sustainability

Article

Traffic Circle—An Example of Sustainable Home Zone Design

Stanisław Majer and Alicja Sołowczuk *

Department of Construction and Road Engineering, West Pomeranian University of Technology in Szczecin, 71-311 Szczecin, Poland; stanislaw.majer@zut.edu.pl
* Correspondence: alicja.solowczuk@zut.edu.pl; Tel.: +48-91-449-40-36

Abstract: A significant number of new metered parking systems have been introduced in recent years by the local authorities of various spa towns in Poland in connection with home zone conversion projects. The traffic signs posted in these locations were limited to the beginning and end of the demarcated parking area. Traffic circle (TC) is an example of a traffic calming measure (TCM) used in home zones to slow down the traffic (case study—home zone in a small spa village). This article presents the results of a study investigating the speed reductions obtained within a home zone and a traffic circle used as traffic calming measure. The indispensable speed surveys were carried out in relation to this study in two periods: in summer when the streets are crowded with tourists and in September with little pedestrian traffic. Two research hypotheses were formulated as part of the speed data analysis to verify the slowing effect of the traffic circle and the relevance of the traffic circle's design parameters and location, road function and the surrounding streetscape. For each hypothesis, statistical analyses were carried out using two nonparametric tests: two-sample Kolmogorov–Smirnov test and median test. The third research hypothesis formulated in this study was related to sustainable development factors related to fuel consumption and traffic-related air pollution, including carbon dioxide, carbon monoxide, nitrogen oxide and hydrocarbons. This hypothesis was verified by estimating the amount of air pollution in the home zone under analysis in three different situations (scenarios): in summer with the travel speed reduced by pedestrian traffic to ca. 8–10 km/h, in September with a small number of pedestrians and 20–25 km/h resulting speed between traffic circles, reduced at the traffic circle, and in a theoretical 30 km/h zone with 25–30 km/h assumed speed between traffic circles, dropping at the traffic circle. These analyses confirmed the appropriateness of the traffic circle as a home zone traffic calming measure, as long as its design is based on a detailed analysis of the relevant factors, including location, road function and the surrounding streetscape.

Keywords: traffic calming; traffic circle; reduce speed; home zone; sustainability; air pollution; streetscape character

Citation: Majer, S.; Sołowczuk, A. Traffic Circle—An Example of Sustainable Home Zone Design. *Sustainability* **2023**, *15*, 16751. https://doi.org/10.3390/su152416751

Academic Editors: Luca D'Acierno, Salvatore Leonardi and Natalia Distefano

Received: 23 October 2023
Revised: 6 December 2023
Accepted: 7 December 2023
Published: 12 December 2023

1. Introduction

In the field of road construction, sustainability is understood as construction or reconstruction of road components intended to serve the needs of the current and future generations, while maintaining a balance between economic growth on the one hand and environmental protection and community well-being on the other. Four sustainability types (or pillars) have been distinguished: human, social, economic and environmental. Sustainable transport systems are distinguished by environmental and cost awareness, including the cost of land purchase, construction and future operation, which belong to the environmental and economic sustainability pillars. This article tackles, in particular, the issue of the effective redesign of urban streets and public spaces from the viewpoint of sustainable mobility in urban areas. According to Horn and Jansson [1], redesigning of urban streets and public spaces always involves considerable environmental, economic and social costs in the long run. Therefore, it is so important to assess the effectiveness of any contemplated projects, which should include reference to the social dimension, i.e., the desired coincidence and integration of environmental and traffic safety benefits.

The ever growing or flourishing economy has brought a massive increase in the number of motor vehicles, mainly private cars, which has affected public space quality [2]. This is particularly true of small towns and spas, where public spaces play a specific role by defining the prestige and attractiveness of the place. However, this must not affect the well-being of the local community or compromise the safety of traffic or the availability of transport means. Bearing in mind the sustainable development of the urban environment, these requirements should be considered and implemented in line with accepted urban planning principles. As the first step in the process, the existing transport system of the spa town should be analysed, paying attention to the designated functions [3,4]. This should include determination of local residents' and tourists' needs, bearing in mind the intended use and function of a given public space. Towns can have one of the following spatial structures (Figures 1 and 2):

- monocentric, with a clear-cut centre both functionally and spatially and a generally oblong, elliptical, square, rectangular or semi-circular shape (Figure 2a,b),
- bipolar, made up of two or more distinctly bordered urban entities that may merge into a rectangular or tubular system (Figure 2c),
- polycentric, formed through development and merging of smaller entities (Figure 2d).

Figure 1. Small seaside spa villages in the West Pomerania region of Poland showing the spatial structure type (shown in Figure 2 below) and indicative number of inhabitants. Source: own picture drawn on Google Earth satellite image [5].

Figure 2 shows some Polish seaside settlements, where brighter orange areas represent the historic centres and indigenous residents' homes and paler orange areas are occupied by recently built resorts and homes of the younger generations. The route of the provincial road running through these illustrative spas is also marked.

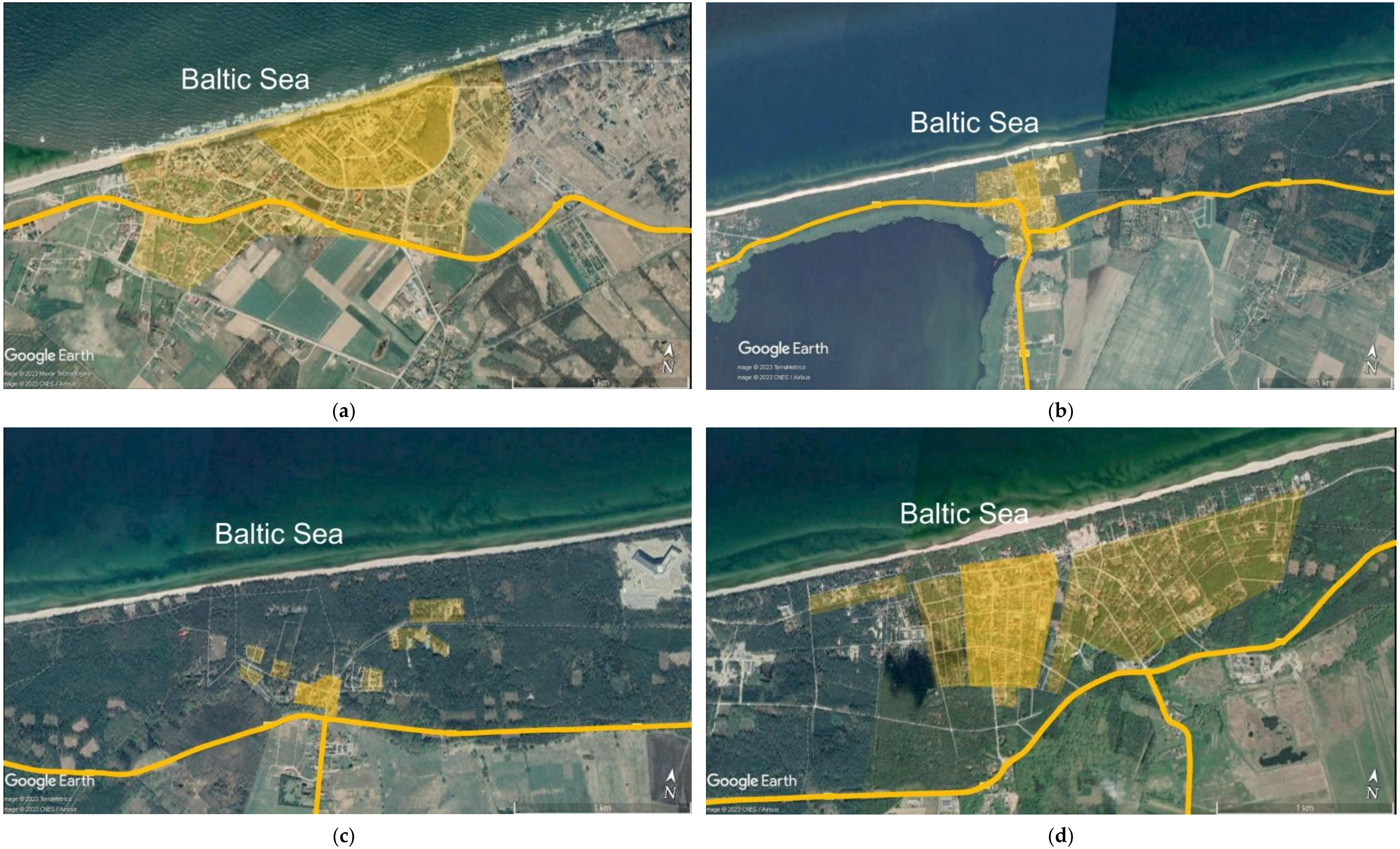


Figure 2. Spatial structures of selected seaside settlements in Poland: (**a**) monocentric semi-circular system of Pobierowo; (**b**) rectangular monocentric system of Dziwnówek; (**c**) bipolar system of Łukęcin; (**d**) polycentric system of Rewal. Source: own work against the background of a satellite image from Google Earth [5].

When contemplating projects intended to address transport issues and revive smaller settlements and spas in line with sustainable development principles, it is indispensable to consider the four above-mentioned sustainability pillars: human, social, economic and environmental. The first wave of urban sustainability projects aimed at public space, social or economic revival involved regeneration of urban green areas, planning of green streets and green infrastructure and care for the natural environment [6–9]. These factors should be taken collectively as the basis for the preparation of traffic calming projects. In the case of public space revival projects, it is also necessary to consider a factor related to the safety of pedestrians, cyclists and drivers or passengers, because pedestrian fatalities constitute a high percentage of all urban road accidents [10–12] (ca. 70% according to [12]). Broken down by age, 9% of these fatalities are people up to 24 years of age, 42% are between 25 and 65 years old and 49% are older than 65 years [11]. As reported in [12], pedestrian fatalities constitute 36% of all urban road accident fatalities in urban areas, as compared to 14% cyclists, 19% motorised two wheelers, 26% car occupants, etc.

Other challenges to public space revival planning are air pollution issues (related to the ever-increasing number of motor vehicles) and traffic noise pollution caused by road traffic in general and with consideration of effective traffic management strategies (TMS) [13–16]. The air pollution and traffic noise pollution issues are the main considerations in the selection of appropriate traffic calming measures and the planning of traffic calming systems in urban areas [17,18]. These considerations may be addressed through appropriate modelling [19] or field monitoring of existing traffic calming measures [13]. A number of studies have investigated the issue of air pollution in the vicinity of existing traffic calming measures as part of traffic calming studies [13,20–22]. Traffic calming measures generally cause sudden slowing of traffic, making vertical and horizontal deflections an undesired option when considered from the air pollution and traffic noise pollution angles [23]. Noteworthy, the resistance to this kind of traffic calming measure, as shown by locals, road authorities, road and landscape engineers and urban planners, is directed more towards vertical deflections and less towards horizontal deflections.

Traffic calming may involve urban traffic management, functional classification of streets and/or introduction of home or 30 km/h zones in the area concerned. Other than in larger towns where 30 km/h zones may be applied in combination with home zones, in smaller towns and spa towns home zones are the preferred option, bearing in mind pedestrian amenity improvements. This issue is particularly evident in spa villages and recreational resorts. Various traffic calming measures, i.e., horizontal and vertical deflections, can be used to slow down the traffic as part of traffic calming projects [24–33]. These include chicanes, road narrowing, speed tables or speed humps and mini roundabouts. Two-way to one-way conversions may also be implemented as part of a traffic calming project [34].

Raised junctions, mini roundabouts or traffic circles are often used in home or 30 km/h zones. The differences between roundabouts and traffic circles can be found in different publications [35,36]. However, they generally refer to older designs of these road components, covering larger surface areas [36]. However, in traffic calming areas, home zones in particular, there is a tendency to design traffic circles without reconstructing the approach legs, realigning of kerb-lines, etc. [37] to cut the project cost. Then, it is appropriate to refer to them with the term proposed in [38], i.e., “mini traffic calming circle”. Figure 3 shows some examples of such traffic circles that can be found in traffic calming areas in Poland. The traffic circle’s central island may be elevated above (Figure 3a) or installed flush with the surrounding road surface (Figure 3b). The central island may, but not necessarily, promote circular traffic. It may be imposed by appropriately used traffic signs and pavement markings. An example of a traffic circle with traffic signs imposing circular traffic around a raised central island is shown in Figure 3a. In Figure 3b, the traffic circle extends over the entire area between the kerb-lines, without imposing circular traffic as a result.

