 45.75 m (150 feet) were removed to provide a distance of 91.5 m (300 feet) [29]. Ewing [52] showed how speed in the middle points could be related to the distance between TCMs (Figure 1) from data from different countries. Research in the US indicated a speed increase of approximately 0.8 to 1.6 km/h (0.5 to 1.0 mile/h) for every 30.5 m (100 feet) of spacing between humps for distances below 305 m [29].

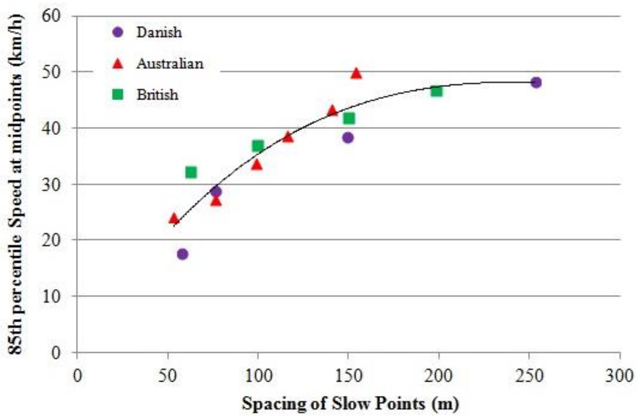


Figure 1. Speed at intermediate points (km/h) as a function of the distance (m) between slow points with data from various countries.

Nevertheless, commented researches were conducted in the 20th century in residential areas in the suburbs of the big cities in the USA. Since then, there has been a great spreading on the employment of TCM around the world. At present, in Europe TCMs are mainly placed in city centers, in downtowns, trying to make these areas more peaceful with the aim of providing friendly spaces for pedestrians, from both the point of view of road safety and the environment [21,35,38,53–55]. Moreover, nowadays, drivers are more used to this kind of speed control measures. Nonetheless, scarce literature can be found about the adequate distance between them. García et al. [54] studied the influence of the distance between TCMs on the capacity of cross-town road and conclude that a range between 50 and 400 m was critical. Kveladze and Agerholm [55] observed that variable spacing influenced the median speed in the intermediate points of the segments, but without providing any specific relationship. Yeo et al. [56] analyzed the influence of speed humps on the 85th percentile of the speed distribution and suggested that a spacing of 20 m to achieve a speed of 30 km/h, and a maximum of 70 m. Similarly, Vaitkus et al. [57] concluded that when two TCMs were spaced more than 200 m, drivers accelerate until 10 km/h over the speed limit of 50 km/h and recommended a spacing of 150–200 m, 100 m and 75 m for speed limits of 50, 40 and 30 km/h, respectively. Therefore, the aim of this paper is to analyze the speed in the intermediate points between vertical traffic calming measures and relate it with the distance between them to propose models for predicting the speed in those midpoints. For this purpose, measures were taken in stretches with successive vertical deflections in Poland and in Spain to observe drivers' behavior in different countries.

The manuscript is organized as follows: Section 2 presents the selected streets where speed data were collected. In Section 3, results are presented and discussed. Finally, Section 4 summarizes the obtained conclusions.

2. Methodology and Case Study

2.1. Site Description

Field measures were conducted to show the effectiveness of various traffic calming measures placed in a sequence for determining the ideal spacing with regard to the established maximum speed. Speeds were measured in the city of Bialystok in Poland, with a population around 292,000 inhabitants, and in the city of Basauri, (40,000 inhabitants), in Spain, which is included in the metropolitan area of Bilbao, with a total population of one million people. Selected stretches are located in urban areas and have a succession of different vertical traffic calming measures. Middle points (MP) were selected as control section because it is assumed that the maximum speed between calming measures is achieved in the middle point [29]. After passing a TCM, drivers accelerate, but if another TCM is near, they may start decelerating to accommodate their speed to the new obstacle. Analyzed vertical TCMs included raised intersections (RI), raised crosswalks (RCW), speed humps (SH) and speed cushions (SC). The width of all the streets is 3.50 m for all the lanes and the speed limit is 50 km/h in all the cases. Measured stretches in Bialystok were the following:

- Zachodnia Street. This street is the main street serving the housing estate with kindergartens and shops along it. The sequence of the controlled stretch has these traffic calming measures: raised intersection, raised intersection, speed cushion, raised crosswalk and raised intersections and the distances between the central point of the TCMs are 130 m, 127 m, 120 m and 190 m, respectively. Speed was measured in all the vertical TCMs (RI 1, RI 2, SC 3, RCW 4 and RI 5) and in the middle points (MP) between them (from MP 1–2 to MP 4–5) (Figure 2a).
- Wschodnia Street. This street is the main street in the single-family housing estate. The controlled stretch is composed of three successive speed humps, with long distance between them, 187 m and 293 m. The speeds were measured in the central speed hump (SH 2), in the intermediate points between speed humps (MP 1–2 and MP 2–3) and before SH 1, outside the calmed area (Outside), as a control point, more than 100 m away from the first speed cushion in order to see how drivers operate in non-calmed areas (Figure 2b).
- Pulaskiego Street. This street runs through the housing estate and has a collective function for nearby residents. The selected stretch is composed of three consecutive raised crosswalks, with short spaces between them of 114 m and 63 m. Speed measures were collected in the central raised crosswalk (RCW 2) and in the middle points between them (MP 1–2 and MP 2–3) (Figure 2c).
- Transportowa Street. This street runs on the outskirts of a housing estate and is an access road to the city's bypass. In a part of this street there are three speed cushions in a sequence, with 150 m and 110 m between them. Measures were taken in the second and third speed cushions (SC 2 and SC 3), in the intermediate points (MP 1–2 and MP 2–3) and a point outside the calmed area (Outside) (Figure 2d).

