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Article

Design of Turbo-Roundabouts Based on the Rules of Vehicle Movement Geometry on Curvilinear Approaches

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Abstract: The construction of turbo-roundabouts is an increasingly frequent choice when it comes to improving flow capacity and traffic safety at road intersections. The existing design guidelines, as a rule, give parameters for turbo-roundabouts with approaches set at right angles to each other. The article presents turbo-roundabout design methods, taking into account swept path analyses of the chosen design vehicles when the approach legs are curvilinear and oriented to each other at a non-right angle. Based on the analysis of three different design vehicles, it was proven that their swept paths have a major influence on the geometrical parameters of the roundabout and, consequently, on the land take area, i.e., they can significantly impact the project's construction costs. In the case of curvilinear approaches, which are oriented to each other at a non-right angle, it is impossible to impose on the designer specific values of the circulatory lane widths and the entry and exit curve radii as they depend primarily on the chosen design vehicle. The aim of the article was to demonstrate that in the case of the curvilinear approach on the Basic type turbo-roundabout, the design process should include the swept path analysis for the chosen design vehicle for each of the approaches. This should lead to the design of wider swept paths and higher curve lane divider entry and exit radii.

Keywords: turbo-roundabout; raised separation lane; swept path; curvilinear approaches; fastest-path speeds

Citation: Sołowczuk, A.B.; Benedysiuk, W. Design of Turbo-Roundabouts Based on the Rules of Vehicle Movement Geometry on Curvilinear Approaches. *Sustainability* **2023**, *15*, 13882. https://doi.org/10.3390/su151813882

Academic Editors: Elżbieta Macioszek, Anna Granà, Tullio Giuffrè and Tomaž Tollazzi

Received: 26 June 2023
Revised: 24 August 2023
Accepted: 13 September 2023
Published: 18 September 2023

1. Introduction

At the end of the twentieth century in the Netherlands [1,2], the circular traffic intersections problem was given close attention, and as a result, turbo-roundabouts were proposed to ensure greater traffic safety and capacity at these junctions. Within a span of a dozen-plus years, tens of turbo-roundabouts were built in the Netherlands [3], and the first turbo-roundabout design guidelines were developed in the early 2000s [4,5]. In the following years, design guidelines for turbo-roundabouts were also developed in other countries. An overview of the geometric design guidelines for turbo-roundabouts is presented in Table 1. The completed turbo-roundabouts became a subject of research work to examine their performance in terms of traffic safety and capacity. A number of publications tackled the problem of turbo-roundabout staking, necessity of widening the circulatory lanes, increasing the entry and exit radii as well as changing separator island locations. A summary of the design recommendations describing this problem is given in Table 1.

Table 1. An overview of the geometric design guidelines for turbo-roundabouts.