(a)

(b)

Figure 3. Examples of traffic circles used in Poland on two-way streets: (**a**) an example of a sectioned-off central island on a raised junction in Mierzyn, including traffic signs directing the traffic around the island. Source: photo by Alicja Sołowczuk; (**b**) example of coloured/textured surface used on the central island of a raised junction in Puławy. Source: Google Earth [5].

The effectiveness of traffic circles in traffic calming applications has not, as yet, been reported in the literature, as opposed to extensively covered experiments and evaluations to verify the effectiveness of speed tables. Where the central island does not impose circular traffic, traffic circles are similar to speed tables in terms of traversability. Among the key benefits of traffic circle retrofitting projects are calming of traffic, reduced travel delay, compact size making it possible to keep within the existing right-of-way, low project cost and improved traffic safety.

This motivated the authors to undertake the research described in this article, i.e., an evaluation of the effectiveness of traffic circles as a traffic calming measure in home zones. The initial assumptions included a defined transverse profile of the traffic circles' central island and the relevance of pedestrian traffic volume in the home zone area. A small seaside spa town featuring a grid street pattern located on the Baltic coast in Poland was chosen as study area.

The following research hypotheses were defined:

Hypothesis H1. *"A traffic circle has a significant traffic calming effect when located in a home zone of a spa village".*

Hypothesis H2. *"The central island should have its transverse profile appropriate to the street function and location and the surrounding streetscape's character".*

Hypothesis H3. *"Provision of traffic circles in home zones of small spa towns should be considered as part of the urban street and public space redesign projects contemplated in these locations".*

Since Hypothesis H2 consists of three independent parts, three auxiliary hypotheses have been formulated:

Hypothesis 2A. *"Are the "before" and "after" speeds and speed reductions influenced by pedestrian traffic?"—speed data from two traffic surveys carried out at two different times of the year were considered to test this hypothesis.*

Hypothesis 2B. *"Are the "before" and "after" speeds and speed reductions influenced by the TC lo-cation and its place in the sequence along the streets, or by the surrounding streetscape?"—only traffic circles located on the same street were considered.*

Hypothesis 2C. *"Are the "before" and "after" speeds and speed reductions influenced by the street function and surrounding streetscape?"—traffic circles with parallel locations on two analysed streets with different importance, function and streetscape were considered.*

Section 2 of this article describes the object of study, which are seven traffic circles built about 20 years ago in a small seaside spa town in Poland, and the applied research methods. The study results are presented in Section 3. The results are discussed in Section 4 and the final conclusions of the study are given in Section 5. Figure 3 presents the stages of the study on traffic circle effectiveness as a traffic calming measure for home zone areas.

2. Materials and Methodology

2.1. Study Area

The study area was a home zone of Międzywodzie—a small seaside spa town located in Poland (Figure 4). With almost 700 permanent inhabitants, Międzywodzie is considered as a small village. However, in summer over a 12,000 visitors come to the village, turning it into a spa village. The village is divided into two independent parts by the DW102 through road that runs through it. The village is constantly growing with more and more B&Bs, health resorts, small holiday apartments, food outlets, shops, etc., being built all the time. The study area, including the analysed traffic circles, is located in the centre of Międzywodzie and extends over three streets, including a home zone (Figure 5—Zwycięstwa St., Kasztanowa St. and Wojska Polskiego St.).

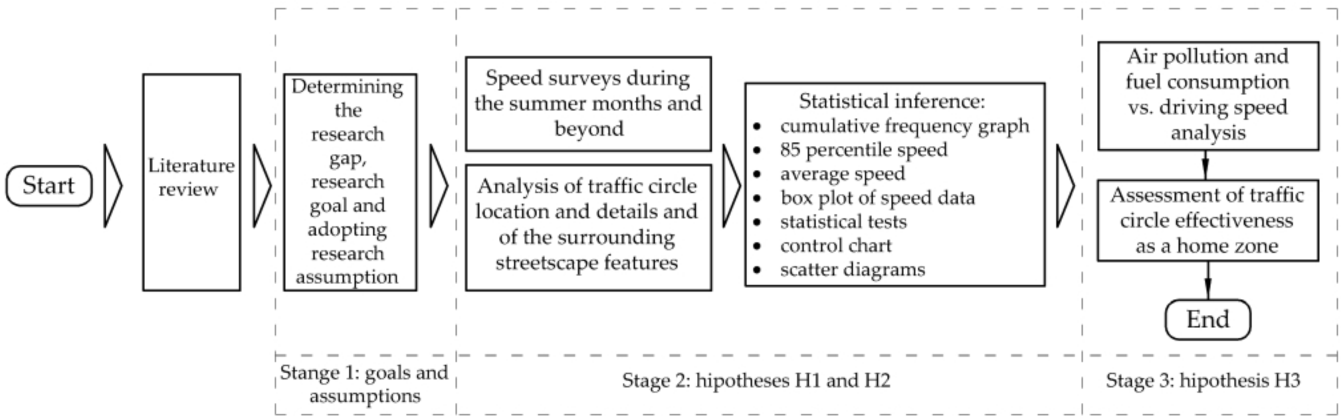


Figure 4. Adopted stages of the research. Source: own work.

With a growing number of tourists in summer, this small spa town has had to deal with serious traffic-related issues. The main challenge was the high volume of pedestrian traffic on the way to and from the beach and a high demand for parking spaces there. Metered Parking Systems with designated and appropriately marked parking places are introduced in such places, similarly to those in home zones, to cope with these growing parking problems. In this situation, a home zone was implemented at the beginning of the 21st century in the central part of Międzywodzie (Figure 5). This involved two-way to one-way conversion of a few streets, constructing a few traffic circles, making the paved paths run flush with the carriageway surface, and demarcating of parking spaces. Improved traffic safety was another benefit of the implemented home zone. However, with no accidents recorded for the period 1995–2023 in the central road accident register SEWIK [39], we cannot give a poor traffic safety record as the grounds for home zone implementation. In fact, it was intended to cope with the parking problems and improve mobility amenities for tourists making their way through the main streets of this spa village.

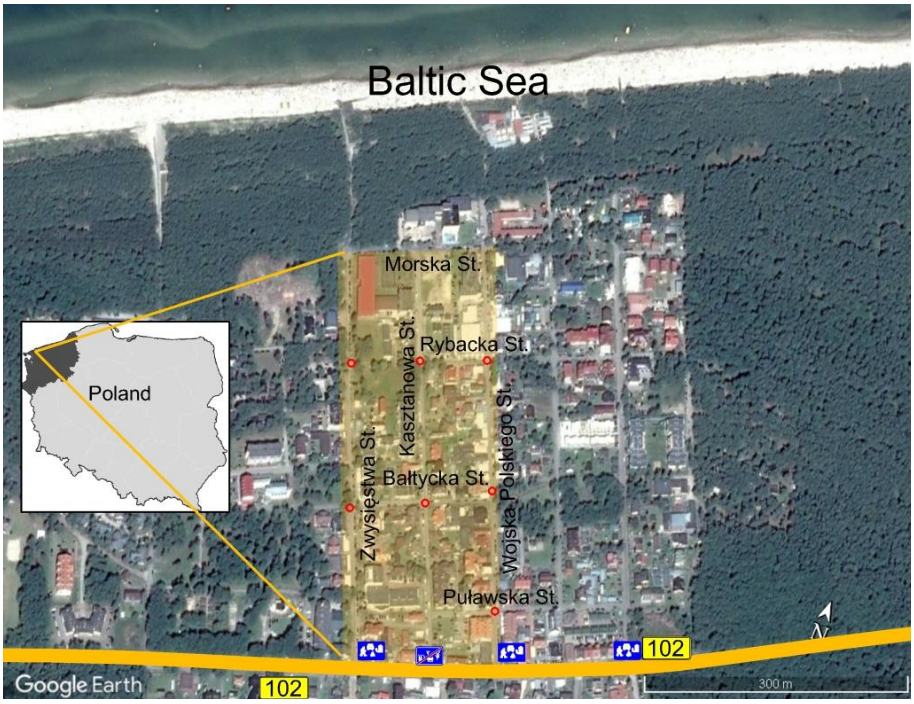


Figure 5. Both the study area and the home zone (marked in orange) are located to the north of the DW102 road (the analysed traffic circle locations are marked with small red circles). Source: own work against the background of a satellite image from Google Earth [5].

Considering the cost of reconstruction and available land constraints, the cheapest project option was chosen with no changes to kerb-lines. Footpaths were brought flush with the road surface and the old asphalt pavement was replaced with block paving on a few street sections and permeable concrete grid paving in the parallel on-street parking areas. Raised traffic circles were built at a few junctions, yet without changing the approach leg widths. All the main streets were 5.0–6.0 m wide. After reconstruction and installation of flush kerbs separating the path from the carriageway, the carriageway width changed to 5.0 m in all cases. Currently, each street includes ca. 2.0 m wide parallel on-street parking spaces. These parking spaces are demarcated by a different surfacing material and with pavement markings applied thereon. Appropriate traffic signs have also been placed to indicate parking locations. Without demarcated pedestrian crossings, pedestrians may walk all over the carriageway and footpath width.

The locations of the seven analysed traffic circles are shown in Figure 6. This number includes two traffic circles located on Zwycięstwa St. (No. 1 and No. 2 in Figure 6). These junctions have three entry legs and one exit leg each. The remaining five traffic circles included three located on four-leg junctions (No. 3, No. 4 and No. 5 in Figure 6) and two located on staggered junctions on Wojska Polskiego St. (No. 6 and No. 7 in Figure 6). Traffic circles No. 5, No. 6 and 7 are located on Wojska Polskiego St., the promenade of Międzywodzie, lined with small restaurants, fishermen's houses, ice cream parlours, pastry shops, small local markets, boutiques, etc. Various events take place during summer weekends along the whole of Wojska Polskiego St. between the DW102 provincial road and traffic circle No. 5. In summer too, further on to the north, a summer fair is held during which stalls are placed over the whole carriageway width. The northern part of Wojska Polskiego St. is blocked as a result. In turn, during the above-mentioned weekend events, stalls selling various merchandise are placed on the footpaths and on the carriageway. At all intersections, the side streets have 5 m wide carriageways, and have no footpaths running along the road or demarcated on-street parking spaces. Figure 5 shows as additional information the traffic directions on the analysed one-way streets and the height Δh of the raised central island.

Figure 6. Study area details: (**a**) traffic circles' locations and numbering; (**b**) home zone divided into functional sub-areas. Source: own work.

2.2. Traffic Volume and Speed Surveys

The object of this case study is a spa village. SR4 traffic detection devices [40] were used to simultaneously measure traffic speeds and volumes as part of this study. The siting of the survey stations is shown in Figure 7. The devices were mounted on the existing traffic delineator posts on the way to and past the analysed traffic circles (before and after), at the one-way street entries and exits and between the junctions. Due to low traffic volumes (up to 35 veh./h) noted in the area under analysis, the surveys were discontinued when the number of logged vehicles exceeded 100. Considering the speed logging characteristics and 0.01 s logging time accuracy, we can assume free traffic flow conditions, allowing each observed vehicle and the following vehicles to move freely without an obstacle vehicle ahead (according to [41]). In the summer, free traffic flow may be arbitrarily related to logged vehicles, as the main obstacles on the road were the pedestrians walking over the whole carriageway width and thus making faster driving impracticable. Information on the gear the drivers used between the junctions was randomly gathered from those who pulled over to park. In September, they generally drove in second gear when making their way through the traffic circle, shifting to third gear on the section between the junctions. This information was then used to calculate fuel consumption.

Taking account of crowded streets in summer and the low number of pedestrians beyond this season, the speed surveys were carried out in two representative periods: in summer and in the last week of September. Considering these low speeds and occupied parking spaces, it was justified to limit the comparative analyses to the values of v_{85} and v_{av}.

(**a**)

(**b**)

Figure 7. Survey station equipment (SR4): (**a**) traffic detection device; (**b**) SR4 sited before and after traffic circle No. 6. Source: photo by Alicja Sołowczuk.

2.3. Methodology

The statistical analysis sequence is shown in Figure 8 below.

For the research hypothesis H3, it was decided to use the conclusions and the data given by Merkisz et al. [22]. The study area included streets with speed humps and zone 30 streets for comparison. Air pollution was measured during a few passes of a test vehicle carrying special gas detection equipment. The air pollution values are the means of the data logged during the respective passes, including vehicle speeds and exhaust emission levels. Based on our analysis, we determined that the traffic conditions during the survey of Merkisz et al. were similar to the conditions prevailing at the traffic circles under analysis.

As regards fuel consumption, it was decided to separately consider two driving scenarios: scenario 1—when the car drives in second gear all the way, and scenario 2—when the car drives in second gear through the traffic circle, shifting to third gear upon entering an in-between section.

