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Effect of Traffic Calming in a Downtown District of Szczecin, Poland

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Abstract: The increasing use of road vehicles has caused a number of transport and environmental issues throughout the world. To cope with them, traffic calming schemes are being increasingly implemented in built-up areas. An example of such schemes are Tempo-30 zones. The traffic calming measures applied as part of this scheme must be carefully planned in terms of location and design details in order to obtain the desired reduction in speed, traffic volume and exhaust emissions and, last but foremost, to increase the safety and facilitate the movement of vulnerable road users. The coexistence and combined effect of these measures and their design details must also be taken into account. The purpose of this study was to investigate whether the applied traffic calming measures had a considerable bearing on the reduction in speed to the desired level, as assumed in the traffic calming plan. Three street sections starting and ending with different intersection types were chosen to examine the synergy of the applied traffic calming measures. The numbers and speeds of vehicles were measured in three day-long continuous surveys. As it was expected, the amount of speed reduction depended on the hourly traffic volume on a one-way street and various other traffic engineering aspects. The obtained results may be used to modify the existing speed profile models and can guide traffic engineers in choosing the most effective traffic calming measures.

Keywords: calming of traffic; Tempo-30 zone; speed reduction; traffic calming measures; choker; speed tables; raised pedestrian crossing

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Citation: Sołowczuk, A. Effect of Traffic Calming in a Downtown District of Szczecin, Poland. *Energies* **2021**, *14*, 5838. https://doi.org/10.3390/en14185838

Academic Editors: Elżbieta Macioszek, Anna Granà, Margarida Coelho, Paulo Fernandes and Massimiliano Gobbi

Received: 26 July 2021
Accepted: 13 September 2021
Published: 15 September 2021

1. Introduction

The increasing use of road vehicles and the resulting high volumes of traffic bring about ever-increasing transport-related problems in urban areas. The first attempts to calm the street traffic in urban areas were made already in the 20th century. The problem of calming the traffic in downtown and uptown locations of cities has been dealt with by many researchers, urban planners, traffic modelling specialists and road engineers. The implementation of Tempo-30 zones in specific streets or whole urban blocks of congested uptown and downtown areas is one of the commonly applied solutions. Increased safety of traffic, volume and speed reduction (resulting in lower exhaust and noise emissions and fuel savings) and making the street more of a true public space rather than purely a transport route are the primary objectives of Tempo-30 zones. On the other hand, a reduction in speed may extend the time of travel and contribute to traffic jams at intersections. Thus, it is extremely important to apply appropriate design guidelines and be aware of the coincident effect of different traffic calming measures. One can look for such guidelines in the basic design manuals [1–3] and guidelines [4,5] published in the U.S. and in the U.K. [6–9] and German [10] guidelines, which describe the proposed applications of: raised intersections, small raised intersections between one-way streets, small raised intersections coupled with a neighbourhood gateway, gateways, traffic circles and the different traffic calming measures typically applied in Tempo-30 zones, i.e., curb extensions (so-called pinchpoints or chokers), curb extensions combined with pedestrian crossings or raised pedestrian crossings at corners of intersections, raised mid-block pedestrian crossings (speed tables) and traffic undulations: speed humps and bumps. This diversity in traffic calming measures is justified by a variety of local conditions, i.e., the traffic control system applied in the street, the route geometry, mid-block section length and different levels of pedestrian and vehicular traffic. The U.S. [4,5], U.K. [6–9] and German [10] guidelines and handbooks [2,3] provide different amounts of the 85th percentile speed reduction across the treatment, depending on the obtained results of studies and analyses. Additionally, the speed reduction ratio, i.e., the speed reduction divided by the initial speed ($w = \Delta v_{85}/{v_{85}}^{before}$), varies between these documents. With different parameters representing the effectiveness of traffic calming measures, designers can decide which of the available traffic calming measures will be the most appropriate for a given street or intersection. This is because this effectiveness depends, to a large extent, on the importance category of the street (2,3,6) and the applicable traffic calming speed reduction category [7,8]. The second parameter, which characterises the effectiveness of a given traffic calming measure, is the reduction in road incidents [4,6–8,11].

Based on the above-mentioned analyses and using the expertise developed during field studies, researchers have developed the principles of modelling traffic calming in traffic-calmed neighbourhoods. The method of modelling the speed profile for streets including traffic calming measures was first proposed in 1966 by Davidson [12] and modified in 1978 also by Davidson [13]. In 1991, Tisato [14] and Akçelik [15] introduced corrections to Davidson's traffic modelling function. In 1995, a further step was made by Barbosa [16], who added a number of new factors characterising the analysed road system to the previously applied ones (i.e., initial speed, amount of speed reduction, geometry of the street, length of mid-block sections and traffic volume). He carried out his research in the city of York on streets where various traffic calming measures had been installed, and the main outcome was a very comprehensive speed profile model. However, in [16], Barbosa concluded that "... the final effect depends on a number of design details applied in a given road system ... ". This conclusion was confirmed in subsequent research projects, and new factors were added, such as information on the applied traffic management system [17], behaviour of drivers waiting in queues before traffic lights [18], parameters of different behaviour patterns [19,20] and parameters of bike-sharing systems [21].

Many researchers have also analysed speed reductions, driving paths, decelerations and accelerations imposed by different traffic calming measures, for example, speed humps and speed bumps (Abdulmawjoud [22] and Baltrènas [23]), different configurations and sequences of bulb-outs and chicanes (Akgol [24]) or speed tables, chicanes and road narrowings (Distefano [25,26]). The effects of speed humps and speed tables on the reduction in speed, exhaust emissions and fuel consumption were reported by Obregón-Biosca [27] and Lav [28]. Similar results concerning exhaust emissions and fuel consumption on a few Tempo-30-zoned streets were published by Int Panis [29] and Da Silva [30]. Additionally, the relationships between the reduction in pollution and fuel consumption and other factors were investigated and discussed for a wide range of speed changes: taking into account the behaviour of drivers and the resulting traffic jams (De Vlieger [31]), shifting gears on the way through the different traffic calming measures (Beckx [32]), speed control schemes, etc. [33–35]. Directly related to the reduction in speed in traffic-calmed neighbourhoods is the issue of noise reduction [36,37]. The speed reduction aspects directly related to air pollution, fuel consumption and traffic noise for different posted speed limits are regulated by an international code of practice [38].

Summing up the above literature review, we can state that the problems of traffic calming in cities and their outskirts have been extensively analysed and investigated. However, the detailed speed reduction data provided in the guidelines [4–10] for different traffic calming measures installed on selected streets do not cover the situations with a few measures installed at the same location or at a close distance from each other, as the case may be. This problem has not been dealt with in the articles published thus far, and this gap was noted already in 1995 by Barbosa [16].

Based on what has been noted in several articles [16–20], in the first place, we see a need for speed reduction analyses in Tempo-30 zones with a few traffic calming measures acting in combination, for example, curb extensions (further called chokers) combined with raised pedestrian crossings and raised intersections connected by short mid-block sections combined with a neighbourhood gateway. Since, as mentioned earlier, the reduction in pollution, fuel consumption and noise is strictly related to the amount of speed reduction, this article presents the results of a study on three different testing grounds at different traffic levels. Section 2 presents the subject of study and provides a detailed description of the testing grounds, taking into account different aspects of the chosen road system. Section 3 presents the data obtained in the traffic surveys and their analyses. This article ends with the discussion in Section 4 and final conclusions presented in Section 5.

2. Materials and Methods

2.1. Subject of Study and Testing Ground

The subject of study was an urban block located in downtown Szczecin, Poland, between two-way streets, in which Tempo-30 zones are being implemented (Figure 1).