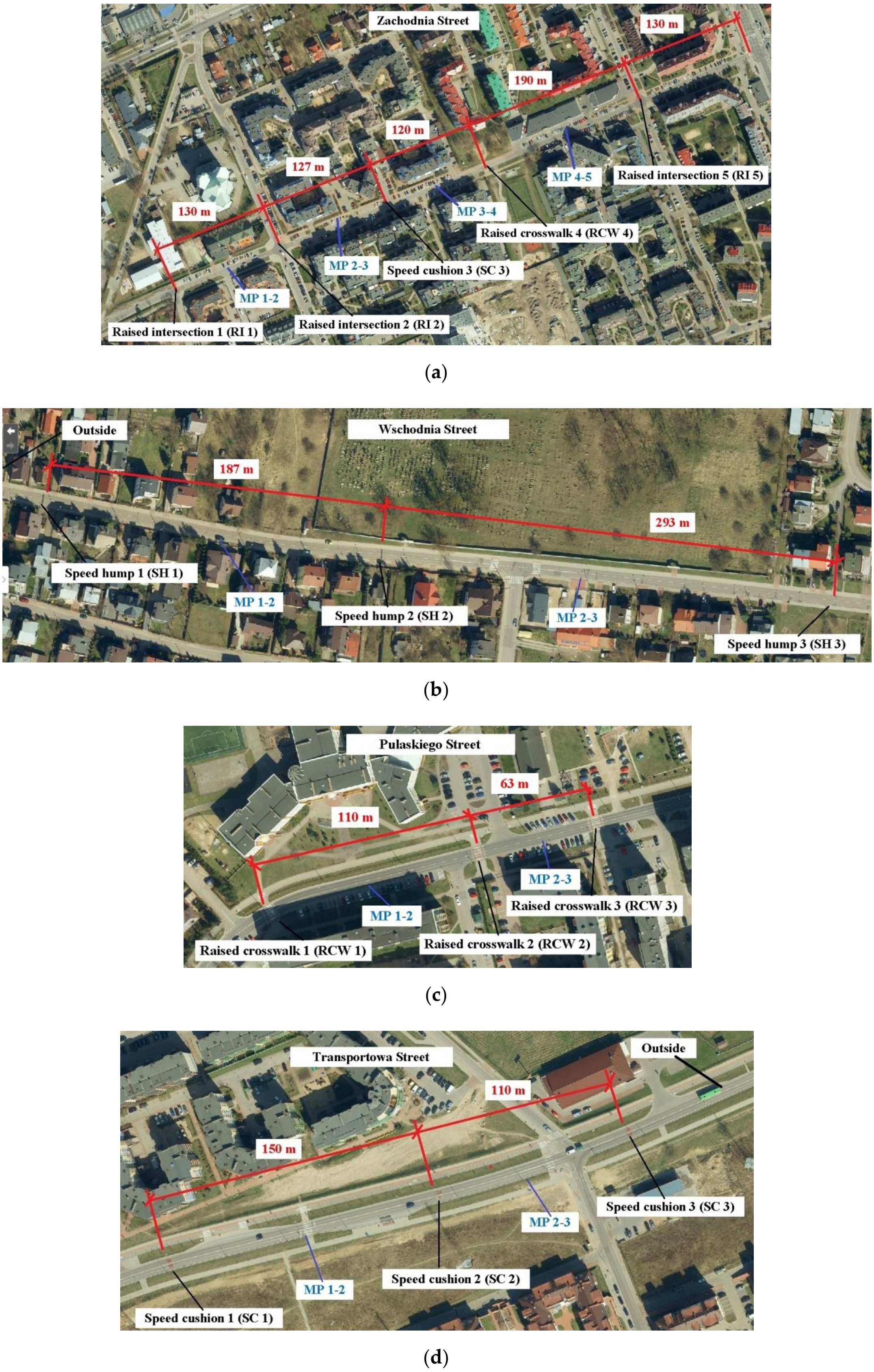
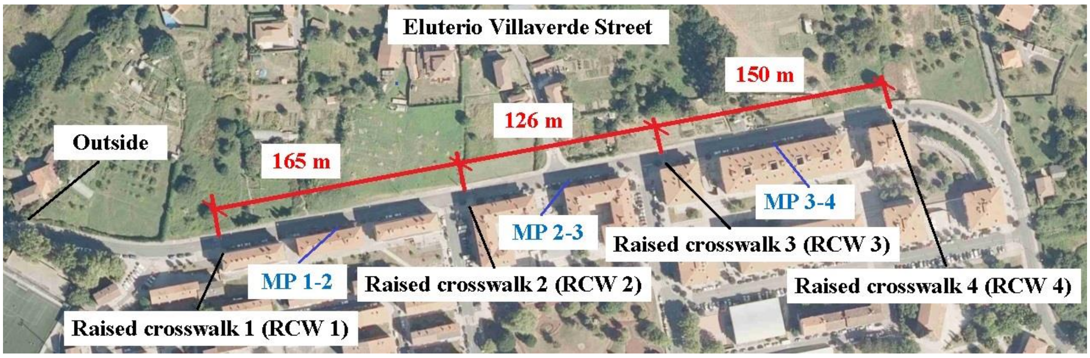