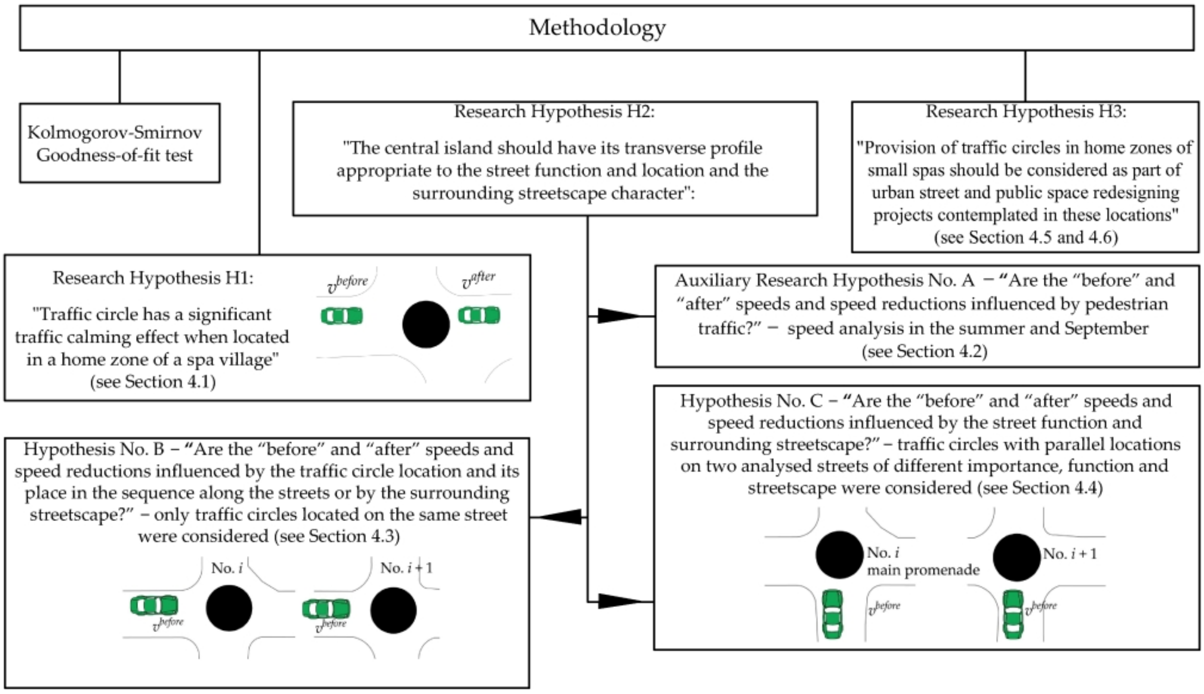


Figure 8. Sequence of statistical analysis. Source: own work.

3. Results

3.1. Characteristics of the Traffic Calming Measurement TCM

In the study area, traffic circles were built as part of the project to convert the existing public spaces to a home zone. The traffic circles' central islands were surfaced with red concrete paving bricks. The junction approach legs were not widened as part of the project. In the whole home zone area, the footpaths were brought flush with the carriageway surface, separated by a kerb-line made of kerb units laid flat. The design allowed leaving the existing drainage system unchanged. On the demarcated parallel on-street parking spaces, a permeable concrete grid pavement was laid. The travel lanes were, in turn, surfaced with grey paving bricks. The parallel on-street parking spaces on Zwycięstwa St. and Kasztanowa St. start and end ca. 7–10 m from the junction edge, thus creating apparent bulb-outs, yet with no kerb-line or markings applied on the pavement surface. On the Międzywodzie promenade, they start and end ca. 3–4 m from the junction edge. The parameters of the analysed traffic circles are given in Table 1 below.

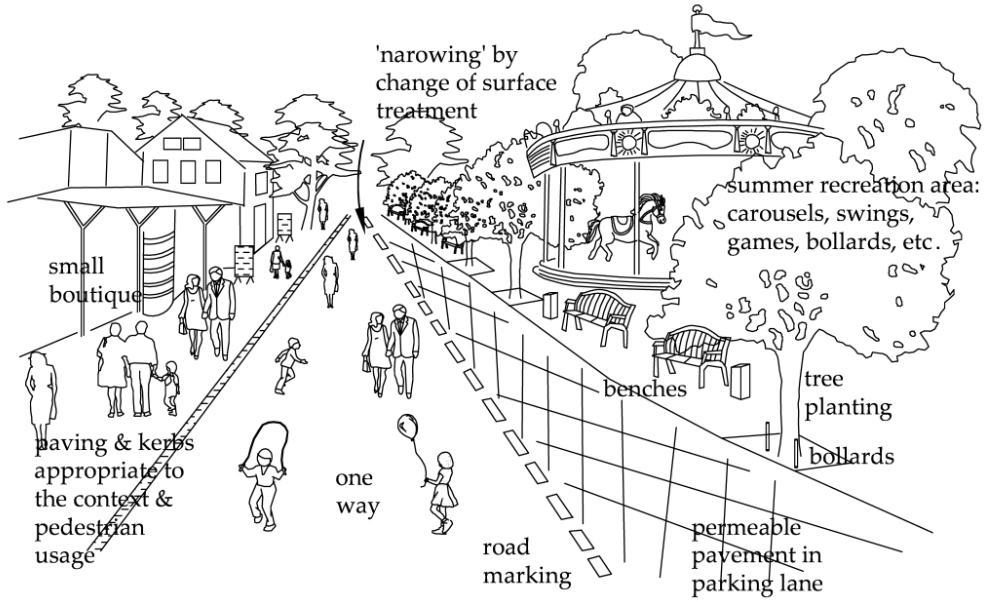
Table 1. Parameters of the analysed traffic circles. Source: own work.

Traffic Circle	Δh [1], m	Street Function	l_1, m [2]	l_2, m [3]	Streetscape Characteristics
No. 1	0.12	footstreet	190	150	summer recreation area
No. 2	0.09	footstreet	150	125	summer recreation area, small businesses open in summer
No. 3	0.17	vehicular street	125	150	private properties
No. 4	0.16	vehicular street	150	125	private properties
No. 5	0.11	main promenade	140	125	small catering and small commercial facilities open in summer
No. 6	0.08	main promenade	135	140	year-round recreation areas and catering businesses
No. 7	0.12	main promenade	60	135	year-round shopping centre, post office, bank, etc.

[1] Δh—difference of level between the central island centre and edge when passing through the traffic circle; [2] l_1—length of traffic circle approach section; [3] l_2—length of road section from the traffic circle end and the next junction.

For streetscape beautification reasons, two-colour paving slabs were used on the footpath and small grafted trees were planted alongside. Kerbing was installed around the trees to prevent oil-contaminated water from penetrating into the plant bed. On the side facing the road, each tree was protected with metal guard posts on either side. In a few places, low-height tree boxes or plant beds were placed within the street width. Benches and litter bins were placed between the newly planted trees. Wider footpath portions are designated to be occupied by stalls, counters and A-frame ads for boutiques and small food serving businesses. The streetscape character of the selected streets for the installed traffic calming measurement TCM is visualised in Figure 9.

(**a**)



(**b**)

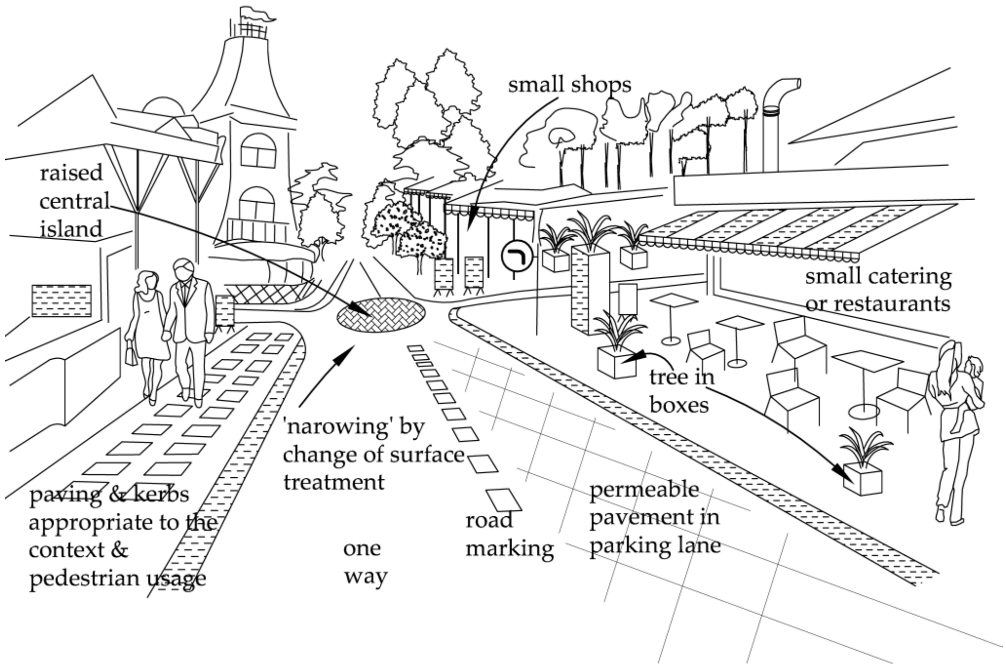


Figure 9. Streetscape and traffic calming measurements and visualisation of the analysed streets: (**a**) one-way street with parallel on-street parking on the right-hand side (Zwycięstwa St.); (**b**) one-way main promenade hosting various weekend events (Wojska Polskiego St.). Source: own drawings.

3.2. Plan and Cross-Section of Selected Traffic Circles

Figure 10 shows transverse cross-sections and plan views of traffic circles located at selected junctions. The island diameter was 4.00 m in all cases. The varying parameter was the difference in level between the island centre and its perimeter. The one-way streets had 5.00 m wide carriageways, including a 2.00 m width demarcated for parallel on-street parking. The side streets had footpaths on some parts and no demarcated parking spaces. The footpaths were surfaced by concrete paving slabs in two contrasting colours. The footpaths were brought flush with the carriageway and separated from it by white kerb units laid flat (Figures 9 and 11).

(**a**)

(**b**)

(**c**)

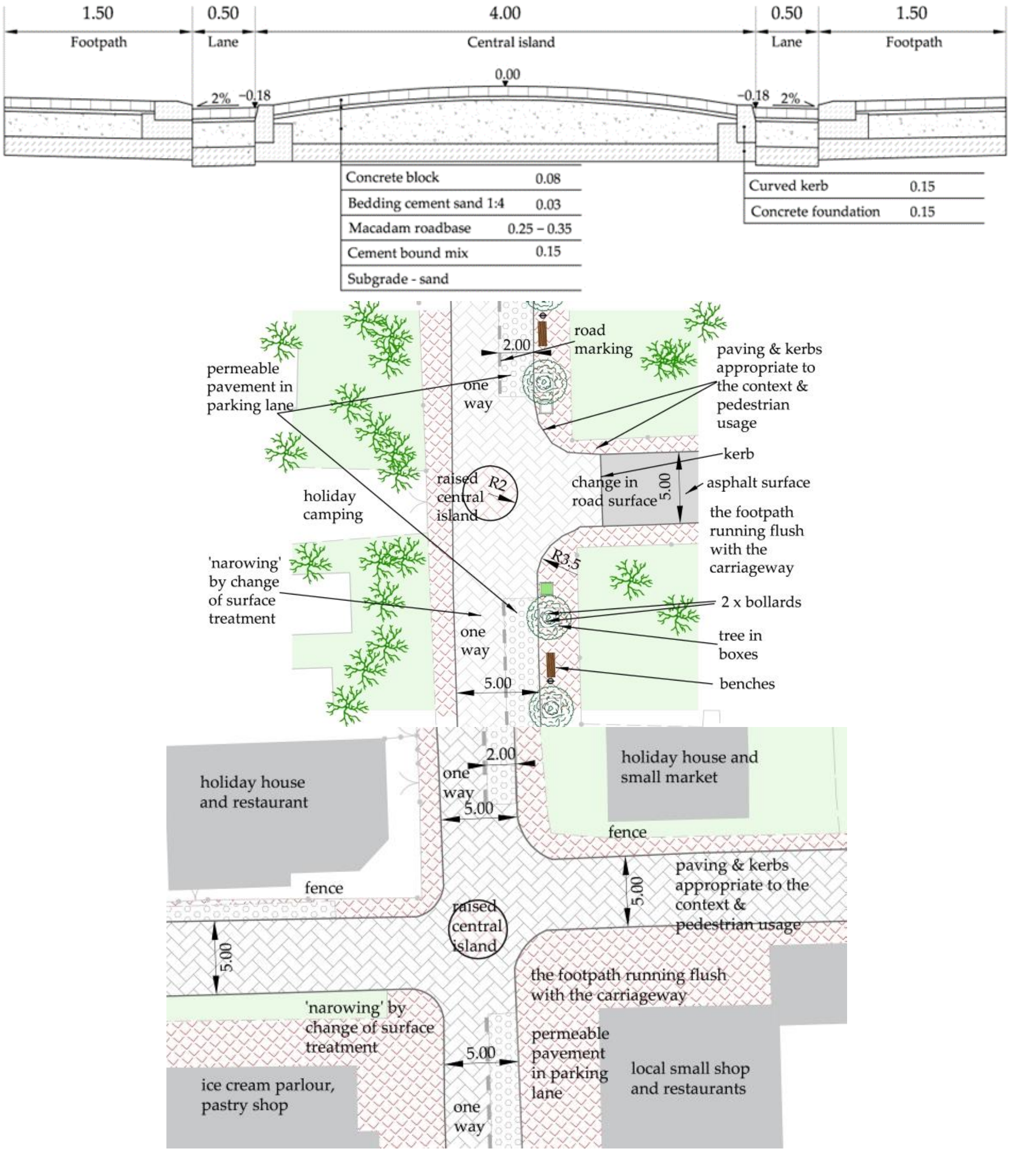


Figure 10. Visualization of the analysed traffic circles: (**a**) transverse cross-section; (**b**) plan view of traffic circle No. 2 located on a T-junction; (**c**) plan view of traffic circle No. 7 located on the main promenade (all dimensions in metres). Source: own work.