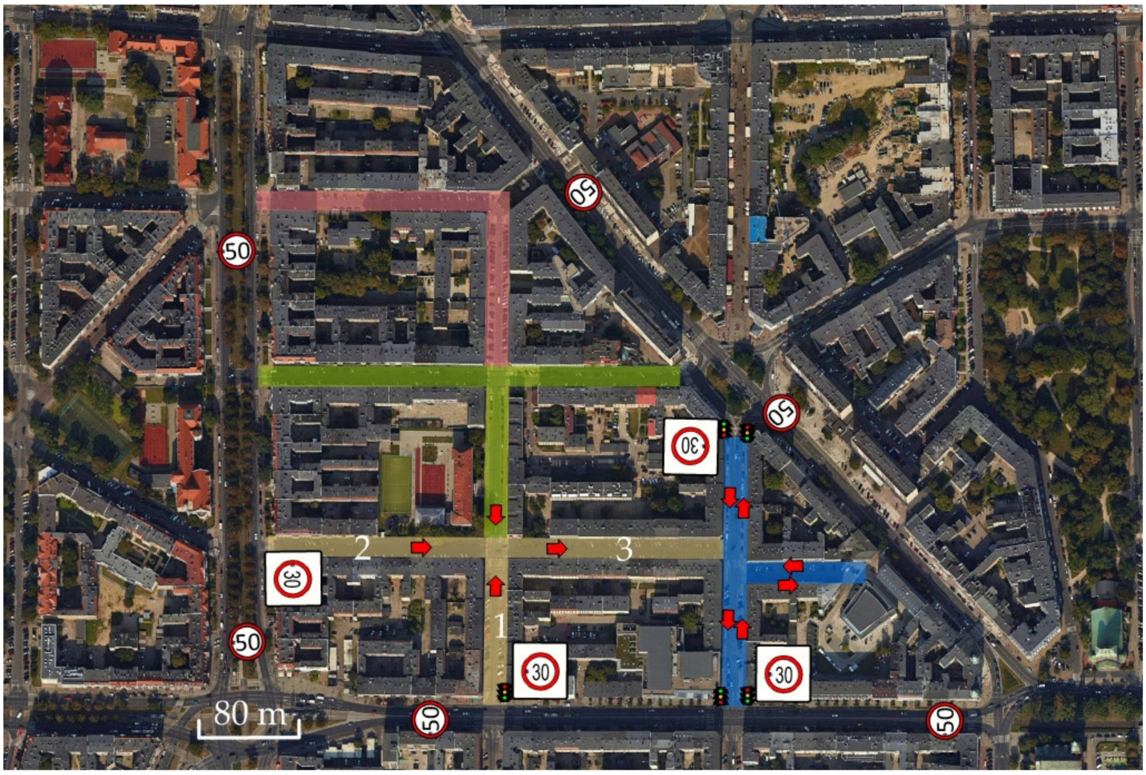


Figure 1. Analysed urban block and testing grounds. Legend: (1) testing ground No. 1; (2) testing ground No. 2; (3) testing ground No. 3. Source: own work of the author using Google Earth satellite imagery [39].

Figure 1 shows testing ground Nos. 1, 2 and 3, reconstructed in 2019 (marked yellow) and the two-way street reconstructed in 2016 (marked blue), i.e., streets with an implemented Tempo-30 zone. The arrows show the direction of traffic. Additionally, shown are the streets where reconstruction is currently taking place (marked green) or has been scheduled (marked red). Before reconstruction, the volume of traffic during peak hours was ca. 200–250 veh/h in both directions. Each of the above-mentioned streets had a 14 m-wide carriageway before reconstruction and carried traffic in both directions. Angled parking was allowed on the carriageway and footway on all these streets. The analysed urban block is bounded by main traffic arterials of Szczecin used by 2500–5500 veh/h during peak hours, including one dual carriageway with a tramway track running in the wide median between the two carriageways and three single-carriageway streets with four traffic lanes.

Each of the respective testing grounds included various traffic calming measures, i.e., mid-block chokers, speed tables, bulb-outs on raised intersections and also bollards blocking access or limiting the parking areas and trees planted on the carriageway between parking stalls (Figure 2).

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

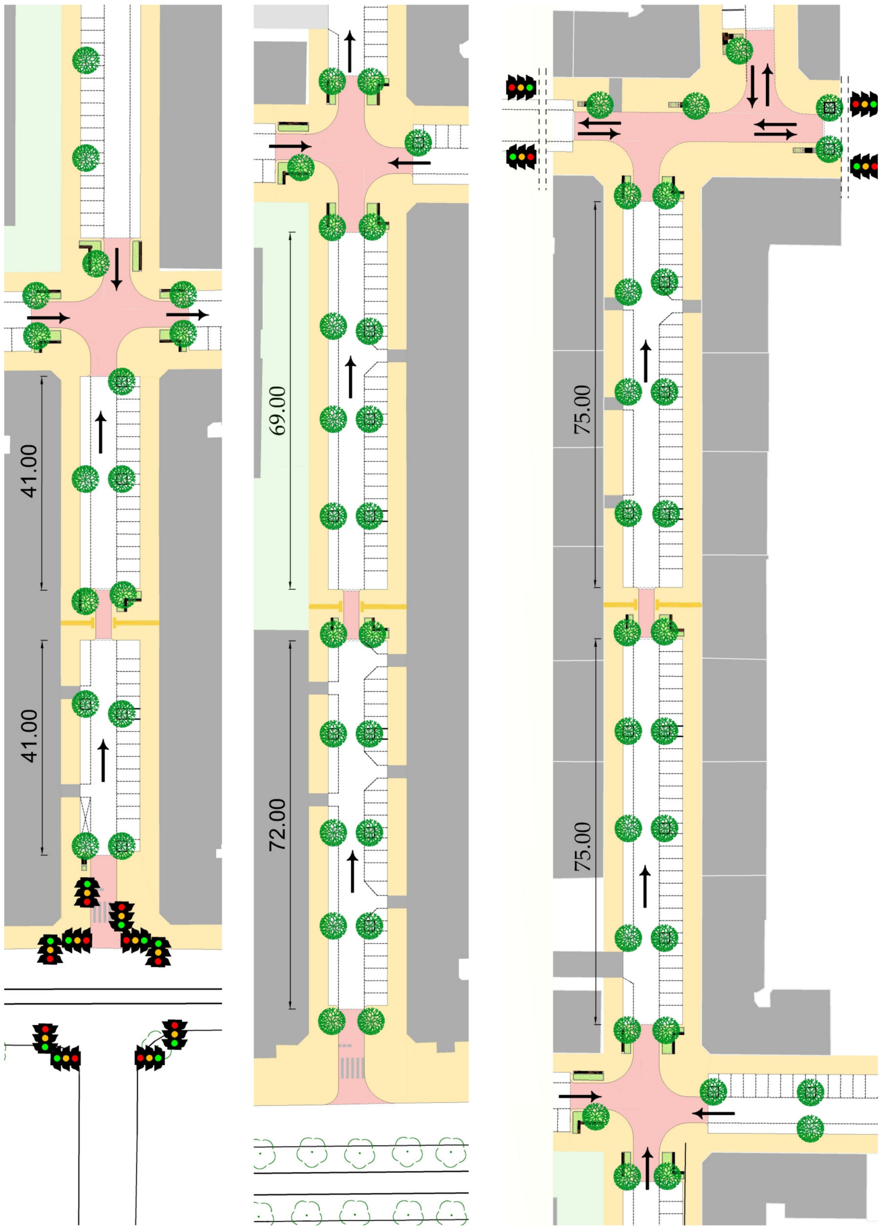
Figure 2. Bollards limiting the parking spaces and greens planted on the carriageway between the parking spaces: (**a**) on on-street perpendicular parking lanes; (**b**) on on-street parallel parking lanes. Source: own work of the author.

The testing grounds were three one-way streets under reconstruction in which a Tempo-30 zone was implemented (Figure 3). The street selected for investigation of the combined effect of different traffic calming measures contained raised intersections at both ends and mid-block chokers combined with a raised pedestrian crossing (speed table). The main design data of the analysed streets were obtained from the plans developed by Maciej Sochanowski Design&Engineering company [40]. The primary difference between the testing grounds chosen to investigate the speed-reducing effect was the different types of intersections at the beginning and end of the mid-block sections. Common to all the testing grounds were raised pavements, chokers and bulb-outs.

There is a signalised intersection with a multilane main street located at the entry to testing ground No. 1. Testing ground No. 1 is a one-way street. Only bicycles may travel both ways. Testing ground No. 1 is left through a small raised intersection (Figure 3a).

Testing ground No. 2 is entered through a raised intersection with a dual carriageway featuring a neighbourhood gateway and ends with a small raised intersection (Figure 3b). As with testing ground No. 1, testing ground No. 2 is also a one-way street.

Testing ground No. 3 has raised intersections at both the entry and exit (Figure 3c). The exit intersection is with a two-way street, and traffic is controlled by signals in both directions (Figure 1). Being a staggered junction, at the outlet of testing ground No. 3, drivers can only turn right or left into the main two-way street (Figure 3c). These turning movements are, to a large extent, governed by the volume of traffic on the two-way street and by the lengths of queues before signals on both sides of the two-way transverse street (Figure 4).



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

Figure 3. Analysed testing grounds: (**a**) testing ground No. 1; (**b**) testing ground No. 2; (**c**) testing ground No. 3. Arrows show the directions of traffic during the surveys. Source: own work of the author based on [40].

Figure 4. Queue of vehicles in testing ground No. 3, and two-way queue of vehicles on the transverse two-way street. Source: own work of the author.

Figure 5 shows test sections on the approach to and after chokers with raised pedestrian crossings in the respective testing grounds. Figure 6 shows the design details of the chokers and raised pedestrian crossings. After reconstruction, the carriageways in all the testing grounds are 5 m wide, narrowing down to 3 m at the chokers. The chokers are 10 m long. In testing ground No. 1, there is a planter on the footway extending towards the carriageway, spaced from the first kerb of the raised crossing by 5.5 m, while in the other testing grounds, there is a constant distance of 0.5 m between these elements. The planters are ca. 0.5 m high and are made of architectural concrete (Figures 5 and 6).