Country, Year	Brief Overview of Recommendations in Selected Guidelines and Scientific Studies
Basic guidelines and studies for turbo-roundabouts with approaches oriented perpendicular to each other	
South Africa [6] 2007, Netherlands [4] 2008, Netherlands [5] 2009, Netherlands [7] 2009, Italy [8] 2012, Netherlands [1] 2013, Portugal [9] 2013, Netherlands [10] 2015, Switzerland [11] 2022	Basic types of turbo-roundabouts are defined, and step-by-step design principles are given. Three types of roundabouts were distinguished based on the traffic design used at the roundabout [4]: classic turbo-roundabouts (with a physical lane separation with raised curbs and meeting four basic design criteria), partial turbo-roundabouts (which do not meet any of the four design principles applicable to classic turbo-roundabouts) and the look-a-like type roundabouts (roundabouts on which lane separation is achieved only with the use of road markings). Later publications [10] also allowed roundabouts with fewer streamlined elements and special shape roundabouts, e.g., with a single exit lane and two or three circulating lanes. In addition, two basic assumptions were formulated: First—approaches to the roundabout should be oriented perpendicular to each other; second—passenger cars cannot pass through the raised separation lane and the truck apron. The truck apron may be a maximum of 5 m wide and can be overrun by vehicles longer than 22 m, negotiating the roundabout in the inner lane. The use of a lane raised separation lane, 0.7 m or 1 m wide, and the use of separator islands. A method was developed for staking a turbo-roundabout based on an Archimedes spiral and plotting incremental radii of arcs from selected points on the translation axis offset from the main axes of the main approaches by angles of 30° or 60°, depending on the type of roundabout. The recommendations did not include analysing the simultaneous movement of design vehicles in adjacent circulatory lanes on the roundabout. However, it was recommended to check the possible speed of a passenger car through the roundabout when moving along the so-called fastest vehicle path. The guidelines [11] assumed a length of 15.5 m for the design vehicle and the use of mountable aprons where necessary and later adopted a length of 16.5 m [10], as recommended in the 2012 European Directive [12].
US [13] 2000, US [14] 2010, Germany [15] 2015, US [16] 2019, UK [17] 2020	It was recommended that conventional multi-lane roundabouts should use spiral traffic rules that mimic the traffic at conventional turbo-roundabouts, bearing in mind the safety of motorcyclists, without the need for a raised separation lane, i.e., look-a-like type roundabouts were recommended. Various types of road markings were introduced on the circulatory carriageway, taking into account the characteristics of the horizontal road markings used in each country. The guidelines did not indicate that roundabout approaches should be designed at a right angle to each other, but in all the examples illustrating roundabouts, the roundabout approaches were oriented to each other at right angles. It was recommended that swept paths of design vehicles should not encroach into the adjacent lanes. In addition, it was recommended that the design speed on the roundabout should be determined depending on the value of the roundabout path radius, the coefficient of adhesion and the transverse gradient on the circulatory carriageway.
Slovenia [18] 2008, Slovenia [19], 2011 Slovenia [20] 2015, Slovenia [21] 2016	No detailed recommendations regarding the location and geometry of roundabout approaches were given in the guidelines. However, in the provided illustrations of completed roundabout projects, in many cases and especially in built-up areas, curved approaches intersecting at other than perpendicular angles were depicted. Numerous modifications of the shape of the central island of the roundabout were proposed, introducing, for instance, a central island circular or elliptical. In addition, the use of variable widths of the truck apron of the roundabout was recommended, achieving different versions of its “flattening” so that it could be used in traffic layouts constrained in terms of available area. The innovative solution proposed for the central island with variable width also provides a good basis for the design process, as it allows for designing roundabouts under very territorially constrained urban conditions, which can contribute to increasing traffic safety and capacity. A different method of staking four-approach roundabouts was developed due to the suggested different position of the translation axis, located along the axes of the main approaches and not, as recommended in the Dutch guidelines [5], in the clockwise direction “at five to five”. Other shapes of splitter islands were also proposed, and it was permitted to position the approaches to each other at angles deviating by 5–10° from right angles.
Poland [22] 2022, Poland [23] 2022	Roundabouts with raised separation lanes and roundabouts with nothing but road markings on the circulatory carriageway were permitted. If a raised separation lane was planned for the roundabout, a different shape of a separator island was proposed, and a 0.6 m-wide separation lane was recommended. In addition, it was recommended that the existing conventional two-lane roundabouts should be converted to turbo-roundabouts with two uniform half-rings (truck apron) of 1–2.5 m width each. Traffic of design vehicles was allowed on this truck apron. Greater ring widths were only allowed in cases where passing over the separation lane in emergency situations is not possible. The spiral movement provides a shift of half of the existing conventional two-lane roundabout with respect to the translation axis aligned with that of the opposite main approaches. The offset of the half-rings (truck apron) was recommended to be equal to the width of the outer circulatory lane and half the width of the separation lane.