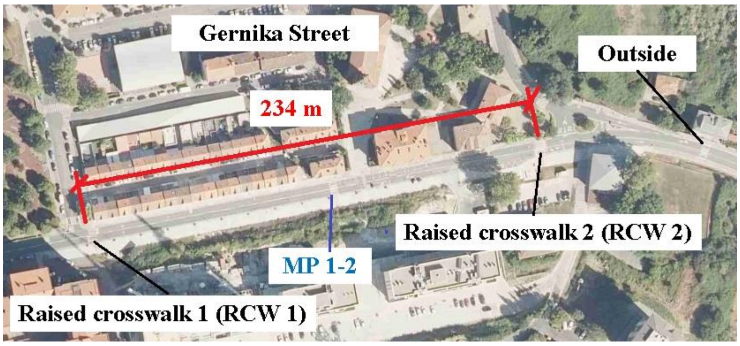
Figure 2. Schemes of traffic calming measures and measuring point in selected streets in Bialystok (Poland): (**a**) Zachodnia Street; (**b**) Wschodnia Street; (**c**) Pulaskiego Street; (**d**) Transportowa Street.

Measured stretches in Basauri were the following:

- Eluterio Villaverde Street. This street makes a bypass of the neighborhood of San Miguel to avoid crossing the center of it, where various traffic lights are placed. In order to calm the traffic in this area, four raised crosswalks were displayed, with varying spacing between them: 165 m, 126 m and 150 m between the axes of the crosswalks. Speed data were collected in the four TCMs (from RCW 1 to RCW 4), in the intermediate points (MP 1–2, MP 2–3 and MP 3–4) and before the sequence (Outside) (Figure 3a).
- Gernika Street. This street is the main road of the neighborhood of San Miguel and in one extreme has two raised crosswalks. They were installed to calm the traffic before the traffic lights in the center of the neighborhood. The second raised crosswalk (RCW 2) works as a frontier between the interurban and the urban area. Measures were conducted in the middle point (MP 1–2), in the crosswalk that serves as the warning for entering the urban area (RCW 2) and in a point outside the urban area (Outside), at 110 m from RCW 2 (Figure 3b).



(**a**)



(**b**)

Figure 3. Schemes of traffic calming measures and measuring point in selected streets in Basauri (Spain): (**a**) Eluterio Villaverde Street; (**b**) Gernika Street.

2.2. Speed Data for Analysis

Measures were taken in the selected urban streets with a speed radar and a speed gun during various days. According to the specifications, both devices have a maximum error of accuracy of 5%. Measures were taken during the day, with day-light conditions in all the segments. None of the data was collected at night. During the speed measurements, weather conditions were not extreme: heavy rain, high wind, snow. Sunny or cloudy days were selected, with light rain in some cases for short periods.

For each measuring point, the following variables were calculated: the maximum (V_{max}) and minimum speed (V_{min}), the average speed (V_m); and, the 85th percentile of the speed distribution

(V_{85}), i.e., the speed below which 85 percent of vehicles in the traffic stream travel or, in other words, the speed exceeded by 15% of the vehicles. As the important point is to know the success of placing vertical TCMs in sequence, both directions of the street were analyzed together, not distinguishing between directions.

2.3. Methodology for Model Development

With the aim to develop a model to predict the average speed (V_m) and the 85th percentile of the speed distribution (V_{85}) in the midpoints between vertical TCMs, various model types were proposed to correlate these speeds with the distance between TCMs as an independent variable (predicting variable). The significance of the model was verified by means of the Fischer-Snedecor test, with a p-value of the F statistic below 0.05 (95% of significance). Additionally, the individual significance of each coefficient and the intercept was tested by the Student's t-test if a p-value < 0.05 is obtained. Furthermore, if a linear regression model is adopted, some hypotheses that are assumed must be verified [58–64]: a linear relationship (checked by the high Pearson coefficient between variables, R), the independence of the observations (certified by the Durbin-Watson statistic near the range 1.5–2.5); the homoscedasticity (evaluated by the absence of any pattern in a plot of the standardized predicted values vs. standardized residuals), and errors are normally distributed (checked by a Shapiro-Wilk normality test).