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

Figure 5. Test sections before and after chokers with raised pedestrian crossings in testing ground No. 1, No. 2 and No. 3: (**a**) test section before choker; (**b**) test section after choker. Source: own work of the author.

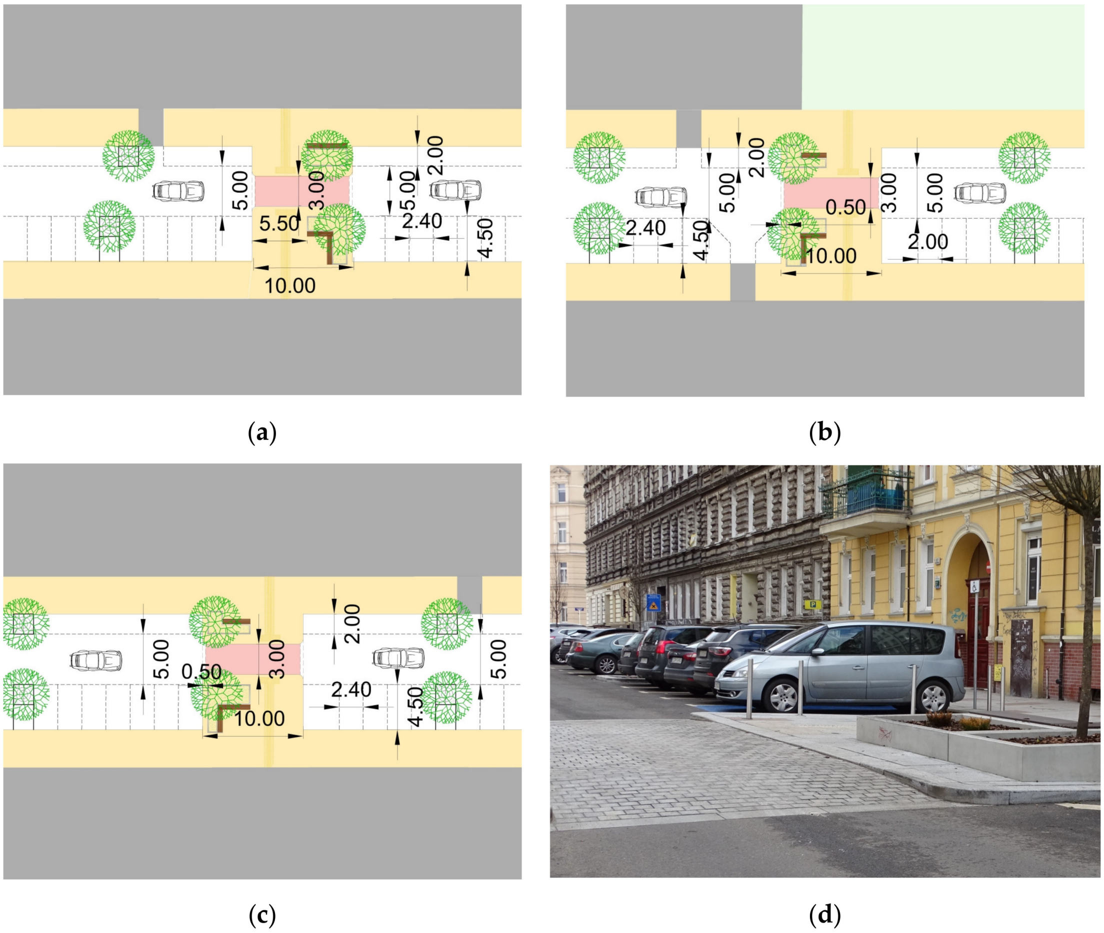


Figure 6. Treatments of chokers/raised pedestrian crossings: (**a**) testing ground No. 1; (**b**) testing ground No. 2; (**c**) testing ground No. 3; (**d**) design details of the sinusoidal approach ramp to the raised crossing and a view of a concrete planter. Source: own work of the author based on the design documentation [40].

The selected testing grounds differ in terms of the test section lengths on the approach to and after passing the choker (Figure 3), architecture (tenement houses with or without courtyard access), layout of on-street parallel and perpendicular parking stalls and a considerable fluctuation in demand for parking, related to the operation of street-level businesses. The main data characterising the public space in the analysed testing grounds are presented in Table 1 below.

Table 1. Public space features in the respective testing grounds.

Analysed Feature		**No. 1**	**No. 2**	**No. 3**
Length of approach to choker, m		41	72	75
Length of approach to intersection, m		41	69	75
Number of street-level businesses	on the left-hand side before choker	7	5	3
Number of access points		2 No.	2 No.	1 No.
Number of street-level businesses	on the right-hand side before choker	5	5	3
Number of access points		–	3 No.	–
Number of street-level businesses	on the left-hand side after choker	2	1	2
Number of access points		–	–	3 No.
Number of street-level businesses	on the right-hand side after choker	3	5	1
Number of access points		–	1 No.	1 No.
Number of trees within the carriageway on the left-hand side before choker		1	3	3
Number of trees within the carriageway on the right-hand side before choker		1	3	3
Number of trees within the carriageway on the left-hand side after choker		1	3	3
Number of trees within the carriageway on the right-hand side after choker		1	3	3
Location of the planter with tree on the choker from the approach edge, m		5.5	0.5	0.5

2.2. Measurement Method

In order to investigate the combined effect of different traffic calming measures installed in the Tempo-30 zone, 24 h vehicle speed and traffic count surveys were carried out for three days on selected streets, both before and after reconstruction. All measurements were performed during dry weather and with a dry pavement surface on Thursday, Friday and Saturday. Both free-flow and steady-flow speeds were measured simultaneously. For simultaneous measurement of driving speed and counting of traffic on the subsequent test sections, synchronised SR4 [41] electronic measuring devices were used. The devices were mounted on the posts of existing traffic signs. The siting of measurement points was based on the requirement of the study, i.e., on the inlets to and outlets from the testing grounds and on the approaches to and after the chokers. Nevertheless, only the data measured at the mid-block chokers were used for the purposes of this article.

The data were grouped in ranges at 25 veh/h intervals. This was conducted to be able to investigate the impact of the traffic volume on the effect of traffic calming. Interestingly enough, as it was established in the study, before reconstruction of streets in testing ground No. 1 and No. 2, the volume of traffic on one lane of a dual-lane carriageway was close to the traffic recorded on the one-way carriageway after implementation of the traffic calming scheme. The traffic volumes recorded after conversion to a one-way street testified to the attainment of one of the primary objectives of the Tempo-30 zone in question, namely, a substantial reduction in the traffic volume. Less traffic and lower speeds bring a reduction in noise and air pollution, i.e., the next objectives of the analysed Tempo-30 zone.

Conversely, in testing ground No. 3, the traffic recorded after reconstruction on the one-way carriageway was much greater than the traffic in both directions before the reconstruction. This was due to the traffic management system applied in the design [40] in which traffic flows from three one-way streets were collected along testing ground No. 3 (Figures 1 and 3c). Thus, a reduction in traffic was not achieved in testing ground No. 3.

We can therefore conclude that the implementation of Tempo-30 zones resulted in a considerable reduction in traffic, which is one of the traffic calming objectives, only in testing ground No. 1 and No. 2. In this way, the former arteries have become part of the public space, enhancing community activities, which is the second objective of traffic calming.

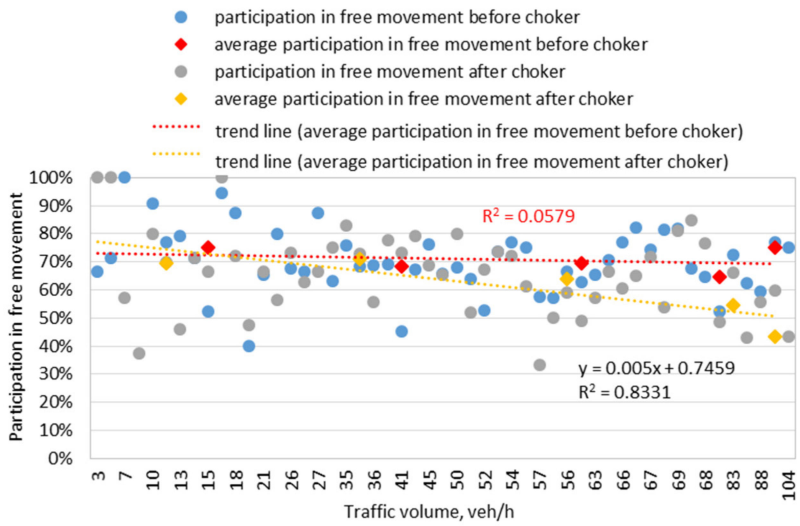
Due to a large variation of factors including traffic volumes, test section lengths (Figure 3) and public space features (Table 1), in order to ensure the consistency of the analysed data, each testing ground was analysed separately, and the effect of the volume of traffic on the recorded speed reductions was investigated. Considering a large proportion of vehicles travelling in linked small traffic flows, the next step of the analysis was to select the vehicles travelling in free-flow conditions, which was due to the following:

- Signalised intersection in testing ground No. 1 (Figure 1);
- Queue of cars waiting at the outlet of testing ground No. 3 (Figure 1) to enter the two-way transverse street with signalised intersections at both ends;
- High fluctuation of parked vehicles in all the testing grounds.