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

Figure 11. Analysed traffic circles: (**a**) traffic circle No. 3—Δh = 0.17 m; (**b**) traffic circle No. 6—Δh = 0.08 m (all dimensions in metres). Source: photo by Alicja Sołowczuk.

3.3. Speed Survey Data Processing

Figures 12 and 13 show the speed ranges calculated from the summer and September survey data, respectively. The red dashed line represents averaged v_{85} values calculated using the summer and September survey data, respectively, for all the survey stations.

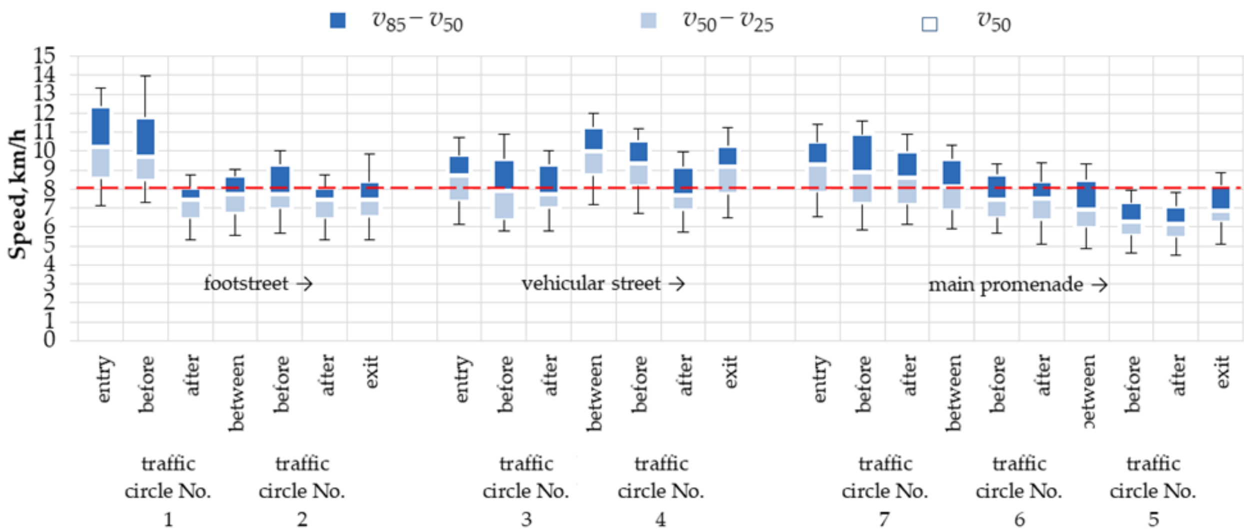


Figure 12. Box plot of speed data measured in summer. The whiskers represent the minimum and maximum values; lower and upper edges of the boxes determine the first and third quartiles; the bold white line designates the median value (the arrow indicates the direction of movement). Source: own work.

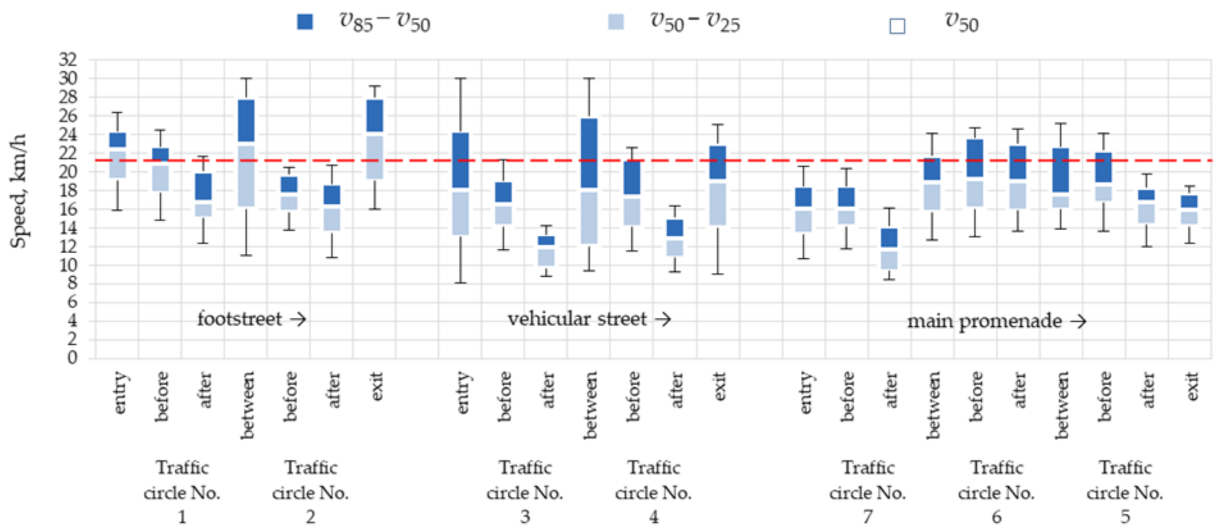


Figure 13. Box plot of speed data measured in September. The whiskers represent the minimum and maximum values; lower and upper edges of the boxes determine the first and third quartiles; the bold white line designates the median value (the arrow indicates the direction of movement). Source: own work.

However, in summer, the main factor slowing the traffic are the tourists walking all over the one-way carriageways and footpaths (Figure 14). During this period, the parallel parking spaces were occupied for most of the time, making the carriageway apparently, and actually, narrower.

(**a**)

(**b**)

(**c**)

(**d**)

Figure 14. Differences in pedestrian traffic on the main promenade in the home zone area: (**a**) summer season—main promenade (Source: Google Earth [5]); (**b**) September—main promenade (Source: photo by Alicja Sołowczuk); (**c**) summer season—traffic circle No. 5 and No. 6 (Source: Google Earth [5]); (**d**) September—traffic circle No. 5 and No. 6 (Source: photo by Alicja Sołowczuk).

In the off-season period, the tourist business is limited to health and spa facilities, a few shops and some boutiques. Other businesses are closed. In the off-season period, only some of the parking spaces were used by owners of the local properties in the area. With less obstacles on the road ahead, traffic can be handled more efficiently and at higher speeds, both between and within the junctions (Figures 13 and 14).

The results given in Figure 13 allow us to conclude that, even without summer visitors, traffic circles effectively slow down the traffic within junctions. In order to traverse the raised central island, the drivers reduce their driving speed by about 12–15 km/h. However, the slowing effect is limited to a max. 10 m distance. In summer, the speeds of travel on the sections between the junctions ranged from 7 to 10 km/h depending on the number of pedestrians and vehicles driving in and out of the parking spaces. In September, this range increased on the sections between the traffic circles to 20–25 km/h, the exact speed depending most probably on the number of parked vehicles.

The cumulative frequency graph in Figure 15 shows the cumulative distribution function (CDF) representing the situation at four traffic circles. The cumulative distribution function and 85th percentile speed differences on these traffic circles stem from different street functions, their place in the sequence and the surrounding and varying streetscape characteristics. All these traffic circles featured a similar difference of level in the range 0.09–0.12 m. The cumulative density functions and values of v_{85} and v_{av} indicate smaller speeds immediately before and past traffic circle No. 2, as well as a smaller approach speed. This may be due to the placing of the sequence of traffic circles (traffic circle No. 2 is passed as the second traffic circle when driving down Zwycięstwa St.), and about 150 m spacing between the subsequent traffic circles. Other relevant factors may include pedestrian traffic, in the summer season, using the whole carriageway width and the surrounding streetscape features. Traffic circle No. 2 and the holiday camping area featured more parked cars and street businesses, including boutiques and food outlets, compared to traffic circle No. 1, with the surrounding developments limited to homes and small resorts.

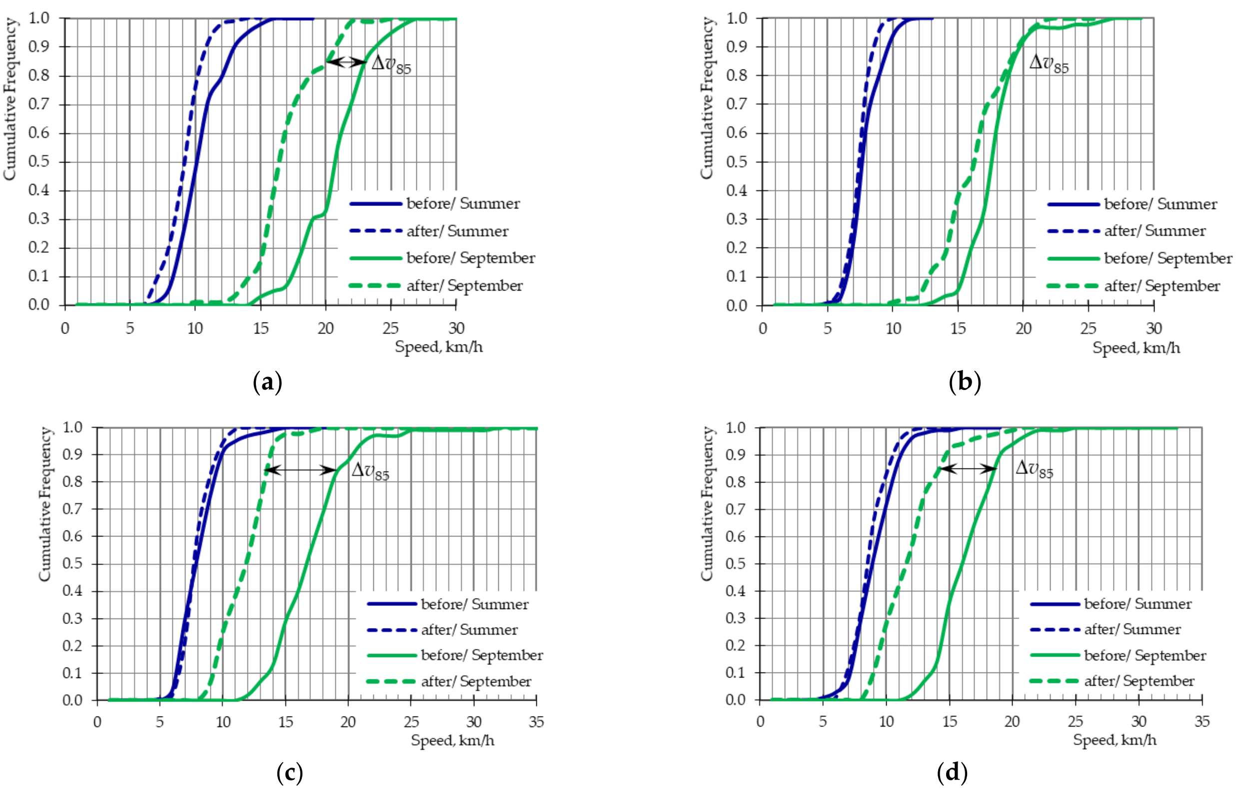


Figure 15. Illustrative cumulative frequency graph of traffic circle crossing speeds: (**a**) traffic circle No. 1; (**b**) traffic circle No. 2; (**c**) traffic circle No. 3; (**d**) traffic circle No. 7. Source: own work.