3. Results and Discussion

Data were collected in 2017 and 2020. A total of 16,420 vehicles were controlled on the described stretches. Average Annual Daily Traffic in selected streets ranged from 1000 to 3500 vehicles/day, so they cannot be regarded as collapsed placed. Moreover, the influence of non free-flowing vehicles was not considered because the time interval shorter than 5 s was only recorded in less than 10–15% of the vehicles.

3.1. Results in Poland

3.1.1. Zachodnia Street

In Zachodnia Street, a similar effect can be observed in similar points (Figure 4). On one hand, although all the vertical TCMs were not the same, similar values were obtained for the average speed (between 30.3 and 33.8 km/h) and for V_{85} (between 33 and 38). Moreover, maximum speeds when crossing them were always below 50 km/h, the speed limit of the street.

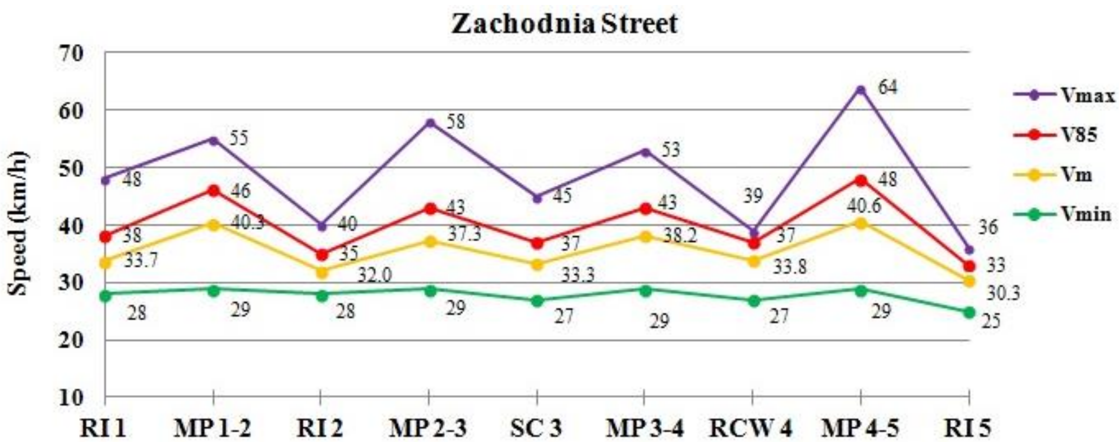


Figure 4. Speed values in the measurement points in Zachodnia Street, in Bialystok (Poland).

On the other hand, approximate values were also registered in the middle points between the TCMS: a range from 37.3 to 40.6 km/h for V_m and a range from 43 to 48 km/h for the V_{85}. As seen, the speed limit was also respected by more than 85% of the drivers and only very few exceeded the limit. The higher values in the middle points were measured in MP 4–5, where there is a longer distance between TCMs (195 m).

3.1.2. Wschodnia Street

Values collected in Wschodnia Street are shown in Figure 5.

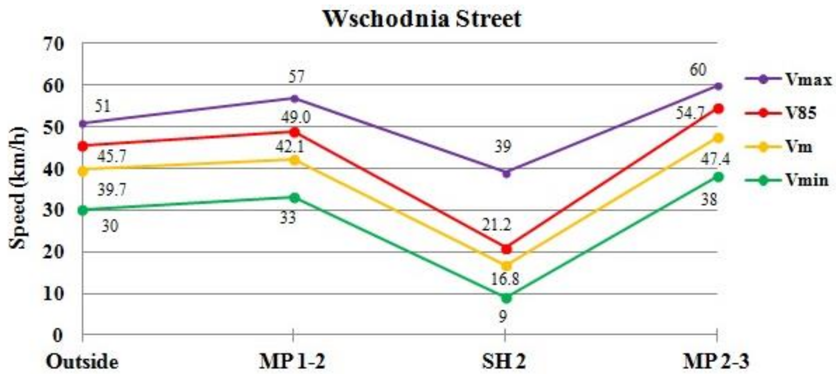


Figure 5. Speed values in the measurement points in Wschodnia Street, in Bialystok (Poland).

As observed, despite the reduced dimensions of a speed hump when compared to other vertical TCMs like raised crosswalks, the speed values on the Speed Hump 2 (SH 2) were low, even for the maximum speed on it. However, since the distance between SH 1 and SH 2, and between SH 2 and SH 3 are high (187 and 293 m, respectively), measured speed values on intermediate points were high. The average speed was over 40 km/h and the V_{85} was around 50 km/h, the speed limit of the street. Nevertheless, a point outside the calmed area (Outside), more than 100 m before the SH 1 was measured, to compare obtained results. As shown, better speed values were collected in this area, implying that long distances do not provide a speed reduction apart from the area around the TCM.

3.1.3. Pulaskiego Street

In Pulaskiego Street, a section with three consecutive raised crosswalks with short distances between them was evaluated. Measured speed values are exposed in Figure 6.