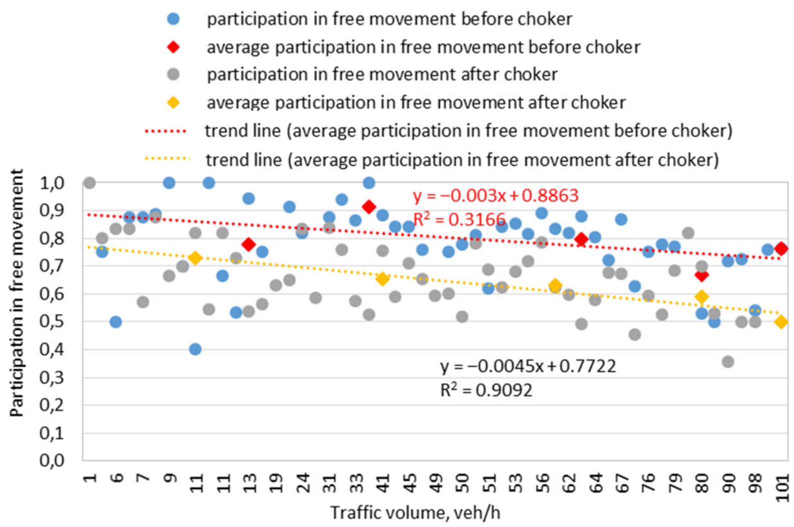
To this end, the functionality of the measuring system software [39] was employed which allowed the use of special procedures. These procedures were set up by the author after a detailed analysis of the initial speed measurements of vehicles parking into and driving out of the parking stalls, synchronised with video recordings of the analysed traffic conditions. Based on the analysis of traffic conditions obtained from three-day 24 h initial measurements, it was decided that the speed of driving into or out of the stall, i.e., less than 8 km/h, should be excluded from the continuous measurement database to be used in further analyses.

The experimental data were used to estimate the 85th percentile speed in the free movement condition at a given traffic volume. The share in free movement varied, as shown by the example in Figure 7, and depended primarily on the hourly traffic volume. Additionally, the road design and traffic conditions have a bearing on these variations. There are a few outliers, shown in Figure 7, which clearly indicate the effect of momentary traffic conditions on the share in the free movement traffic. This was probably due to the temporary impassability of the street section ahead (i.e., a number of cars waiting before traffic signals on the two-way street bounding testing ground No. 3). In summary, we can state that the obtained data validate the speed profile models of [14–19].

Since with the determination factor of 6%, the share in free movement in testing ground No. 1 before the choker does not depend on the traffic volume, the equation was not included in Figure 7a, in line with the principles of statistical analysis. The obtained equations are valid for a specific street only, and thus they should not be used in other analyses. The share in free movement also depends on the importance of the street under analysis, length of the test section between the intersections, number of main street businesses before and after the choker, architecture (multi-storey buildings located away from the footway, row or detached houses, detached public buildings such as schools or kindergartens), demand for parking before and after the choker, downtown or uptown location, etc.

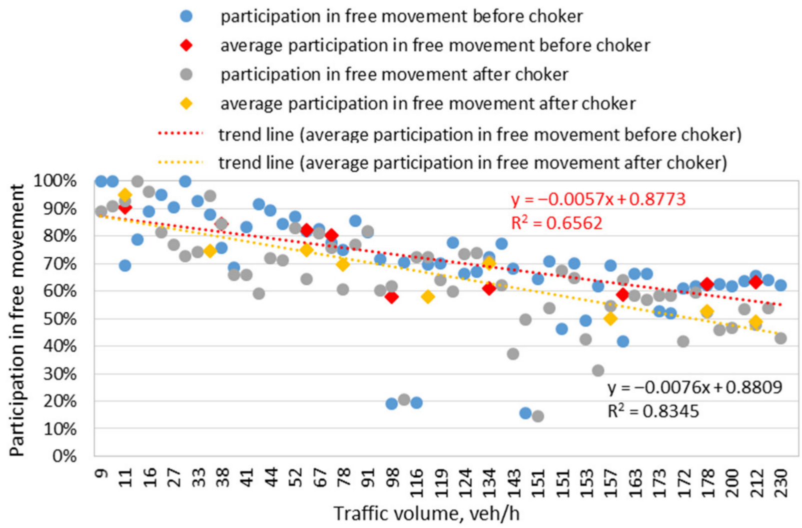


(**a**)



(**b**)

Figure 7. *Cont*.



(**c**)

Figure 7. Variation in the share in free movement using the data obtained in the testing grounds: (**a**) No. 1; (**b**) No. 2; (**c**) No. 3. Source: own work of the author.

2.3. Research Methods

All free movement traffic data were subjected to a standard statistical analysis. A normal distribution of the measurement data was confirmed for all the cases under analysis (Appendix A). In addition, a few statistical tests were carried out (namely, goodness-of-fit, independence and median tests) to verify whether the driving speed depends on the traffic volume, location of the test section and public space features in the testing ground under analysis. The results of these statistical tests are presented in Appendix A. The results of the goodness-of-fit and median tests show statistically significant differences in speeds before and after the choker in all the testing grounds under analysis. The results of the independence test vary strongly only in testing ground No. 1 and No. 2. In testing ground No. 3, all values were positive, indicating a significant difference between the compared speed datasets. The results may be interpreted to indicate the relevance of other determinants in addition to the volume of traffic. These can include different public space characteristics in the respective testing grounds. The differences in this respect between the testing grounds are presented in Table 1. They include different numbers of access points to courtyards of three-storey tenement houses and public premises before and after the chokers, resulting in differing fluctuations in the parking demand. Most probably, the vehicles driving in and out of the parking considerably influenced the measured speeds. Summing up, the results of the statistical analyses performed as part of this study confirm the validity of Barbosa's conclusions [16] that speed profiles also depend on the traffic handling system in place.

The last analysis was an estimation of speed ranges in the respective testing grounds, supplemented with speed data before reconstruction. The obtained results are represented in Figures 8–10.

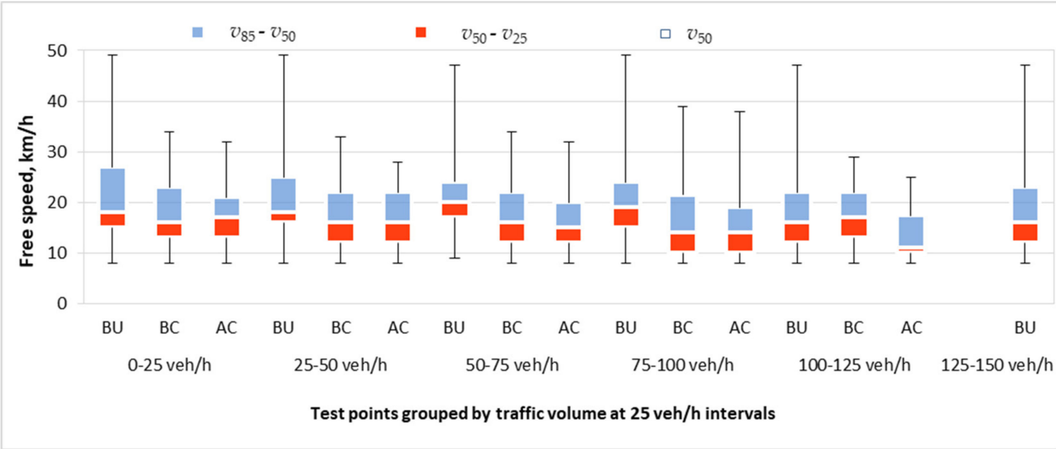


Figure 8. Summary of speed range analysis before and after upgrading, on the approach to and after the choker—data obtained in testing ground No. 1 (BU—before upgrading, BC—before choker, AC—after choker). Source: own work of the author.