In turn, traffic circle No. 3 is the first when driving down Kasztanowa St., located about 120 m from the street entry and featuring the greatest transverse slope of the central island with a Δh = 0.17 m level difference. On the street section leading to traffic circle No. 3, vehicles are parked year-round due to the open spas and health resorts. In addition, the first in the sequence is traffic circle No. 7, located on Wojska Polskiego St. about 60 m from the entry to this one-way street. It has a smaller transverse slope of the central island, with Δh = 0.11 m difference in level. On the way to traffic circle No. 7, vehicles are present at all times due to the central location, with many year-round open shops and public amenities. The cumulative density functions and the calculated values of v_{85} and v_{av} indicate slightly smaller speeds of vehicles passing traffic circle No. 7, attributed to the surrounding streetscape features and more pedestrians.

4. Discussion

The statistical inference method was adopted for processing of the speed data obtained for all the traffic circles under analysis. The process started with the Kolmogorov–Smirnov Goodness-of-fit test, carried out to verify normality of distribution of the analysed speed populations (Equation (1)). Normality of speed distribution was confirmed for all the analysed traffic circles in both traffic survey periods.

$$\text{Kolmogorov–Smirnov Goodness-of-fit test}$$
$$\text{Null hypothesis } H_0 \text{ and alternative hypothesis } H_1 : \begin{cases} H_0 = F(v) = F_0(v) \\ H_1 = F(v) \neq F_0(v) \end{cases}, \lambda_\alpha = 1.36,\ \lambda = 0.05. \quad (1)$$

where: H_0—null hypothesis, H_1—alternative hypothesis, $F(v)$—empirical cumulative frequency curve, $F_0(v)$—theoretical cumulative frequency curve, λ_α—critical values, α—adopted significance level.

Next, two of the three research hypotheses were verified using the obtained speed results research hypotheses: Research Hypothesis H1 and Research Hypothesis H2 (see Section 1). Dealing with a non-measurable characteristic, nonparametric tests (two-sample Kolmogorov–Smirnov test and median test) were chosen to verify the research hypotheses (H1 and H2).

4.1. Research Hypothesis H1—"A Traffic Circle Has a Significant Traffic Calming Effect When Located in a Home Zone of a Spa Village"

These were the two-sample K–S test (Equation (2)) and the median test (Equation (3)). In the case of Research Hypothesis H1, both statistical tests were performed for the summer and September "before" and "after" speed parameters for each of the analysed traffic circles. These tests revealed a significant difference between the "before" and "after" speed parameters for all the traffic circles except for traffic circle No. 6, thus confirming the effect of traffic circles on speed reduction for all the analysed traffic circles (Research Hypothesis H1). Some statistical analysis results obtained for traffic circle No. 1 and No. 2 are given in Table 2 below.

$$\text{Two-sample Kolmogorov–Smirnov test :}$$
$$\text{Null hypothesis } H_0 \text{ and alternative hypothesis } H_1 : \begin{cases} H_0 : F\left(v^{before}\right) = F\left(v^{after}\right), \\ H_1 : F\left(v^{before}\right) \neq F\left(v^{after}\right), \end{cases} \lambda_\alpha = 1.36,\ \alpha = 0.05. \quad (2)$$

where: H_0—null hypothesis, H_1—alternative hypothesis, $F(v^{before})$—before speed cumulative distribution function, $F(v^{after})$—after speed cumulative distribution function, λ_α—critical values, α—adopted significance level.

$$\text{Median test :}$$
$$\text{Null hypothesis } H_0 \text{ and alternative hypothesis } H_1 : \begin{cases} H_0 : F_1(v_{50}) = F_2(v_{50}), \\ H_1 : F_1(v_{50}) \neq F_2(v_{50}), \end{cases} \chi^{2_\alpha} = 3.84,\ \alpha = 0.05. \quad (3)$$

where: H_0—null hypothesis, H_1—alternative hypothesis, $F_1(v_{50})$—number of results below v_{50} from both populations, $F_2(v_{50})$—number of results above v_{50} from both populations, $\chi^2{}_\alpha$—critical values, α—adopted significance level.

Table 2. Sample results of statistical tests—traffic circle No. 1 and No. 2. Source: own work.

	K–S Goodness-of-Fit Test [1] Before	After	**Two-Sample K–S Test [2]**	**Median Test [3]**
		Data from the Summer		
Traffic circle No. 1	$\lambda = 0.76 < \lambda_\alpha = 1.36$	$\lambda = 0.34 < \lambda_\alpha = 1.36$	$\lambda = 4.05 > \lambda_\alpha = 1.36$	$\chi^2 = 30.3 > \chi_\alpha{}^2 = 3.84$
Traffic circle No. 2	$\lambda = 0.73 < \lambda_\alpha = 1.36$	$\lambda = 0.58 < \lambda_\alpha = 1.36$	$\lambda = 4.45 > \lambda_\alpha = 1.36$	$\chi^2 = 38.2 > \chi_\alpha{}^2 = 3.84$
		Data from the September		
Traffic circle No. 1	$\lambda = 0.92 < \lambda_\alpha = 1.36$	$\lambda = 1.00 < \lambda_\alpha = 1.36$	$\lambda = 4.03 > \lambda_\alpha = 1.36$	$\chi^2 = 83.8 > \chi_\alpha{}^2 = 3.84$
Traffic circle No. 2	$\lambda = 0.90 < \lambda_\alpha = 1.36$	$\lambda = 0.75 < \lambda_\alpha = 1.36$	$\lambda = 2.28 > \lambda_\alpha = 1.36$	$\chi^2 = 27.2 > \chi_\alpha{}^2 = 3.84$

[1] Kolmogorov–Smirnov Goodness-of-fit test (Equation (1)): $\lambda_\alpha = 1.36$, $\alpha = 0.05$. [2] Two-sample Kolmogorov–Smirnov test (Equation (2)): $\lambda_\alpha = 1.36$, $\alpha = 0.05$. [3] Median test (Equation (3)): $\chi_\alpha{}^2 = 3.84$, $\alpha = 0.05$.

4.2. Research Hypothesis H2—"The Central Island Should Have Its Transverse Profile Appropriate to the Street Function and Location and the Surrounding Streetscape Character"

4.2.1. Auxiliary Hypothesis 2A—"Are the "Before" and "After" Speeds and Speed Reductions Influenced by Pedestrian Traffic?"

Since the speed variation analysis for the summer and September surveys (Figures 12–14) showed a considerable traffic slowing effect of the pedestrian crowds during the summer season, this factor was also subjected to the statistical tests comparing the summer and September data populations (Equations (4) and (5)). The results of both tests are given in Table 3. Based on these results, showing a difference between the "before" and "after" speed data populations in almost all cases, we can conclude that the analysed factor has a statistically significant traffic slowing effect. This effect was not confirmed only for traffic circle No. 6, for which a result close to the critical value was obtained for the "before" speed in one test only. Traffic circle No. 6 is located on a staggered T-junction (Figures 6 and 11b) without demarcated on-street parallel parking and no parked cars (Figures 6 and 11b).

$$\text{Two-sample Kolmogorov–Smirnov test:}$$
$$\text{Null hypothesis } H_0 \text{ and alternative hypothesis } H_1: \begin{cases} H_0: F\left(v^{Summer}\right) = F\left(v^{September}\right), \\ H_1: F\left(v^{Summer}\right) \neq F\left(v^{September}\right), \end{cases} \lambda_\alpha = 1.36,\ \alpha = 0.05. \quad (4)$$

where: H_0—null hypothesis, H_1—alternative hypothesis, $F(v^{Summer})$—summer speed cumulative distribution function, $F(v^{September})$—September speed cumulative distribution function, λ_α—critical values, α—adopted significance level.

$$\text{Median test:}$$
$$\text{Null hypothesis } H_0 \text{ and alternative hypothesis } H_1: \begin{cases} H_0: F_1(v_{50}) = F_2(v_{50}), \\ H_1: F_1(v_{50}) \neq F_2(v_{50}), \end{cases} \chi^{2_\alpha} = 3.84,\ \alpha = 0.05. \quad (5)$$

where: H_0—null hypothesis, H_1—alternative hypothesis, $F_1(v_{50})$—number of results below v_{50} from both populations, $F_2(v_{50})$—number of results above v_{50} from both populations, $\chi^2{}_\alpha$—critical values, α—adopted significance level.

Table 3. Results of statistical tests related to Hypothesis 2A—effect of pedestrians on the "before" and "after" traffic circle speeds measured in the summer season and in September. Source: own work.

Test	Traffic Circle						
	No. 1	**No. 2**	**No. 3**	**No. 4**	**No. 5**	**No. 6**	**No. 7**
Data from Test K–S test [1]							
Before (Summer and September)	4.05	6.9	5.7	4.5	2.3	1.35	4.9
After (Summer and September)	7.00	7.2	7.5	7.7	7.1	7.3	7.1
Data from Median test [2]							
Before (Summer and September)	26.6	167.9	165.5	174.4	179.7	166.0	164.5
After (Summer and September)	97.9	153.8	139.3	152.4	180.8	197.8	56.1

[1] Two-sample Kolmogorov–Smirnov test λ (Equation (4)): λ_α = 1.36, α = 0.05. [2] Median test (Equation (5)): ${\chi_\alpha}^2$ = 3.84, α = 0.05.

4.2.2. Auxiliary Hypothesis 2B—"Are the "Before" and "After" Speeds and Speed Reductions Influenced by the Traffic Circle Location and Its Place in the Sequence along the Streets or by the Surrounding Streetscape?"

In order to verify Hypothesis 2B concerning the effect of traffic circle location and place in the sequence on a given street and the effect of the immediate surroundings, two statistical tests were conducted for the combined data for paired traffic circles (Equations (6) and (7)). The pairs were made up of consecutive traffic circles located on the same street (Table 4—Equations (6) and (7)). The test results for "before" traffic circle speeds in September are given in Table 4. The obtained statistics show that populations of different traffic circles are different, i.e., must not be combined in one set. This confirms hypothesis B on the statistically significant effect of traffic circle location (i.e., place in the traffic circle sequence when driving down the street), and of the surrounding streetscape character on the obtained speed reduction results.

$$\text{Two-sample Kolmogorov–Smirnov test :}$$
$$\text{Nullhypothesis } H_0 \text{ and alternative hypothesis } H_1: \begin{cases} H_0 : F\left(v^{No.\ \ i}\right) = F\left(v^{No.\ \ i+1}\right), \\ H_1 :\ F\left(v^{No.\ \ i}\right) \neq F\left(v^{No.\ \ i+1}\right), \end{cases} \lambda_\alpha = 1.36,\ \alpha = 0.05. \tag{6}$$

where: H_0—null hypothesis, H_1—alternative hypothesis, $F(v^{No.\ i})$—speed cumulative distribution function on the traffic circle No. i, $F(v^{No.\ i\ +1})$—speed cumulative distribution function on the traffic circle No. i + 1, i—traffic circle preceding, i + 1 traffic circle following, λ_α—critical values, α—adopted significance level.

$$\text{Median test :}$$
$$\text{Null hypothesis } H_0 \text{ and alternative hypothesis } H_1: \begin{cases} H_0 : F_1(v_{50}) = F_2(v_{50}), \\ H_1 :\ F_1(v_{50}) \neq F_2(v_{50}), \end{cases} \chi^{2_\alpha} = 3.84,\ \alpha = 0.05. \tag{7}$$

where: H_0—null hypothesis, H_1—alternative hypothesis, $F_1(v_{50})$—number of results below v_{50} from both populations, $F_2(v_{50})$—number of results above v_{50} from both populations, ${\chi^2}_\alpha$—critical values, α—adopted significance level.

Table 4. Statistics related to Hypothesis 2B to verify the effect of the traffic circle location, place in the sequence and the surrounding streetscape features on the "before" speed measured in the September survey. Source: own work.

Test	Analysis of Traffic Circles Located along the Main Streets			
	No. 1 and 2	**No. 3 and 4**	**No. 5 and 6**	**No. 6 and 7**
Data from Test K–S test [1]	4.1	1.1	1.6	3.3
Data from Median test [2]	48.4	3.6	8.0	67.6

[1] Two-sample Kolmogorov–Smirnov test λ (Equation (6)): $\lambda_\alpha = 1.36$, $\alpha = 0.05$. [2] Median test (Equation (7)): $\chi_\alpha{}^2 = 3.84$, $\alpha = 0.05$.

4.2.3. Auxiliary Hypothesis 2C—"Are the "before" and "after" Speeds and Speed Reductions Influenced by the Street Function and Surrounding Streetscape?"