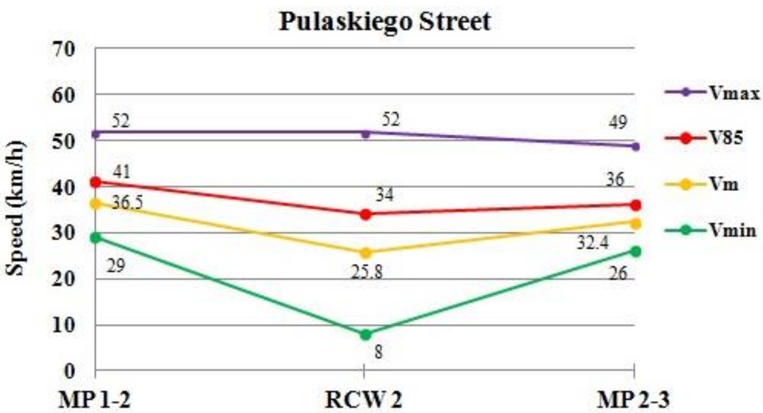


Figure 6. Speed values in the measurement points in Pulaskiego Street, in Bialystok (Poland).

When passing the raised crosswalk in the middle, RCW 2, low speeds were detected. In this case, as the distance to the next RCW is short, drivers did not speed up because they would have to decelerate in a short distance. Therefore, values collected in MP 2–3, when the distance between RCWs is short (63 m), are very similar to the ones of the RWC 2. On the contrary, since the distance from RCW 1 to RCW 2 is longer, 114 m, higher values were registered. As a global assessment, since similar data would have been collected in the other raised crosswalks (RCW 1 and RCW 3), it can be said that all the stretch was really calmed because even the maximum speed was around 50 km/h. This area was aimed to be specially protected due to the presence of a school near a populated neighborhood of Bialystok. Consequently, placing successive vertical TCMs at short distances really achieves a pacified area.

3.1.4. Transportowa Street

Three consecutive speed cushions are located in section in Transportowa Street. Recorded values can be observed in Figure 7.

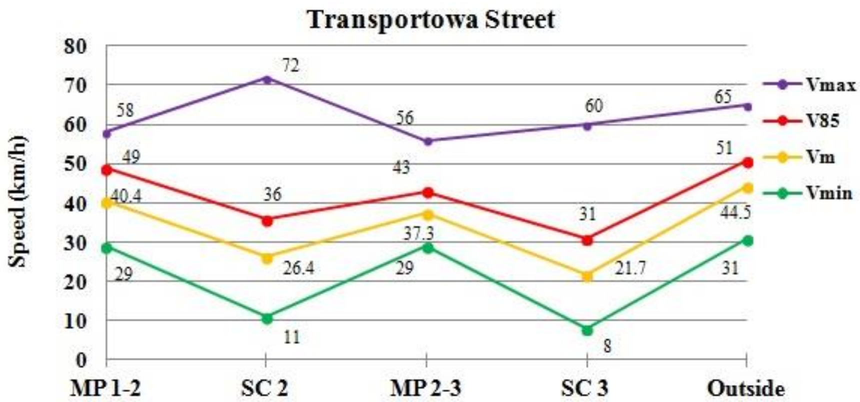


Figure 7. Speed values in the measurement points in Transportowa Street, in Bialystok (Poland).

As seen, the speed cushions (SC 2 and SC 3) caused a real reduction on drivers' speed, as the rest of vertical traffic calming measures. At the middle points (MP 1–2 and MP 2–3) the effect of the consecutive speed cushions can be observed: the average speed was below 40 km/h and the 85th percentile, V_{85}, was maintained below 50 km/h, the speed limit of the street. If these values at the intermediate points are compared with a point placed 100 m away from the last speed cushion (Outside), it can be regarded that after crossing the calmed stretch, drivers tended to speed up since they felt that they had left the controlled area and a higher speed was allowed, although the speed limit is maintained.

3.2. Results in Spain

3.2.1. Eluterio Villaverde Street

The calmed stretch in Eluterio Villaverde Street is composed of four consecutive raised crosswalks (RCW 1, RCW 2, RCW 3, RCW 4). Figures of measured speeds are exposed in Figure 8.

As observed, except from the last raised crosswalk (RWC 4), similar values were measured at the TCMs; an average speed around 28–29 km/h (in RWC 4, 34.6 km/h) and a V_{85} between 33 and 38 km/h (42 km/h in RWC 4). With regard to the middle points, variable values were recorded. The average speed ranges from 36.1 to 41.1 km/h and the 85th percentile from 43 to 50 km/h. This variation is caused by the different distance between TCMs. Lower values were always obtained in MP 2–3, where the spacing is lower.