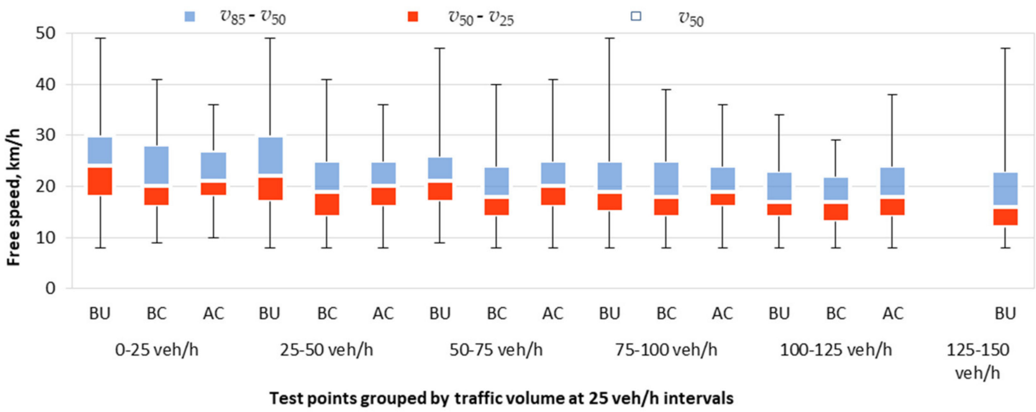


Figure 9. Summary of speed range analysis before and after upgrading, on the approach to and after the choker—data obtained in testing ground No. 2 (BU—before upgrading, BC—before choker, AC—after choker). Source: own work of the author.

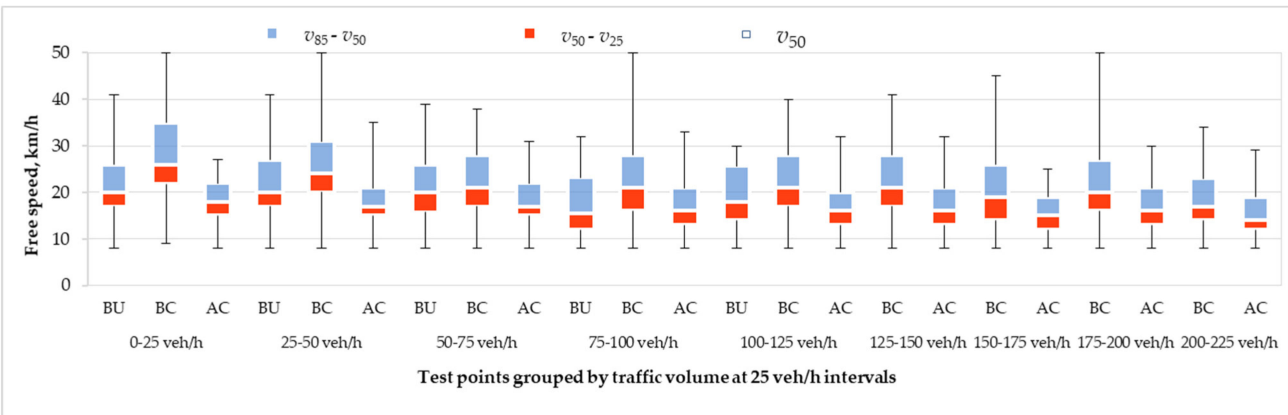
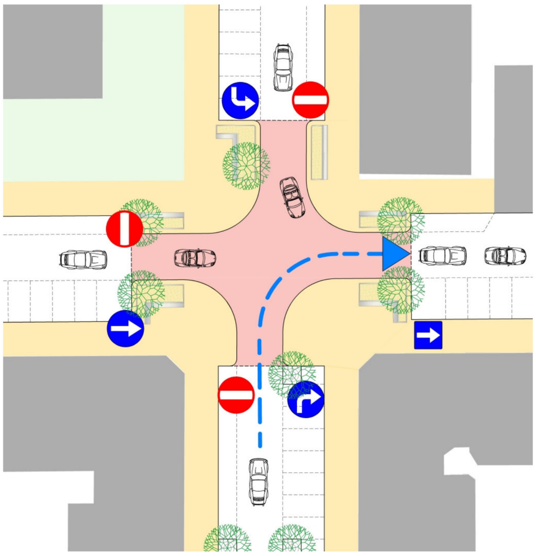
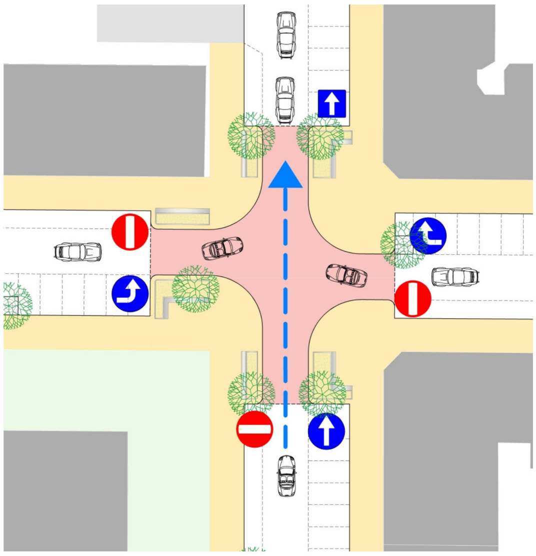


Figure 10. Summary of speed range analysis before and after upgrading, on the approach to and after the choker—data obtained in testing ground No. 3 (BU—before upgrading, BC—before choker, AC—after choker). Source: own work of the author.

The speed range analysis shown in Figures 8 and 9 demonstrated that in testing ground No. 1 and No. 2, the speeds measured before and after the choker/crossing treatment were lower than 30 km/h for almost all traffic volumes. This can be attributed to the short length of the test sections and a view on queues on the section after the small raised intersections located at the ends of both testing grounds (Figure 11), i.e., over the length of testing ground No. 3 (Figure 1). However, it must be clearly noted that isolated cases of higher speeds, up to 40 km/h, were also noted. Nevertheless, compared to the speeds before upgrading, a considerable speed reduction after implementation of the Tempo-30 zone was confirmed. Worth noting is also a higher traffic volume on one lane of the two-way street, as compared to the lower traffic volume on the reconstructed one-way carriageway. This also confirms the effectiveness of the applied traffic calming measures on the reduction in driving speeds and traffic volumes.



(a)



(b)

Figure 11. Traffic conditions and existing traffic management on the raised intersection at the end of: (**a**) testing ground No. 1; (**b**) testing ground No. 2. Source: own work of the author based on [40].

Higher speeds were noted much more frequently in testing ground No. 3 with the longest test sections on the approach to and after the choker (Figure 10). This was caused, most probably, by the view of the unoccupied road ahead (which was the case with traffic volumes up to 100 veh/h) and no queues on the two-way transverse road bounding testing ground No. 3. As a result, the drivers tended to drive faster. In this case, the temporary traffic management implemented on the remaining streets in the block resulted in a considerable increase in the traffic volume on the one-way street after the implementation of the Tempo-30 zone in testing ground No. 3 up to 225 veh/h, as compared to the previous volume of 125 veh/h on one traffic lane of the two-way street. The traffic management and conditions on the raised intersection located at the end of testing ground No. 3 and on the two-way transverse street are presented in Figure 12.

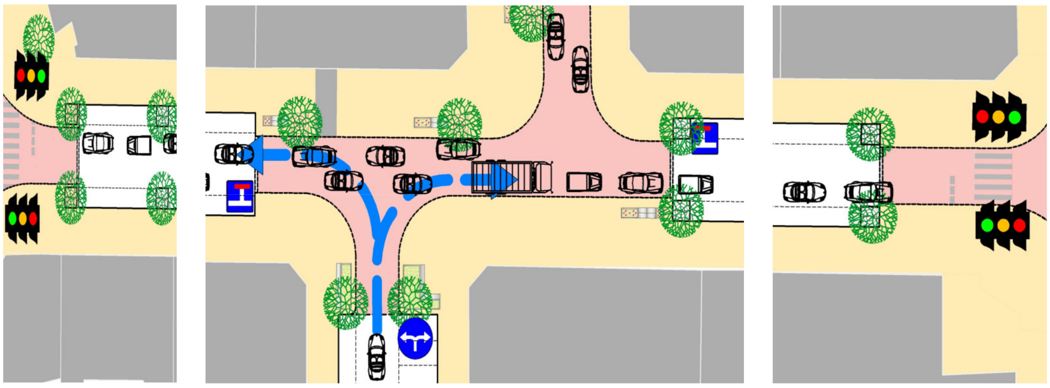


Figure 12. Traffic conditions and existing traffic management at the end of testing ground No. 3. Source: own work of the author based on [40].