In order to verify Hypothesis 2C, two statistical tests were conducted for combined data for paired traffic circles (Equations (7) and (8)). The pairs were made up of traffic circles located on neighbouring streets at parallel locations (Table 5—Equations (7) and (8)). The test results for "before" traffic circle speeds in September are given in Table 5. The obtained statistics show that populations of different traffic circles are different, i.e., must not be combined in one set. This confirms hypothesis C on the statistically significant effect of traffic circle location, street function and of the surrounding streetscape character on the obtained speed reduction results.

$$\text{Two-sample Kolmogorov–Smirnov test}: \quad \text{Null hypothesis } H_0 \text{ and alternative hypothesis } H_1: \begin{cases} H_0 : F\left(v^{No.\ \ i}\right) = F\left(v^{No.\ \ i+1}\right), \\ H_1 : F\left(v^{No.\ \ i}\right) \neq F\left(v^{No.\ \ i+1}\right), \end{cases} \lambda_\alpha = 1.36,\ \alpha = 0.05. \tag{8}$$

where: H_0—null hypothesis, H_1—alternative hypothesis, $F(v^{No.\ i})$—speed cumulative distribution function on the traffic circle No. i, $F(v^{No.\ i\ +\ 1})$—speed cumulative distribution function on the traffic circle No. $i + 1$, i—traffic circle on the analysed street, $i + 1$—traffic circle on the adjacent street at a parallel location, λ_α—critical values, α—adopted significance level.

Table 5. Statistics related to Hypothesis 2C to verify the effect of the traffic circle location and the surrounding streetscape features at a parallel location on the "before" speed measured in the September survey. Source: own work.

Test	Analysis of Traffic Circle Located on Parallel Side Streets			
	No. 1 and 7	**No. 2 and 5**	**No. 3 and 5**	**No. 4 and 7**
Data from Test K–S test [1]	4.3	1.32	2.1	1.6
Data from Median test [2]	83.8	8.6	8.7	15.7

[1] Two-sample Kolmogorov–Smirnov test λ (Equation (8)): $\lambda_\alpha = 1.36$, $\alpha = 0.05$. [2] Median test (Equation (7)): $\chi_\alpha{}^2 = 3.84$, $\alpha = 0.05$.

Now we can conclude that both hypotheses (Research Hypothesis H1 and Research Hypothesis H2) were confirmed in the statistical inference process. Thus, whenever traffic circles are designed in home zones, the location, street function and the surrounding streetscape features should be taken into account in the process and the traffic circle design parameters should be implemented accordingly.

4.3. Trajectory and Speed Profile Analysis

As mentioned, a traffic circle may (but not necessarily) promote circular movement. In this case, the only 3 m wide carriageway, along the one-way street with demarcated on-street parallel parking, passing the traffic circle makes keeping to the right-hand side impracticable. Instead, the drivers tended to pull left, navigating past the raised central island on its left-hand side. This constitutes the main difference between a traffic circle located on a one-way street and a mini roundabout located on a two-way carriageway. Figure 16 shows examples of different travel paths noted during the surveys. Driving through a traffic circle depended on the driver's skills and habits, differences in level of the central island, vehicle ground clearance, and the surrounding features, including street stalls, buildings, various fences and dense shrubs that could obscure the view of the side road junctions (Figures 14 and 16c,d).

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

Figure 16. Examples of passenger cars driving through traffic circles: (**a**) traversing the island on the left-hand side; (**b**) traversing the island on the right-hand side; (**c**) traversing through the central part of the island; (**d**) bypassing the island by pulling right. Source: photo by Alicja Sołowczuk.

The v_{85} and v_{av} profiles are presented in Figure 17 for different slopes of the traffic circle central islands, different longitudinal slopes on the way to and past the traffic circle, and different surrounding streetscapes. In addition, these profiles include the speeds on the way to, immediately before, within and past the traffic circle, in order to expose the actual speed variation. The results of both surveys are included.

Firstly, the speed profile data reveal completely different traffic conditions at the times of the two surveys, i.e., in summer and in September (Figure 17). In the former case, with crowds of tourists walking on the footpath and on the carriageway, the traffic circles had some, though a rather small, slowing effect on the road traffic. Much higher speeds and a much more pronounced slowing effect of the traffic circles was noted in September when pedestrian traffic is limited to the guests at the health resorts and spas of Międzywodzie. The greatest speed reductions were recorded at traffic circles No. 3 and No. 4 located on Kasztanowa St. The speed reduction differences between these two are attributed to different longitudinal slopes on the junction approach sections. The next in order of speed reduction amount were the traffic circles located on Wojska Polskiego St. and Zwycięstwa St., with central island level difference of Δh = 0.11–0.12 m. Speed reductions of about 4 km/h were obtained on traffic circles No. 5 and No. 7, depending on the approach and departure speeds and the surrounding streetscape features. For example, in the case of traffic circle No. 5, there are local markets and boutiques at the main legs and the demarcated on-street parking spaces start as close as 3–4 m from the secondary leg kerb-line. These parking spaces are used by the spa house and are occupied also in autumn, prominently narrowing the travel lane. These are the main factors contributing to the obtained speed reductions. Traffic circle No. 7 is located 60 m from the home zone entry and this location defines the observed approach speeds. The home zone entry area and the junction corners are occupied by year-round open markets and public amenities, including post office, bank, pharmacy, etc., generating pedestrian traffic and frequent driving in and out of the parking spaces. The situation is different at traffic circles No. 1 and No. 2, with very few pedestrians or parked vehicles in autumn. This resulted in a smaller amount of speed reduction in autumn, in the order of 2 km/h.

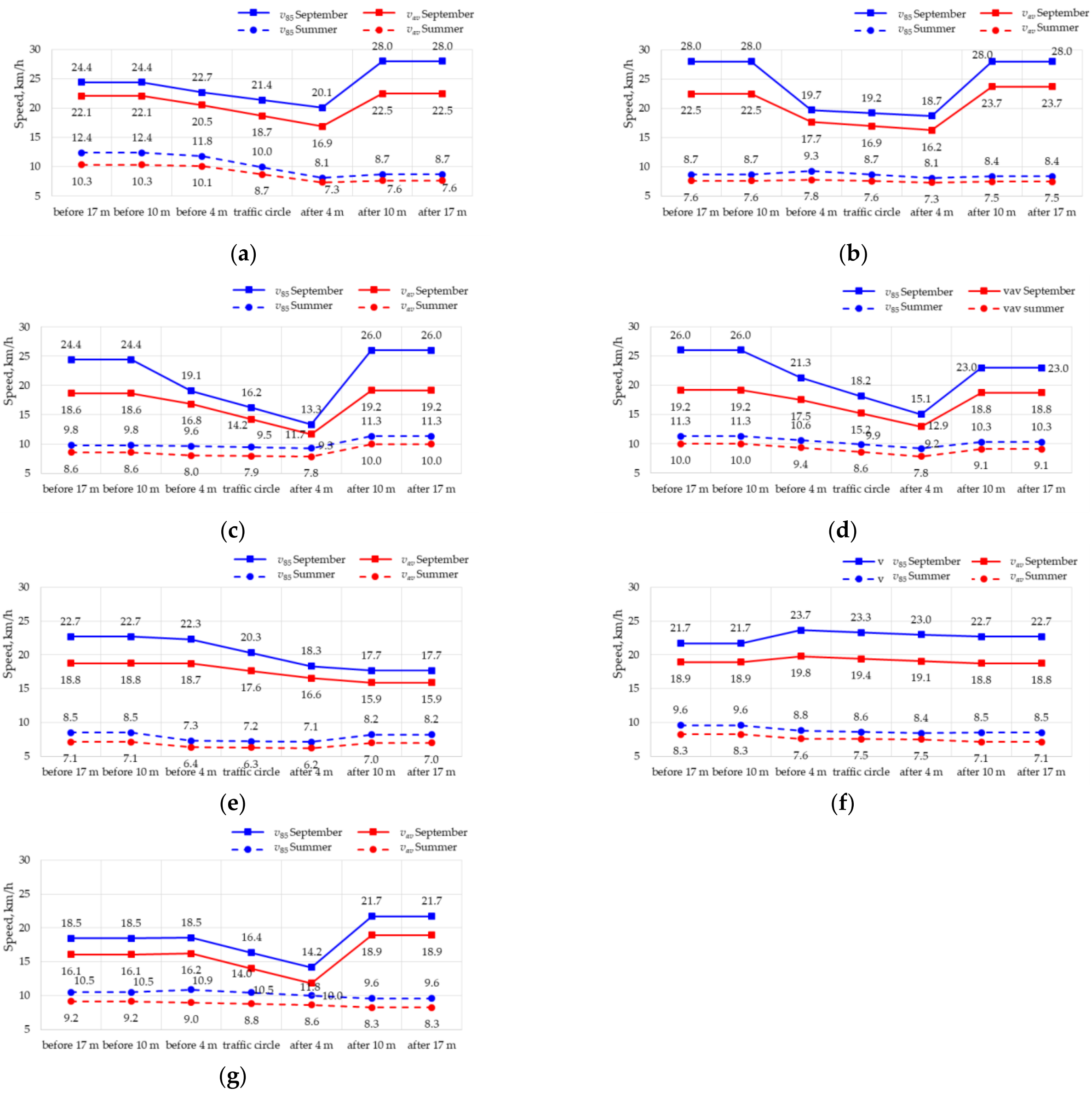


Figure 17. Traffic circle driving speed profiles: (**a**) No. 1—Δh = 0.12 m; (**b**) No. 2—Δh = 0.09 m; (**c**) No. 3—Δh = 0.17 m; (**d**) No. 4—Δh = 0.16 m; (**e**) No. 5—Δh = 0.12 m; (**f**) No. 6—Δh = 0.08 m; (**g**) No. 7—Δh = 0.11 m. Source: own work.

The least traffic slowing effect was noted for traffic circle No. 6, which featured a small difference in level of Δh = 0.07 m and no demarcated on-street parking next to it. To the right of the one-way street, behind the footpath, there is an urban park, and on the left-hand side there are year-round open small food outlets. The above factors mean that drivers practically have at their disposal the entire width of the road, equal to 5 m, and do not slow down when crossing traffic circle No. 6. Driving speeds become steady on the section between traffic circle No. 7 and traffic circle No. 5 due to the low number of pedestrians in September and a small number of parked vehicles (Figures 11b and 16).

4.4. Regression Analysis

Summing up, we can say that the speed reduction obtained with traffic circles depends on the central island difference in level, longitudinal slope of the approach section, effective carriageway width (whether or not limited by vehicles parked in the demarcated parking spaces), presence of pedestrians, traffic circle location and the surrounding streetscape features. Figure 18 represents the relationship between the obtained speed reductions and the difference in level of the central island, based on the September survey data.

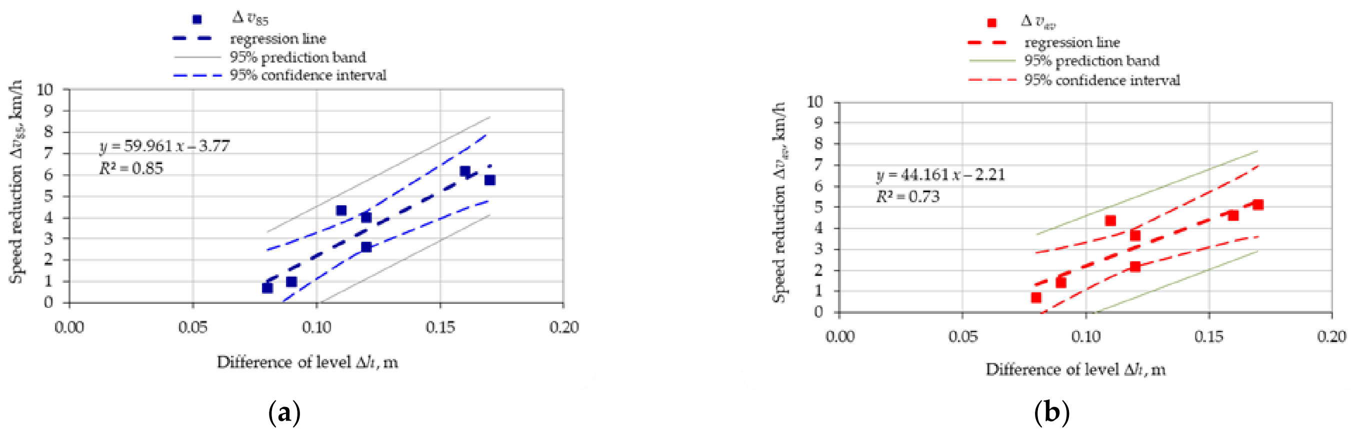


Figure 18. Speed reduction vs. central island difference of level Δh: (**a**) v_{85}; (**b**) v_{av}. Source: own work.