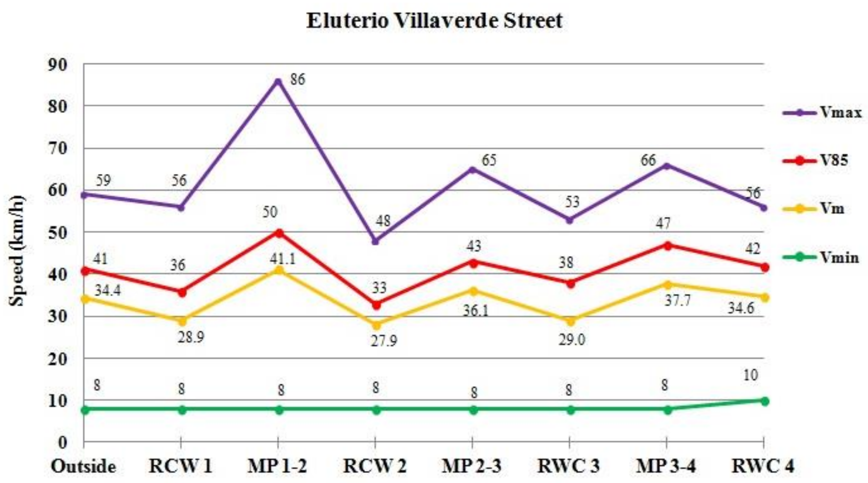


Figure 8. Speed values in the measurement points in Eluterio Villaverde Street, in Basauri (Spain).

3.2.2. Gernika Street

This stretch comprises two raised crosswalks before the area where traffic lights are placed in the center of the neighborhood. The distance between them is high, 234 m. Results are available in Figure 9.

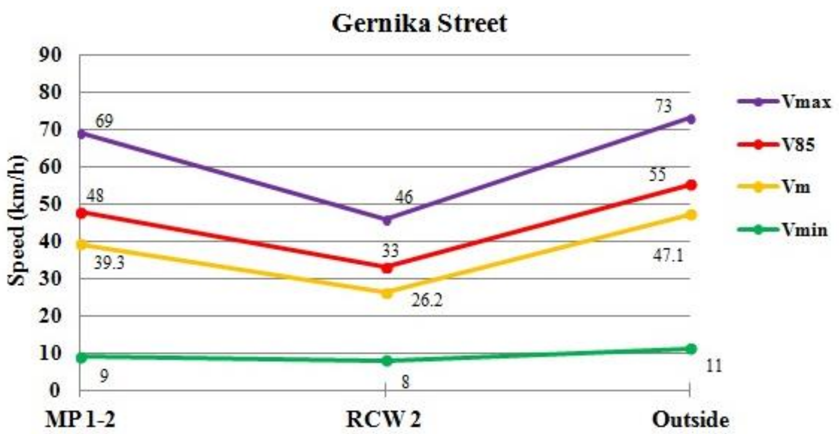


Figure 9. Speed values in the measurement points in Gernika Street, in Basauri (Spain).

The data at the RCW 2 were similar to the ones collected in the other TCMs in Spain. Despite the long distance between raised crosswalks, in the intermediate point, enough good values were obtained, with the average speed and the V_{85} below 50 km/h. If these figures are compared with those of the point outside the calmed area (Outside), which is an interurban area and higher speed is allowed (70 km/h), higher values were registered. It indicates that the inclusion of a traffic calming measure before entering an urban area, as a barrier, provides good results.

3.3. Model Development

Firstly, the speed reduction in the vertical TCMs was observed. Table 2 compares the values in the different places.

Although raised intersections provide safe crossings due to the speed reductions, it seems that, after the vertical deflection of the beginning, a higher value was recorded in the middle point of the TCM. However, they still provided a safer atmosphere for urban intersections. According to the results, it seems that raised crosswalks can be crossed at the highest speeds. The reduction effect of vertical deflections is said to be dependent mainly on its geometric design [45–47]. Their characteristics were not evaluated for this research, as it is outside its scope. The speed hump gave the lowest figures. Nevertheless, a unique place was evaluated so it is not regarded as representative. Finally, speed cushions caused an important speed reduction, although high maximum values can also be detected, 72 and 60 km/h.

Table 2. Summary of obtained speed values at the traffic calming measures.

Type of TCM	Street	Point	V_{max} (km/h)	V_{85} (km/h)	V_m (km/h)
Raised intersection	Zachodnia	RI 1	48	38	33.7
		RI 2	40	35	32
		RI 3	36	33	30.3
	Mean values		**41.3**	**35.3**	**32.0**
Raised crosswalk	Zachodnia	RCW 4	39	37	33.8
	Pulaskiego	RWC 2	52	34	25.8
	Eluterio Villaverde	RCW 1	56	36	28.9
		RCW 2	48	33	27.9
		RCW 3	53	38	29
		RCW 4	56	42	34.6
	Mean values		**50.7**	**36.7**	**30.0**
Speed hump	Wschodnia	SH 2	**39**	**21.2**	**16.8**
Speed cushions	Zachodnia	SC 3	45	37	33.3
	Transportowa	SC 2	72	36	26.4
		SC 3	60	31	21.7
	Mean values		**59.0**	**34.7**	**27.1**
Mean values of all TCMs			**49.5**	**34.7**	**28.8**

Nonetheless, the major interest of the manuscript is the relationship between the distance between different vertical traffic calming measures and the speed recorded in the intermediate points between them. A correlation was observed, and various functions were proposed to try to correlate the values. Table 3 exposes the analyzed models and the obtained determination coefficients (R^2).

Table 3. Summary of analyzed model types to correlate the distance and V_{85} and V_m and obtained R^2.