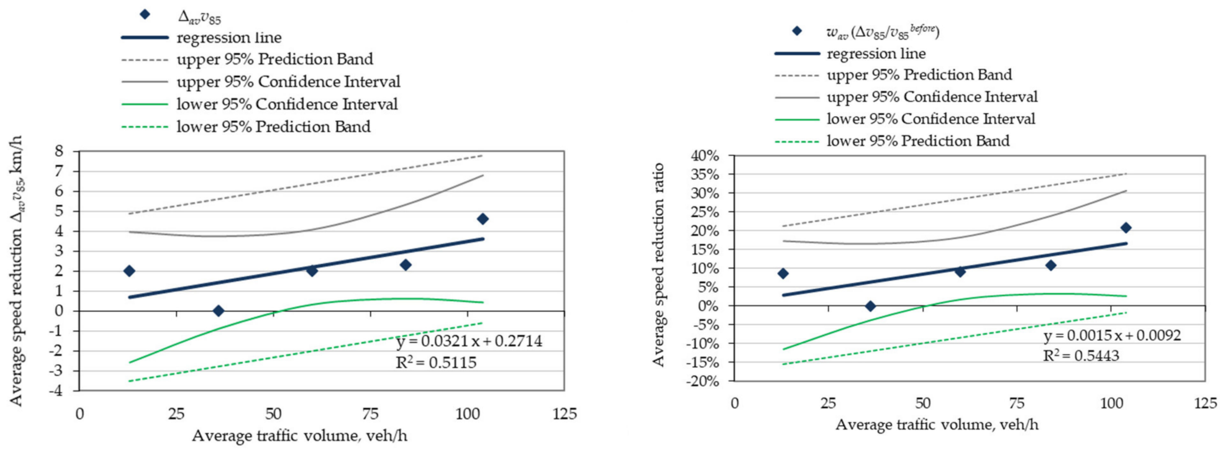
3. Results

As the next step, the speed reductions obtained by the choker/crossing treatments were estimated. To this end, speed reductions were calculated for all the recorded traffic volumes. Next, average values were calculated for traffic volume ranges at 25 veh/h intervals. The total duration of the three-day 24 h continuous surveys provides 10–18 h of measurement per traffic volume range, which is considered a sufficient basis for further analyses. Additionally, the number of individual speed data in free movement of 300–1300 per traffic volume range is considered sufficient.

The speed change ratio was also calculated in accordance with the design guidelines [4–10] since the amount of speed reduction, the primary objective of the Tempo-30 zones, depends primarily on the initial speed, before the implementation of a traffic calming measure(s). The obtained results were subjected to regression analyses, separately for each testing ground. This is in line with Barbosa's suggestion [16] that the final speed reduction depends on various details concerning a specific traffic system. Therefore, the chosen testing grounds had different test section lengths, numbers of parking stalls, access points and types of inlet and outlet intersections.

The results of the regression analysis of the results obtained in the respective testing grounds and change in the 85th percentile speed, in accordance with the above assumptions, are presented in Figures 13–18. From the results of the regression analyses in Figures 13, 15 and 17, we see that, only in one case, only one result falls beyond the regression area (Figure 17). The confidence interval upper and lower bounds are also presented for a single observation, represented by dashed lines in Figures 13, 15 and 17. All the data under analysis fall within the area limited by these lines. As Barbosa's speed profile modelling [16] takes into account traffic handling and spatial layout parameters (Table 1), as well as traffic conditions, Figures 13, 15 and 17 also show regression equations for each of the testing grounds in turn.

Table 2 below compiles the main parameters associated with the regression analysis, i.e., coefficients of regression equations, correlation coefficient, coefficient of determination and also Guildford's and Pearson's interpretations of the magnitude of correlation.



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

Figure 13. Regression analyses (testing ground No. 1) for the following relationships: (**a**) average reduction in free-flow speed Δv_{85} and average traffic volume (R = 0.72); (**b**) speed reduction ratio and average traffic volume (R = 0.74). Source: own work of the author.

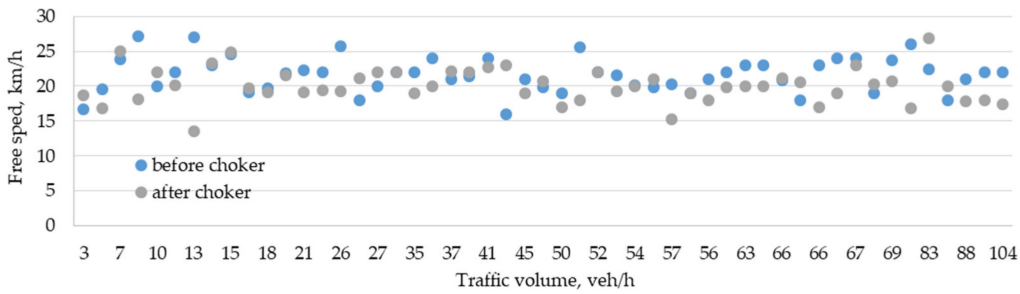
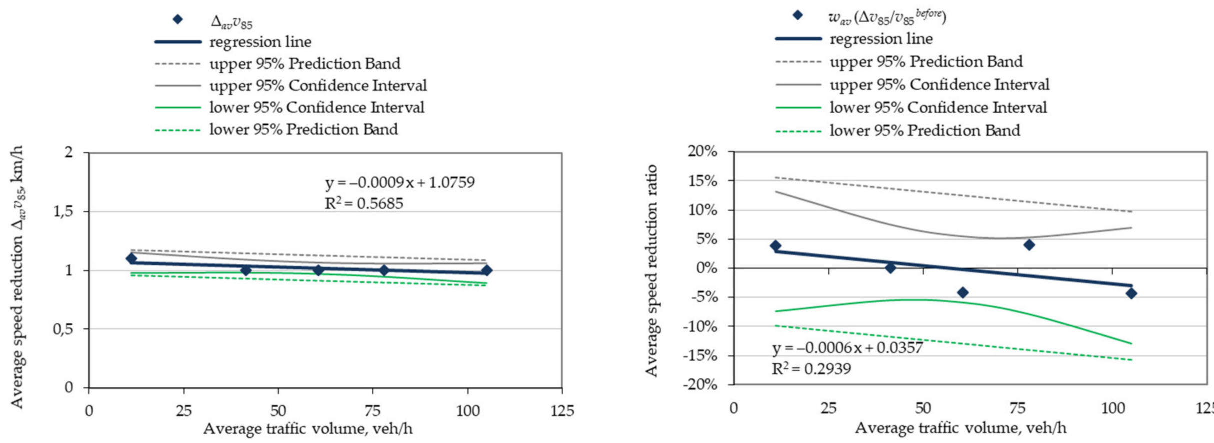


Figure 14. Summary of 85th percentile free-flow speed changes depending on hourly traffic (testing ground No. 1). Source: own work of the author.



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

Figure 15. Regression analyses (testing ground No. 2) for the following relationships: (**a**) average reduction in free-flow speed Δv_{85} and average traffic volume (R = −0.75); (**b**) speed reduction ratio and average traffic volume (R = −0.54). Source: own work of the author.

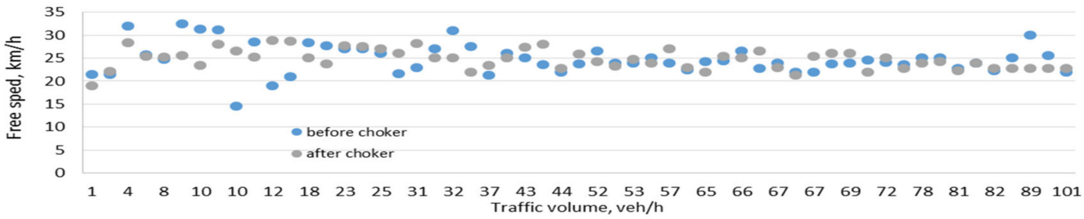
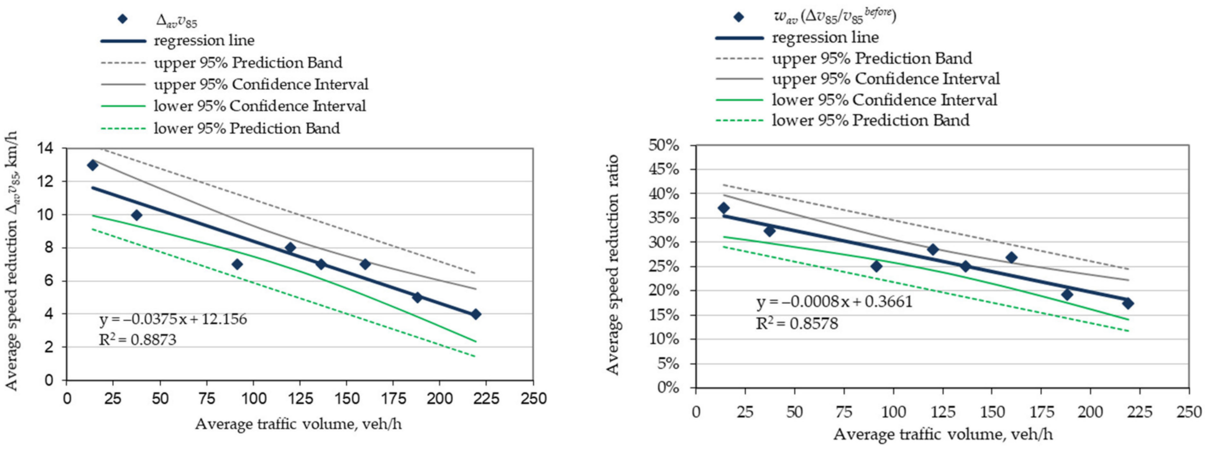


Figure 16. Summary of 85th percentile free-flow speed changes depending on hourly traffic (testing ground No. 2). Source: own work of the author.