Therefore, in sustainable redesigning of urban streets and public spaces, which may include setting up home zones, it is important to select the appropriate traffic calming measures and use appropriate design parameters, matching the existing streetscape features, as the resulting speed reductions have a considerable bearing on the noise and air pollution in the area [42]. These dependencies are related to the third of the research hypotheses, i.e., research Hypothesis H3. For sustainable home zone projects, it is therefore important to avoid sudden speed drops [42] and consider the range in impact of traffic calming measures when planning their locations [26,43–45]. Bearing this in mind, when analysing the speed reductions obtained for the analysed traffic circles, references were made to the results obtained by other researchers reporting similar speed reductions obtained with speed tables [22,43]. The different traffic calming measures (speed table and traffic circle) have different applications and, for example, speed tables are an option for places with a 30 km/h or 40 km/h desired speed, and thus they are not appropriate for home zones requiring reduction to lower speeds. With similar climbing phase characteristics, driving with these two traffic calming measures differs due to the inclined top surface in the case of traffic circles and the level surface in the case of speed tables. The literature does not, as yet give any experimental results comparing these two traffic calming measures in home zone applications. This being so, this article presents the results obtained on three one-way streets, including seven traffic circles having different central island transverse slopes.

4.5. Air Pollution in Three Traffic Scenarios—Research Hypothesis H3

The home zone speed recommendations differ between countries and guidelines, ranging from walking speed, as recommended by the Dutch guidelines [46], to 16 km/h in England [47], to 20 km/h in several other countries [30,33,48–51]. Therefore, air and traffic noise pollution estimations were based on the data obtained for driving through speed tables at speeds in the range of 10–30 km/h [22,43]. Considering the driving speeds measured between the junctions, which also did not exceed the specified speed range (Figures 15 and 16), we can conclude that the analysed traffic circles did not cause abrupt accelerations and decelerations that could be considered undesired due to the impact on the surrounding environment, as per [18,22,43,52]. The level of air pollution was estimated by comparing the three scenarios analysed in this article, using for comparison the research data published by Merkisz et al. [22]. In the first scenario, a vehicle drove through a home zone traffic circle in summer at an almost steady speed of 8–10 km/h, as shown in Figure 15. The second scenario concerned the speeds logged in the home zone September survey, as shown in Figure 16, varying over a considerably wider range of 10–25 km/h. The third scenario was added for comparison, in order to demonstrate the traffic circle's effectiveness as a home zone traffic calming measure TCM. The simulated air pollution in the 30 km/h zone was based on the assumption that the raised central island of the traffic circle causes a speed reduction corresponding to that determined during the home zone traffic survey of September. On the sections between the traffic circles, driving speeds were assumed to vary between 25 and 30 km/h. The air pollution results for these three scenarios are given in Figure 19 below, broken down into carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxide (NO_x) and hydrocarbons (HC).

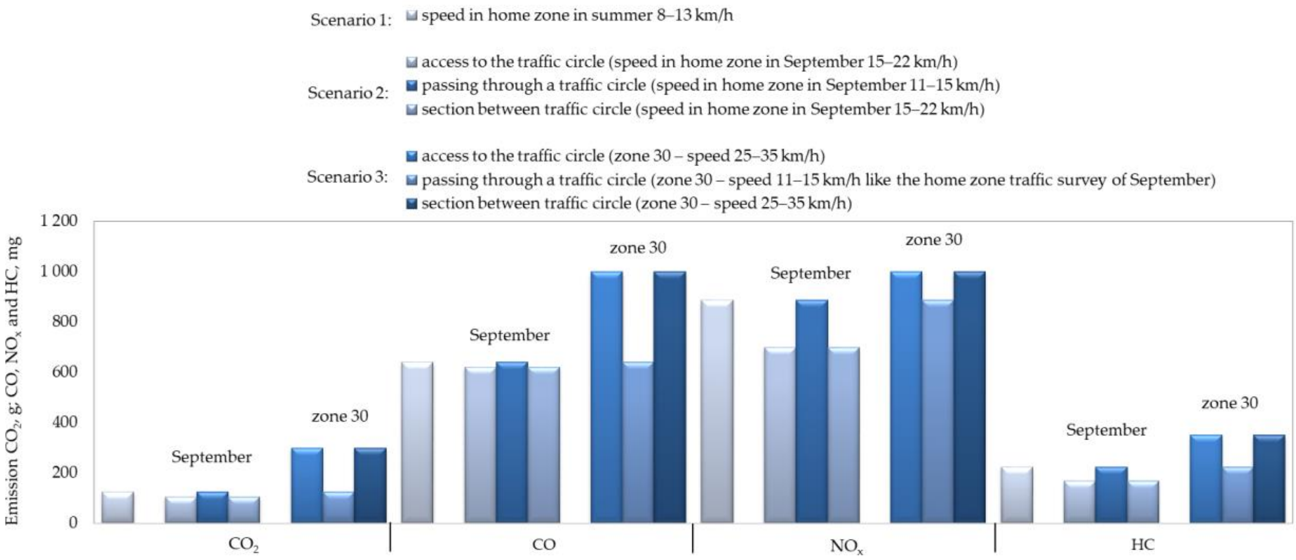


Figure 19. Air pollution in the three main street driving scenarios. Source: own work.

The analysis of the home zone data given in Figure 19 and the 30 km/h zone simulated data showed that the traffic circle related air pollution may be higher in the 30 km/h zone than in a home zone. Comparing the home zone air pollution data in summer and in September, it is justified to conclude that carbon dioxide and carbon monoxide pollution along the street does not differ between the summer and September despite different driving speeds recorded in these periods, due to an almost steady speed in summer of about 8–10 km/h (Figures 12 and 15). The levels of nitrogen oxides and hydrocarbons were, in turn, different in the home zone under analysis. That said, the level of air pollution will be definitely lower in summer due to steadier driving speeds.

4.6. Fuel Consumption in Three Traffic Scenarios

Sudden speed variations would also influence fuel consumption. However, with the short distances between the subsequent traffic circles and small driving speed variations on the way, and with steady speeds of 8–10 km/h due to pedestrian traffic, we can expect drivers to shift to second gear. In September, the driving speeds ranged from 20 to 25 km/h, depending on the number of pedestrians, decreasing only right at the traffic circle. Some drivers drove in third gear, thus reducing fuel consumption. However, almost all the interviewed drivers confirmed shifting to second gear on the approach to the traffic circle. Considering the short distances of travel through the analysed streets and using the mean fuel consumption data in litres/100 km depending on gear, as given in [53], we may expect only very slight differences in fuel consumption. For example, travelling at 8–10 km/h in second gear in summer, the car would use about 0.043 litres of petrol to reach the end of the street, and in September this amount would drop to 0.033 litres due to using third gear, with 20–25 km/h travel speeds practicable on this section. However, if a 30 km/h zone were implemented in this street, a car would use 0.035 litres of petrol driving between the traffic circles in third gear at 25–30 km/h.

The comparisons performed as part of this study, covering pedestrian safety (especially in summer), reduction in driving speed, air pollution and fuel consumption, indicate the suitability of the traffic circle as an effective and economic traffic calming measure for use in home zone applications.

5. Conclusions

The following conclusions may be drawn based on the results of the above-described analyses:

- The traffic calming effect and the amount of speed reduction due to traffic circles depend, to a large extent, on the height of the raised central island Δh. The resulting values of R^2 (v_{85}) = 0.85 and R^2 (v_{av}) = 0.72 indicate that 85% or 72% of the dependent variable variation (v_{85}, v_{av}) may be explained by a relationship with the independent variable (Δh). Now, the remaining 15% or 28% of the variability should be attributed to the effect of other relevant factors (traffic circle location, place in the sequence, street function and the surrounding streetscape features), and other random factors.
- The transverse slope of the central island should be determined in a prior analytical study and implemented in the home zone design, taking into account the following factors:
    - travel lane width,
    - distance between the start and end of the on-street parallel parking spaces and the side street edge,
    - spacing distance between subsequent traffic circles,
    - the surrounding features, such as the locations and opening hours of markets, restaurants and public amenities throughout all seasons of the year.
- The research findings and verification of the formulated research hypotheses show that, for main promenades lined with many retail outlets (seasonal, generating high pedestrian traffic in summer) in home zones located in spa villages, Δh values should be moderate, i.e., max. 8–10 cm. This value may be increased to max. 11–12 cm in other streets with smaller pedestrian traffic and a smaller number of retail businesses and other outlets. In turn, much greater Δh values should be applied in primarily vehicular streets that are not lined with retail businesses or other outlets and have much lighter pedestrian traffic. These higher values of Δh recommended for the above-described type of street may, for example, ranging from 17–19 cm when, past the traffic circle, the street runs for another 150 m or more. For shorter remaining street lengths, such as 50–100 m, Δh should preferably range between 14–16 cm.
- When the traffic calming areas are designed in line with sustainability principles, allowing for extensive use of the carriageway space by pedestrian traffic, as is the case

in this article, one-way traffic should be the first option, and green street/infrastructure components should be used, as far as practicable, for beautification reasons.

- In order to prevent exceeding of the desired speed range on the sections between traffic circles, encouraged by a lack of vehicles parked on the street, fixed-type side obstacles should be designed at the beginning and end of such sections. These obstacles include flowerbeds, planters, and concrete or wooden tree boxes, as shown in Figure A1 in Appendix A.
- Finally, the authors believe that the issue of increased fuel consumption due to driving in lower gears in traffic calmed areas, such as home zones, may be effectively resolved by the global transition to electric vehicles and sustainable design of traffic calming projects.

There are a few limitations that affect this study. One example concerns the speeds in the September traffic survey, which are defined by driving habits typical of Polish drivers and Polish traffic rules. Thus, slightly different speeds may be obtained in research projects carried out in other countries. Fuel consumption estimates in this project were also based on geographically specific French data and different estimates may be obtained with input data typical of other locations.

Author Contributions: Conceptualization, S.M. and A.S.; methodology, S.M. and A.S.; software, S.M.; formal analysis, S.M. and A.S.; data curation, S.M. and A.S.; writing—original draft preparation, S.M. and A.S.; writing—review and editing, S.M. and A.S.; visualization, S.M. and A.S.; supervision, S.M.; project administration, S.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

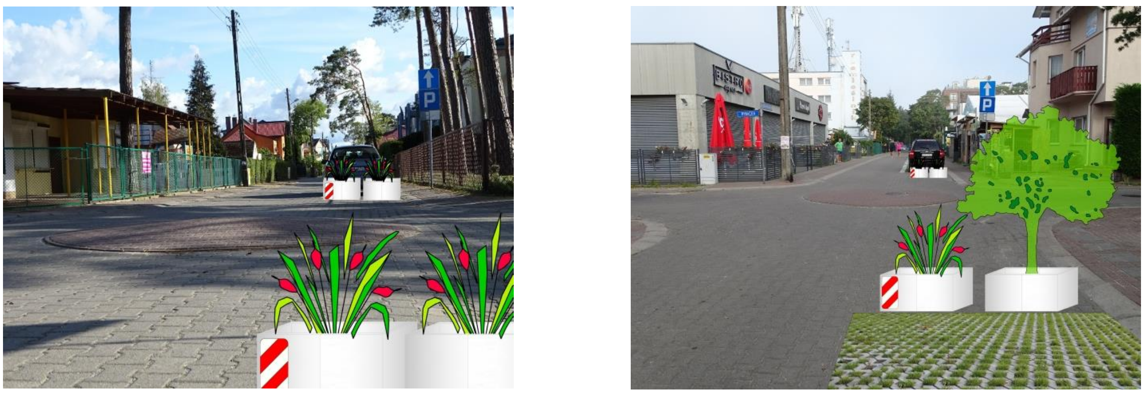
Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in the article.

Acknowledgments: The authors would like to thank Marcin Jóźwiak and the employees of the Public Roads Authority in Kamień Pomorski for their assistance during the traffic surveys carried out as part of this study and for providing us with the information on the home zone conversion project in Międzywodzie.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A



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

Figure A1. Visualization of the proposed traffic safety improvement measures using green infrastructure components suitable for home zone applications: (**a**) tree boxes with appropriately selected species used as side obstacles (greenery resistant to drought, frost, exhaust emissions); (**b**) side obstacles with appropriate grafted tree species. Source: own work.