Analyzed Model Type	R^2 for V_{85} vs. Distance	R^2 for V_m vs. Distance
Linear	0.817	0.795
Logarithmic	0.885	0.797
Inverse	0.828	0.706
Quadratic	0.875	0.799
Cubic	0.899	0.856
Potential	0.899	0.813
Exponential	0.788	0.779

Almost all the models have a determination coefficient near 0.80, which implies a quite good correlation. Although they were not the best models for predicting the V_{85} and the V_m, linear models were selected as the proposed ones due to their simplicity and their facility to be interpreted. Hence, proposed model for predicting the V_{85} in an intermediate point between consecutive TCMs is shown in Equation (1):

$$V_{85} = 34.36 + 0.075 \cdot d \quad (1)$$

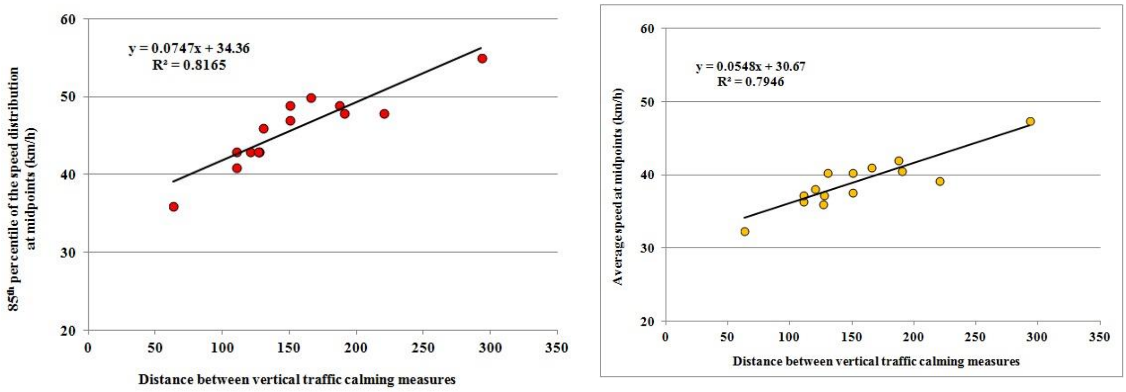
where V_{85} is the 85th percentile of the speed distribution in an intermediate point between consecutive vertical traffic calming measures and d is the distance between the axes of the TCMs.

Similarly, for predicting the average speed in an intermediate point, Equation (2) is proposed.

$$V_m = 30.67 + 0.055 \cdot d \tag{2}$$

where V_m is the average speed in an intermediate point between consecutive vertical traffic calming measures and d is described as in Equation (1).

Figure 10 shows the plot of both models. Table 4 presents the Analysis of Variance (ANOVA) of the model of Equation (1) and Table 5 the ANOVA of the model of Equation (2). As observed, both models are significant (p-value of the F-test below 0.05), and each of the coefficients of the variables and the intercept are statistically significant too (p-values < 0.05). Furthermore, the hypotheses assumed in a linear regression model were verified: high value of the Pearson coefficient (R); the Durbin-Watson statistic is near the range 1.5–2.5; there is not any pattern in the plot of standardized predicted values vs. Standardized residuals (Figure 11); and errors are normally distributed.



(**a**) (**b**)

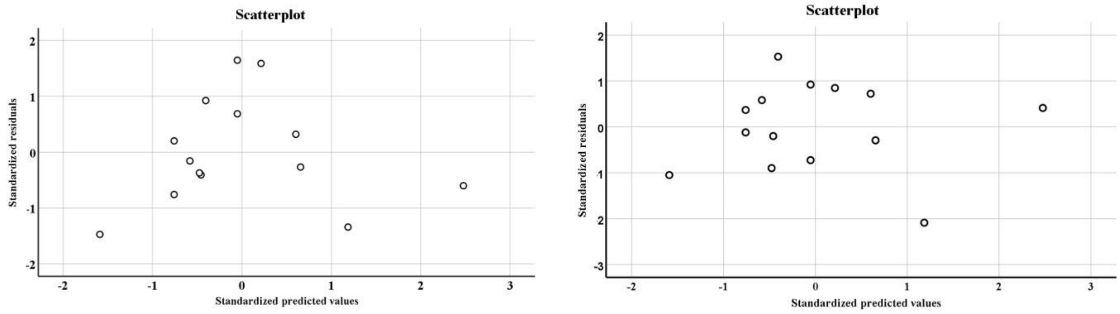
Figure 10. Plots of the proposed models: (**a**) Equation (1); (**b**) Equation (2).

Table 4. Analysis of the Variance of the model of Equation (1).

Source	Sum of Squares	Degrees of Freedom	Mean Squares	F Value	p-Value	Durbin-Watson	Root Mean Square Error	R
Model	232.189	1	232.189	53.409	<0.001	2.198	2.08504	0.904
Error	52.169	12	4.347				**R^2**	**Adj. R^2**
Corrected total	284.357	13					0.817	0.801
		Parameter estimates					**Colinearity statistics**	
Variable	**Parameter estimate**	**Standard error**	**t value**	**p-value**	**95% confidence limits**		**Tolerance**	**VIF**
Intercept	34.360	1.660	20.702	<0.001	30.744	37.976		
Distance	0.0747	0.010	7.308	<0.001	0.052	0.097	1.000	1.000

Table 5. Analysis of the Variance of the model of Equation (2).