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

Figure 17. Regression analyses (testing ground No. 3) for the following relationships: (**a**) reduction in free-flow Δv_{85} and average traffic volume (R = −0.94); (**b**) speed reduction ratio and average traffic volume (R = −0.93). Source: own work of the author.

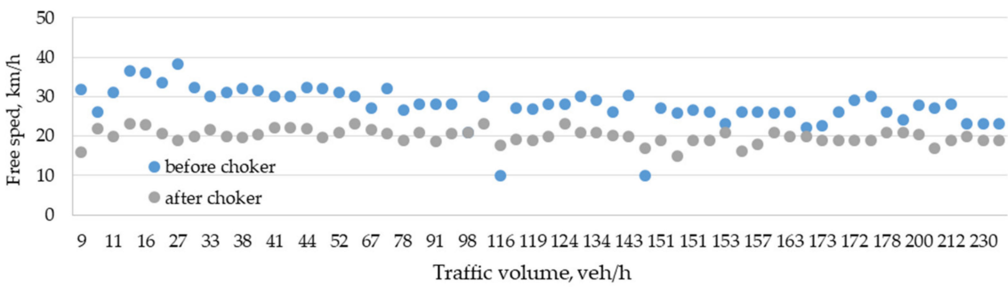


Figure 18. Summary of 85th percentile free-flow speed changes depending on hourly traffic (testing ground No. 3). Source: own work of the author.

Table 2. Regression analysis parameters.

Testing Ground	Relationship	Coefficients		R	R²	Guilford's Interpretation of the Magnitude of Significant Correlations	Pearson's Interpretation of the Magnitude of Significant Correlations
		a	*b*				
No. 1	$\Delta_{av}v_{85} = f(N_{av})$	0.0321	0.271	0.72	51%	High correlation	High degree
No. 2		−0.0009	1.076	−0.75	57%	High correlation	High degree
No. 3		−0.0375	12.155	−0.94	89%	Very high correlation	Perfect
No. 1	$w = f(N_{av})$	0.0015	0.009	0.74	55%	High correlation	High degree
No. 2		−0.0006	0.036	−0.54	29%	Moderate correlation	High degree
No. 3		−0.0008	0.366	−0.93	86%	Very high correlation	Perfect

4. Discussion

As mentioned above, following the suggestions of Barbosa [16] and the factors included in the speed profile models found in [17,19], further analyses were carried out separately for the respective testing grounds.

The results of the regression analysis for the results obtained in testing ground No. 1 are represented in Figure 13. The value of the correlation coefficient (R = 0.72) indicates that speed reduction increases with the increase in the traffic volume, yet not exclusively. This relationship is also confirmed by the correlation coefficient obtained in relation to the speed change ratio (R = 0.74). It is worth noting that all the data considered in the regression analysis fall within the bounds of the confidence interval. Considering the low traffic volumes in the cases under analysis, only five ranges of traffic volume changes were used, and the relevant speed reductions ranged from 0 to 5 km/h. Taking into account the speeds recorded before upgrading, which are presented in Figure 8, we see a considerable reduction in speed for all the traffic volumes under analysis, both for these speeds and for the speeds measured on the chicane approach section.

The analysis of the obtained regression results also showed the relevance of the relationship between speed changes before and after the choker and the volume of traffic, as represented in Figure 14. From a simultaneous analysis of both results represented in Figures 13 and 14, it transpires that for smaller traffic volumes, the speed reduction is small and increases proportionally to the growth in traffic. The 85th percentile free-flow speeds on the approach to the choker are higher than the values of the 85th percentile free-flow speeds after the choker. The obtained increase in the speed reduction with the increase in the traffic volume depends not only on the traffic volume but also on the complex road system and traffic conditions noted in testing ground No. 1. Most probably, also relevant are the following: only 41 m-long test sections on the approach to and after the choker; the raised, signalised intersection at the entry to testing ground No. 1, splitting the traffic flow into small portions; and the small raised intersection at the end of the testing ground with a right turn being the only allowed movement (Figures 3a and 11). Additionally, worth noting are numerous street-level businesses (including boutiques) located in the testing ground, which increase the parking needs. In the free flow of traffic, on a short section after the choker, the drivers take into account the traffic conditions on the road ahead but also on the end intersection of testing ground No. 1 (Figure 5b).

The results of the analyses carried out as part of this study show the relevance, for the case under analysis, of the driver behaviour parameters, as described in [19]. Taking into account much smaller speeds and smaller traffic volumes, these results may be used to supplement the description of the time of travel models for traffic-calmed streets, as described in [19].

Figure 15 shows the regression analysis for the results obtained in testing ground No. 2. The value of the correlation coefficient ($R = -0.75$) indicates that speed reduction may depend on the increase in the traffic volume. However, the speed reductions of only 1 km/h are drastically different from the results obtained in testing ground No. 1. As regards the speed change ratio, $R = -0.54$, the relationship with the traffic volume was not confirmed with such small speed reduction values. Additionally, in testing ground No. 2, all the data fall within the bounds of the confidence interval, thus validating the obtained relationships. Setting the 0–1 km/h reductions next to the speed values presented in Figure 9, we see a substantial reduction in speed, compared to the situation before upgrading. That said, a statistically significant reduction in speed across the applied choker was not confirmed. Thus, the most probable primary determinants of speed reduction in testing ground No. 2 include the number of access points, parking demand fluctuation caused by numerous public premises located there and the fence along the school premises on the left-hand side of the street after the choker, which discourages pedestrians from crossing the street at this point.

The analysis of the obtained speed changes before and after the choker depending on the traffic volume, as shown in Figure 14, indicates completely different traffic conditions in testing ground No. 2. The free-flow speed changes at traffic volumes exceeding 25 veh/h indicate a 20–25 km/h stabilised speed both on the approach to and after the choker. This indicates that in testing ground No. 2, there were other parameters relevant to the obtained speed reductions. Most probably, much more important were the length of both test sections of ca. 70 m (Figure 3b) and also the uncongested entry into the Tempo-30 zone from the dual carriageway street through the raised intersection with a neighbourhood gate. In this case, stabilised speed values were recorded already on the initial test section on the approach to the choker. This can be attributed to the presence of street-level businesses and courtyard access points, i.e., the public space features. These features are missing after the choker, and the very stable speed, which is quite independent from the traffic volume, was due to the location of a primary school on the right-hand side of the street, with a chain link fence along the footway (Figures 1 and 3b). The above factors should also be introduced into the above-mentioned speed models [16,17,19]. Summing up the above discussion, it should be made clear that the Tempo-30 zone in testing ground No. 2 calmed the traffic, which is the primary objective of this scheme. This conclusion is supported by the data in Figure 9. Before the upgrading on one lane of the then two-way street, the traffic volumes and speeds were greater than on the one-way street after the implementation of the Tempo-30 zone. The variations in the 85th percentile free-flow speed were generally small in this case, with only isolated cases of ca. 40 km/h. Despite the small speed reductions, the results indicate a high effectiveness of the implemented traffic calming measures (choker, raised pedestrian crossing, sinusoidal approach and exit ramp, planters on extended footways discouraging drivers from making undesired manoeuvres to negotiate roadside obstacles and bollards). The obtained primary results, namely, the stabilisation of the speed over the whole length of testing ground No. 2, should be, most probably, attributed to the synergy of the above-mentioned traffic calming measures influencing the behaviour of drivers.

The results of the regression analysis for the results obtained in testing ground No. 2 are represented in Figure 17. The value of the correlation coefficient ($R = -0.94$) indicates that speed reduction depends primarily on the increase in the traffic volume. This relationship is also confirmed by the correlation coefficient obtained in relation to the speed change ratio ($R = -0.93$). In this case, all the data but one fall within the bounds of the confidence intervals. Overall, the speed drops from 4 to 12 km/h proportionally to the increase in the traffic volume. When the obtained relationships are paired with the speed values presented in Figure 10, similar to the previous testing grounds, we see that upgrading brought a large reduction in speed for all the traffic volumes in consideration. The relevant factors, besides the already mentioned raised intersection at the end of testing ground No. 3, include, most probably, the choker and reduced parking demand on this section.