References

1. Horn, B.E.; Jansson, A.H.H. Traffic safety and environment: Conflict or integration. *Int. Assoc. Traffic Saf. Sci. IATSS Res.* **2000**, *24*, 21–29.
2. Boglietti, S.; Tiboni, M. Analyzing the criticalities of public spaces to promote sustainable mobility, XXV International Conference Living and Walking in Cities—New scenarios for safe mobility in urban areas (LWC 2021), 9-10 September 2021, Brescia, Italy. *Transp. Res. Procedia* **2022**, *60*, 172–179. [CrossRef]
3. Paszkowski, Z. *Miasto Idealne w Perspektywie Europejskiej z jego Związki z Urbanistyką Współczesną*; Towarzystwo Autorów i Wydawców Prac Naukowych UNIVERSITAS: Kraków, Poland, 2011. (In Polish)
4. Paszkowski, Z. *Historia Idei Miasta od Antyku do Renesansu*; Zachodniopomorski Uniwersytet Technologiczny w Szczecinie: Szczecin, Poland, 2015. (In Polish)
5. Google Earth. Available online: http://www.earth.google.com (accessed on 2 September 2023).
6. Mell, I.; Clement, S. Progressing Green Infrastructure planning: Understanding its scalar, temporal, geo-spatial and disciplinary evolution. *Impact Assess. Proj. Apprais.* **2020**, *38*, 449–463. [CrossRef]
7. Meerow, S. A green infrastructure spatial planning model for evaluating ecosystem service tradeoffs and synergies across three coastal megacities. *Environ. Res. Lett.* **2019**, *14*, 125011. [CrossRef]
8. Learn about Green Streets. Available online: https://www.epa.gov/G3/learn-about-green-streets (accessed on 18 July 2023).
9. *Green Streets, Residential Streets Commercial Streets Arterial Streets Alleys. A Conceptual Guide to Effective Design Solutions*; United States Enviromental Ptotection Agency US EPA Region 3: Philadelphia, PA, USA, 2009. Available online: https://nepis.epa.gov/Exe/ZyPDF.cgi/P10059Y4.PDF?Dockey=P10059Y4.PDF (accessed on 18 July 2023).
10. WHO. *Pedestrian Safety: A Road Safety Manual for Decision-Makers and Practitioners*; WHO: Geneva, Switzerland, 2013.
11. Slootmans, F. *European Road Safety Observatory Facts and Figures—Pedestrians*; European Commission, Directorate General for Transport: Brussels, Belgium, 2021. Available online: https://road-safety.transport.ec.europa.eu/system/files/2023-02/ff_pedestrians_20230213.pdf (accessed on 18 July 2023).
12. Slootmans, F. *European Road Safety Observatory Facts and Figures—Urban Areas*; European Commission, Directorate General for Transport: Brussels, Belgium, 2022. Available online: https://road-safety.transport.ec.europa.eu/system/files/2022-07/ff_roads_inside_urban_areas_20220707.pdf (accessed on 18 July 2023).
13. Bigazzi, A.Y.; Rouleau, M. Can traffic management strategies improve urban air quality? A review of the evidence. *J. Transp. Health* **2017**, *7*, 111–124. [CrossRef]
14. Harris, G.J.; Stait, R.E.; Abbott, P.G.; Watts, G.R. *Traffic Calming: Vehicle Generated Noise and Ground-Borne Vibration Alongside Sinusoidal, Round-Top and Flat-Top Road Humps*; TRL Report 416; Transport Research Laboratory: Crowthorne, Berkshire, UK, 1999. Available online: https://trl.co.uk/uploads/trl/documents/TRL416.pdf (accessed on 18 July 2023).
15. Lu, X.; Kang, J.; Zhu, P.; Cai, J.; Fei Guo, F.; Zhang, Y. Influence of urban road characteristics on traffic noise. *Transp. Res. Part D Transp. Environ.* **2019**, *75*, 136–155. [CrossRef]
16. McAlexander, T.P.; Gershon, R.R.; Neitzel, R.L. Street-level noise in an urban setting: Assessment and contribution to personal exposure. *Environ. Health* **2015**, *14*, 18. [CrossRef]
17. Ahn, K.; Rakha, H. A field evaluation case study of the environmental and energy impacts of traffic calming. *Transp. Res. Part D Transp. Environ.* **2009**, *14*, 411–424. [CrossRef]
18. Yang, X.; McCoy, E.; Hough, K.; de Nazelle, A. Evaluation of low traffic neighbourhood (LTN) impacts on NO_2 and traffic. *Transp. Res. Part D Transp. Environ.* **2022**, *113*, 103536. [CrossRef]
19. Cloke, J.; Boulter, P.; Davies, G.P.; Hickman, A.J.; Layfield, R.E.; McCrae, I.S.; Nelson, P.M. *Traffic Management and Air Quality Research Programme*; TRL Report 327;Transport Research Laboratory: Crowthorne, Berkshire, UK, 1998.
20. Vardoulakis, S.; Kettle, R.; Cosford, P.; Lincoln, P.; Holgate, S.; Grigg, J.; Kelly, F.; Pencheon, D. Local action on outdoor air pollution to improve public health. *Int. J. Public Health* **2018**, *63*, 557–565. [CrossRef] [PubMed]
21. Burns, J.; Boogaard, H.; Polus, S.; Pfadenhauer, L.M.; Rohwer, A.C.; van Erp, A.M.; Turley, R.; Rehfues, E.A. Interventions to reduce ambient air pollution and their effects on health: An abridged Cochrane systematic review. *Environ. Int.* **2020**, *135*, 105400. [CrossRef]
22. Merkisz, J.; Pielucha, J.; Fuć, P.; Nowak, M. Assessment of vehicle emission indicators for diverse urban microinfrastructure. *Combust. Engines* **2013**, *154*, 787–793.
23. Kuss, P.; Nicholas, K.A. A dozen effective interventions to reduce car use in European cities: Lessons learned from a meta-analysis and transition management. *Case Stud. Transp. Policy* **2022**, *10*, 1494–1513. [CrossRef]
24. Mass Hingway. *Traffic Calming and Traffic Management, Chapter 16*; Mass Hingway: Winchester, MA, USA, 2006. Available online: https://www.winchester.us/DocumentCenter/View/4073/MassDOT-Traffic-Calming-and-Traffic-Management (accessed on 18 July 2023).
25. *Traffic Calming Guidelines Chapter 6*; Devon County Council, Engineering and Planning Department: Devon, UK, 1995.
26. *Roads Development Guide*; East Ayrshire, Strathclyde Regional Council London: Kilmarnock, UK, 2010.
27. *Traffic Calming, Local Transport Note 1/07*; Department for Regional Development (Northern Ireland): Newry, Ireland; Scottish Executives, Welsh Assembly Government: London, UK, 2007.
28. Webster, P. *Traffic Calming—Design Guide, Nottinghamshire County Council*; Department for Transport: Nottingham, UK, 2004.

29. OMGEVING cvba. *IPOD, Richtlijnen, Dimensioneringen, Statuten en Checklist Voor het Openbaar Domein in Gent*; OMGEVING cvba: Berchem-Antwerpia, The Neterlands, 2011.
30. *Vejdirektoratet, Urban Traffic Areas—Part 7—Speed Reducers*; Vejdirektoratet-Vejregeludvalget: Copenhagen, Denmark, 1991.
31. Lárus, Á.L. *Techniques of Speed Reduction—Danish Experiences*; ICTCT International Co-operation on Theories and Concepts in Traffic Safety No. 277/99; ICTCT: Copenhagen, Denmark, 1999.
32. *Traffic Calming Guidelines TCG*; Devon County Council, Engineering and Planning Department: Devon, UK, 1991.
33. *Directives for the Design of Urban Roads*; RASt 06; Road and Transportation Research Association (FGSV): Köln, Germany, 2006.
34. Ignaccolo, M.; Zampino, S.; Maternini, G.; Tiboni, M.; Leonardi, S.; Inturri, G.; Le Pira, M.; Elena Cocuzza, E.; Distefano, N.; Giuffrida, N.; et al. How to redesign urbanized arterial roads? The case of Italian small cities. In Proceedings of the XXV International Conference Living and Walking in Cities—New scenarios for Safe Mobility in Urban Areas (LWC 2021), Brescia, Italy, 9–10 September 2021. [CrossRef]
35. Are Roundabouts and Traffic Circles the Same? The Answer Might Surprise You. Available online: https://www.motorbiscuit.com/roundabouts-traffic-circles-same-answer-surprise (accessed on 18 July 2023).
36. Traffic Circles and Roundabouts. Available online: https://www.surrey.ca/services-payments/parking-streets-transportation/roads-in-surrey/traffic-circles-and-roundabouts (accessed on 18 July 2023).
37. Melton, L.; Shumard, D. *Mini Roundabouts and Neighborhood Traffic Circles*; NCTCOG Public Works Roundup, City Council Regular Meeting: Burleson, TX, USA, 21 May 2019. Available online: https://www.nctcog.org/getmedia/57bdd772-1d6b-4d1f-a344-94ab249ec392/2019PWR-MiniRAB-FINAL.pdf (accessed on 18 July 2022).
38. Rao, P.S.N.; Bhagwati, S.; Satish Khanna, S. *City Level Projects: Street Design Guidelines*; Delhi Urban Art Commission: Delhi, India, 2020.
39. System Ewidencji Wypadków i Kolizji. Available online: https://sewik.pl/ (accessed on 18 July 2023).
40. *Speed Displays Traffic Detection, Radar, Detection, Software*; Vitronic: Kędzierzyn Koźle, Poland, 2015.
41. Transportation Research Board Highway. *Capacity Manual HCM 2000*; Transportation Research Board TRB: Washington, DC, USA, 2000.
42. Künzler, P.; Dietiker, J.; Steiner, R. *Nachhaltige Gestaltung von Verkehrsräumen im Siedlungsbereich, Grundlagen für Planung, Bau und Reparatur von Verkehrsräumen*; Herausgegeben vom Bundesamt für Umwelt BAFU: Bern, Switzerland, 2011. Available online: https://www.bafu.admin.ch/dam/bafu/de/dokumente/luft/uw-umwelt-wissen/nachhaltige_gestaltungvonverkehrsraeumenimsiedlungsbereich.pdf (accessed on 12 August 2023).
43. Faheem, H. Suitability of existing traffic calming measures for use on some highways in Egypt. In Proceedings of the 9th International Conference on Civil and Architecture Engineering, Cairo, Egypt, 29–31 May 2012. Available online: https://iccae.journals.ekb.eg/article_44388.html (accessed on 2 September 2023). [CrossRef]
44. Wirksamkeit Geschwindigkeitsdämpfender Maßnahmen Außerorts; Hessisches Landesamt für Straßen-und Verkehrswesen: Hessen, Germany. 1997. Available online: https://docplayer.org/57666796-Wirksamkeit-geschwindigkeitsdaempfender-massnahmen.html (accessed on 2 August 2020).
45. Distefano, N.; Leonardi, S. Evaluation of the benefits of traffic calming on vehicle speed reduction. *Civ. Eng. Archit.* **2019**, *7*, 200–214. [CrossRef]
46. Centre for Research and Contract Standardization in Civil Engineering (CROW). *Recommendations for Traffic Provisions in Built-Up Areas: ASVV*; CROW: Ede, The Netherlands, 1998.
47. Department for Transport (DfT). *Home Zones: Challenging the Future of Our Street*; Department for Transport (DfT): London, UK, 2005.
48. Gharehbaglou, M.; Khajeh-Saeed, F. Woonerf: A Study of Urban Landscape Components on Living Streets. *MANZAR* **2018**, *10*, 40–49. [CrossRef]
49. Van den Boomen, T. Wed Met de Regels! Het Nieuwe Woonerf (Away with the Rules! he New Woonerf). *NCR Handelsblad* **2002**, *5*.
50. Collarte, N. The Woonerf Concept. Rethinking a Residential Street in Somerville, Master of Arts in Urban and Environmental Policy and Planning MA (857), Tufts University, 7 December 2012. Available online: https://docplayer.net/35878575-The-woonerf-concept-rethinking-a-residential-street-in-somerville-natalia-collarte-60-wadsworth-street-apt-12h-cambridge-ma-857.html (accessed on 18 July 2023).
51. Clayden, A.; McKay, K.; Wild, A. Improving residential liveability in the UK: Home zones and alternative approaches. *J. Urban Des.* **2006**, *11*, 55–71. [CrossRef]
52. Pérez-Acebo, H.; Ziółkowski, R.; Linares-Unamunzaga, A.; Gonzalo-Orden, H. A Series of Vertical Deflections, a Promising Traffic Calming Measure: Analysis and Recommendations for Spacing. *Appl. Sci.* **2020**, *10*, 3368. [CrossRef]
53. Nina67. Consommation D'essence en Fonction de Vitesse et Rapport, Astuces-Pratiques; Article of 23 July 2015. Available online: https://www.astuces-pratiques.fr/auto-moto/consommation-d-essence-en-fonction-de-vitesse-et-rapport (accessed on 12 August 2023).