Source	Sum of Squares	Degrees of Freedom	Mean Squares	F Value	p-Value	Durbin-Watson	Root Mean Square Error	R
Model	124.889	1	124.889	46.418	< 0.001	1.333	1.64029	0.891
Error	32.286	12	2.691				**R^2**	**Adj. R^2**
Corrected total	157.175	13					0.795	0.777
		Parameter estimates					**Colinearity statistics**	
Variable	**Parameter estimate**	**Standard error**	**t value**	**p-value**	**95% confidence limits**		**Tolerance**	**VIF**
Intercept	30.670	1.306	23.489	< 0.001	27.826	33.515		
Distance	0.055	0.008	6.813	< 0.001	0.037	0.072	1.000	1.000



(**a**) (**b**)

Figure 11. Scatter plot of the standardized predicted values vs. standardized residuals. (**a**) Model of Equation (1); (**b**) Model of Equation (2).

The proposed models indicate that the V_{85} is increased by 0.75 km/h along with every additional 10 m distance between the TCMs. Furthermore, when reducing the distance towards zero, a minimum value for V_{85} would be achieved, 34.4 km/h. These values correspond to the average value of the observed 85th percentile in the TCMs (34.7 km/h), shown in Table 2. Therefore, the model is consistent. The average V_{85} crossing a TCM is 34.7 km/h and depending on the distance from the previous TCM, the speed is increased by 0.75 km/h along with every additional 10 m distance. Similarly, the intercept of Equation (2) (30.67) would mean the minimum value of the average speed when two TCM are very close, and it corresponds with the average value of the observed average values within the investigated TCM types (28.8 km/h). Once again, the model is consistent and indicates that the average value 30.7 km/h is achieved at any vertical TCM. The speed in the middle point between two consecutive TCMs is increased as a function of the distance from the obstacle, 0.55 km/h every 10 m.

It must be noted that these models are only dependent on the distance between TCMs and do not consider other variables like the geometry of the vertical measures. The design of a very specific TCM that could imply a great speed reduction is not considered. We only considered typical geometries, employed in two different countries of the EU. Other factors were not taken into account, such as, the percentage of vehicles turning in the crossings or making maneuvers for parking. Hence, when the values of these variables are important, obtained speed can be highly influenced by them.

If obtained values are compared with previous studies in the literature, it must be said that Ewing [29] indicated a speed increase between 0.26 and 0.53 km/h every additional 10 m distance and in this study speed increases between 0.55 and 0.75 km/h were obtained, implying that at present, drivers tend to accelerate more rapidly between TCMs. Vaitkus et al. [57] recommended a maximum distance of 200 m, 100 m, and 75 m, for speed limits of 50 km/h, 40 km/h and 30 km/h, respectively. Using developed models, for a V_{85} of 50 km/h a maximum distance of 200 m is also recommended. However, for a V_{85} of 40 km/h in the midpoints, a maximum spacing of 75 m is suggested. However, for a value of 30 km/h in the 85th percentile of the speed distribution, proposed model is not recommended, because the minimum value that can be achieved (and even the measured values in the TCMs) are over this value (> 30 km/h). For a more restricted area of 30 km/h, the model of Yeo et al. [56] is suggested, which was mainly measured in school and pedestrian areas, with distances between TCMs in the range of 23 and 90 m.

These models are verified for distances between 63 and 293, so it can be proposed for distances between 60 and 250 m.

4. Conclusions

Due to the scarce literature about the relationship between the distances between two or more consecutive traffic calming measures (TCM) and the speed achieved in the intermediate point between the TCM in the 21st century, data were collected in various streets in Bialystok (Poland) and in Basauri (Spain) where two or more vertical TCMs were placed. Different types were assessed, including raised intersections, raised crosswalks, speed humps and speed cushions. The analyzed speed values were the minimum (V_{min}) and the maximum speed (V_{max}), the average speed (V_{m}) and the 85th percentile of the speed distribution (V_{85}) at the selected points.

Variable speeds were measured at the TCMs, depending on the type. The influence of the geometry mainly affects the speed reduction. However, a high correlation was observed between the distance between two consecutive vertical TCMs and the speed achieved in the middle point between them. This point was selected because it is supposed to be the point where the highest speeds are achieved. If TCMs are in a close distance from each other, drivers do not have enough space to speed up just after passing a previous one. With the high correlation, two linear models were proposed to predict V_{m} and V_{85} as a function of the distance between calming measures. The determination coefficient is around 0.80. Moreover, the intercept, which means the value when the variable is zero (in this case, the distance between TCMs), is very similar to the average speed of the V_{m} and the V_{85} registered at the calming measures. This fact reinforces the consistency of the proposed models, increasing their validity and applicability.

Maximum distances of 200 m and 75 m between vertical TCMs are recommended to achieve a value of 50 km/h and 40 km/h, respectively, for the 85th percentile of the speed distribution. For lower speed values, these models are not recommended.

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