However, attention is drawn to the specific nature of testing ground No. 3 in that the one-way street collects traffic from three access streets (Figures 1 and 3c), and this was, most probably, the primary factor that caused the increased volume of traffic on the analysed street after upgrading. From the chart in Figure 10, it transpires that the traffic volume on one traffic lane of the two-way street did not exceed 125 veh/h before upgrading, and after upgrading, twice the traffic volume was noted on the one-way street, i.e., up to 250 veh/h. It is also important to include this, in the future, in the speed profile models of the free-flow speed (Figure 7), since the traffic management at the entry to testing ground No. 3, represented in Figures 3c and 11, and at the end of testing ground No. 3, represented in Figure 12, largely influenced the traffic conditions in this area and the test results obtained in testing ground No. 3. A simultaneous analysis of the data in Figures 17 and 18 indicates that the amount of speed reduction decreases with the increase in traffic, i.e., it is inversely related to the growth in traffic. The changes in speed on the approach to and after the choker, represented in Figure 18, both for each of the respective traffic volumes separately and for the average values, point to the existence of a strong relationship between speed reduction and the volume of traffic in testing ground No. 3. However, it must be stressed that in this case, the strong relationship between speed reduction and traffic volume (confirmed by the high correlation coefficients) was due to the applied road system and traffic conditions in testing ground No. 3. The traffic conditions, i.e., combined movements from three streets and the queue of vehicles on the bounding street (Figure 4), were the main determinants of the measured speeds on the approach to and after the choker. Additionally, the test section lengths (75 m) most probably had a bearing on the measurement data. Worth noting are a few street-level businesses located in testing ground No. 3 on both sides of the one-way carriageway, which reduce the demand for parking in their area.

The drivers' behaviour, described in [19,20], had less effect on the final results in testing ground No. 3, since in this case, the speed depended on the queues in the bounding street or free carriageway without such queues visible to the driver, allowing turning movements without waiting. The results of the analysis confirm the necessity to take into account the traffic management parameters, as described in Cascetta's model [17].

Based on the results of this study carried out on traffic-calmed streets, we see the necessity to also include in the presently used speed profile models the above-mentioned factors which concern not only the road system but also the traffic conditions, locations of access points and street-level businesses and the applied traffic management.

Nevertheless, the results obtained in all the testing grounds clearly confirm the effectiveness of the applied traffic calming and reduction in free-flow speed as compared to the situation before upgrading. Since in the traffic-calmed neighbourhoods, the reductions in noise [36–39], exhaust emissions [27–30,38,42,43] and fuel consumption depend primarily on the actual speeds of vehicles, it is justified to state that the remaining objectives of the Tempo-30 zones were also attained on the analysed streets.

5. Conclusions

The primary objectives of the Tempo-30 zones include an improvement in traffic safety, reduction in speed and traffic volume and less noise, pollution and fuel consumption. Since no serious road incidents were noted in the analysed block before the upgrading [40], we can definitely declare that the remaining traffic calming objectives (reduction in speed, traffic volume, noise and air pollution and consumption of fuel, all of which are related to the driving speed) were attained on the upgraded streets.

The results of the Tempo-30 zone traffic calming measures show the effectiveness of the chokers applied combined with the mid-block crosswalks, bollards and concrete planters. The most impressive were the speed reductions obtained on streets featuring less access points to courtyards and less public premises. An effective speed reduction can also be obtained in streets featuring more access points and public premises. The amount of this speed reduction is smaller though. Beside the traffic volume, the speed reduction determinants include entry and exit intersections, the traffic management scheme and also street furniture along the street.

It must be noted that after the trial period with temporary traffic management to relieve testing ground No. 3 from excessive traffic, the responsible road engineer proposed that testing ground No. 2 should remain a one-way street, yet with the opposite direction of traffic. This change has actually relieved testing ground No. 3 from excessive traffic and long queues of cars. It is therefore postulated to pay particular attention when designing the directions of traffic on one-way streets in Tempo-30 zones, in order to avoid overcrowding other streets. Barbosa's modified traffic model can be used as a suitable tool.

In summary of the study results (elaborating on Barobosa's hypothesis), we can declare their suitability for the necessary modification of the existing speed profile models, allowing for a detailed description of the road system and traffic conditions in traffic-calmed neighbourhoods. The revisions that must be made to the existing Barbosa [16], Davidson [12,13] and Tisato [14] traffic models should concern the description of the parameters characterising different Tempo-30 zone sections, their lengths, number of access points, number of public premises, parking spaces and intersections at both ends of the analysed street section. Furthermore, the above-mentioned models should also consider speed reductions by chokers and mid-block crosswalks combined with safety barriers and street furniture for different traffic volumes.

In the near future, i.e., after the completion of the upgrading of all the streets in the analysed block, the author plans to repeat the traffic volume and speed reduction measurements with the purpose of supplementing the existing Tempo-30 zone speed profiles, if appropriate and required.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The author would like to thank Maciej Sochanowski of Maciej Sochanowski Design&Engineering of Szczecin for providing details of the upgrading of the analysed city district.

Conflicts of Interest: The author declares no conflict of interest.

Appendix A

Table A1. Results of standard statistical goodness-of-fit tests.

Traffic Volume, veh/h	Goodness-of-Fit Test K-S λ H_0: $F(v) = F_0(v)$; H_1: $F(v) \neq F_0(v)$, $\lambda_{\alpha = 0.05} = 1.36$					
	Testing Ground No. 1		Testing Ground No. 2		Testing Ground No. 3	
	$\lambda^{(v \text{ before})}$	$\lambda^{(v\ after)}$	$\lambda^{(v \text{ before})}$	$\lambda^{(v\ after)}$	$\lambda^{(v \text{ before})}$	$\lambda^{(v\ after)}$
0–25	0.51	0.52	0.44	0.57	0.38	0.46
25–50	0.89	1.06	0.62	0.51	0.62	0.87
50–75	0.92	0.80	0.78	1.31	0.38	0.53
75–100	0.74	0.56	0.69	1.13	0.47	0.38
100–125	0.30	0.53	0.41	0.28	0.93	0.86
125–150	–	–	–	–	0.69	0.54
150–175	–	–	–	–	0.65	1.29
175–200	–	–	–	–	0.91	0.80
200–225	–	–	–	–	0.36	0.69

Appendix B

Table A2. Results of two-sample Kolmogorov–Smirnov test.

Traffic Volume, veh/h	Two-Sample Kolmogorov–Smirnov Test λ H_0: $F(v^{before}) = F(v^{after})$; H_1: $F(v^{before}) \neq F(v^{after})$					
	Testing Ground No. 1		Testing Ground No. 2		Testing Ground No. 3	
	λ	$\lambda_{\alpha,\ \alpha = 0.05}$	λ	$\lambda_{\alpha,\ \alpha = 0.05}$	λ	$\lambda_{\alpha,\ \alpha = 0.05}$
0–25	8.06	1.36	8.59	1.36	6.77	1.36
25–50	12.54	1.36	13.01	1.36	11.93	1.36
50–75	19.79	1.36	2.07	1.36	7.91	1.36
75–100	10.92	1.36	13.76	1.36	13.28	1.36
100–125	5.35	1.36	0.56	1.36	14.47	1.36
125–150	–	–	–	–	14.72	1.36
150–175	–	–	–	–	23.67	1.36
175–200	–	–	–	–	14.96	1.36
200–225	–	–	–	–	9.56	1.36

Appendix C

Table A3. Results of the test of independence and median test.

Traffic Volume, veh/h	Test of Independence H_0: $P\{X = v^{before}{}_i, Y = v^{after}{}_i\} = P\{X = v^{before}{}_i\}\, P\{Y = v^{after}{}_i\}$ H_1: $P\{X = v^{before}{}_i, Y = v^{after}{}_i\} \neq P\{X = v^{before}{}_i\}\, P\{Y = v^{after}{}_i\}$ $\chi_\alpha{}^2 = 3.84$, $\alpha = 0.05$			The Median Test H_0: $F_1(x) = F_2(x)$ H_1: $F_1(x) \neq F_2(x)$ $\chi_\alpha{}^2 = 3.84$, $\alpha = 0.05$		
	Testing Ground:			Testing Ground:		
	No. 1	No. 2	No. 3	No. 1	No. 2	No. 3
0–25	1.01	1.46	27.43	11.94	22.72	69.04
25–50	1.87	2.52	51.40	379	273	962
50–75	0.50	0.02	11.57	3731	850	164
75–100	0.02	4.62	27.18	162	508	1482
100–125	0.57	0.04	23.96	7.32	4.28	1599
125–150	–	–	25.87	–	–	1643
150–175	–	–	47.50	–	–	12917
175–200	–	–	19.77	–	–	964
200–225	–	–	4.86	–	–	639

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