Table 1. *Cont.*

Country, Year	Brief Overview of Recommendations in Selected Guidelines and Scientific Studies
Design of a turbo-roundabout based on the analysis of vehicle swept path on the circulatory carriageway.	
New Zealand [24] 2012	Considering the length of the design vehicles of 17.9 m (with a four-axle semitrailer), adjustments to the location of the separator island on the roundabout carriageway were proposed. The design recommendations allowed encroachment on the traversable separator island and on the truck apron of the roundabout during left-turning movement. Swept paths were also analysed for a simultaneous passage of design vehicles in both lanes during straight-ahead movements and during the combination of a left turn and straight-ahead movement. However, simultaneous straight and right turn movements were excluded from the analyses, as the vehicle entering the inner lane would overrun the traversable separator island as assumed.
US [25] 2014	The authors of the research study under description mainly analysed look-a-like roundabouts and referred to them as multi-lane roundabouts with spiral transitions. On roundabouts designed according to the parameters recommended in the Dutch guidelines [5], required lane widths were analysed for three different design vehicles adopted: a heavy goods vehicle of 9.14 m length, a bus of 12.36 m length and a semitrailer tractor of 15.5 m length. A 0.30 m-wide lane divider between driving lanes was included in the analyses by analogy to the width of the raised curb recommended in the Dutch guidelines [5]. In accordance with guidelines [26], the distance between the edge of the swept path envelope and the face of the curb was also assumed to be 0.3 m. In addition, the notion of "opening width" was introduced, which was directly related to the widened circulatory lanes that were being analysed. For four sizes of roundabouts (mini, small, medium and large), the publication analysed the circulatory lane widths accommodating the swept paths of the three aforementioned design vehicles on the Basic, Egg and Knee turbo-roundabouts. The research study results obtained demonstrated a close relationship between the swept path of a specific design vehicle and the width of the circulatory lanes, and it was recommended that the geometric design of a turbo-roundabout should take into account the actual design vehicles travelling on the roundabout.
Design of a turbo-roundabout based on an analysis of the swept paths on the approaches and on the circulatory carriageway of the roundabout.	
Serbia [27] 2012, Croatia [28] 2014, Croatia [29] 2016, Croatia [30] 2017	The publications consider Croatian and Serbian road marking rules and assume the width of both strips of 0.5 m instead of the 0.45 m width proposed by the Dutch guidelines [5]. The Serbian [27] and Croatian [28] guidelines recommend a width from 2.0 m up to 2.5 m for the truck apron and allow special emergency vehicles and regular vehicles to stop on it only in emergencies. Different dimensions and designs of the separator island were introduced. Publication [29] analyses different locations of the separator island in terms of accommodation of the swept paths of the design vehicles (of 16.5 m length with a three-axle semitrailer) and shows some inaccuracies in the staking of the truck apron of the roundabout and the resulting staking errors of up to 5 cm. Based on an analysis of the swept paths of the adopted design vehicles, revised parameters of the turbo block were proposed, depending on the type of roundabout and the adopted exit diameter, and much larger roundabout entry and exit radii, instead of the 12 m radii proposed in the Dutch guidelines [5].
Czech Republic [31] 2015, Czech Republic [32] 2017, Czech Republic [33] 2021	Various country-specific designs of turbo-roundabouts were taken into account, with a particular focus on roundabout entry conditions. The analyses primarily considered the geometric layout of the turbo-roundabout elements (the shape of the turbo-roundabout, separation lane and separator islands) that ensure physical separation of the traffic on the circulatory lanes and effectiveness of the proposed innovative changes to the entry section (e.g., the use of basket arcs), compared to the recommendations of the design guidelines in force in other countries. In addition, it was allowed, given insufficient traffic lane widths, for the driving corridor of a long design vehicle to partially encroach into the adjacent lane. Based on an analysis of the swept paths of the adopted design vehicles, it was proposed to use the following: Corrected turbo block parameters, depending on the type of roundabout and input diameter adopted; Basket curves with radii between 25 and 33 m at the entry and exit of the roundabout instead of the 12 m radii proposed in the Dutch guidelines [5].
Croatia [34] 2020	Conclusions from previous studies [29,30] demonstrated that existing roundabout design procedures, in which trajectory analyses are carried out at the end of the design process, contain some flaws and understatements that can lead to unsatisfactory roundabout geometries, low capacity, little improvement in traffic safety, poor driving comfort and high construction costs. For the hypothetically formulated new design proposals, in situ verification studies were conducted to confirm the initial hypotheses.

From the literature review given in Table 1, it is apparent that the staking of turbo-roundabout geometry should be closely linked to the swept paths of the design vehicles (DV). Still, not every roundabout needs to accommodate the largest DVs circulating in the country, but it should accommodate the DVs predicted to travel through this particular roundabout. The studies described in the report [35,36] show that the edges of the vehicle body and tyre tracks of the analysed DVs can affect various areas of the roundabout geometry. More attention should be paid to the analysis of the swept paths of the adopted DVs, taking the above into account in the roundabout design process. For instance, in Europe, on the basis of the European Directive [12], a two-axle tractor unit with a three-axle semitrailer with an overall length of 16.5 m should be accepted as the design vehicle. However, in Croatia, other longer DVs are also permitted, and for this reason, a different DV, a three-axle tractor unit with a three-axle semitrailer is recommended in the Croatian Design Guidelines [28]. Additionally, in Scandinavian countries, other longest DVs are allowed on designated roads according to [37]: in Norway—17.5 m, in Denmark and Iceland—18.75 m, in Finland—23 m and in Sweden—24 m. Other DV lengths are also recommended in the US [25] and New Zealand [24]. Taking into account the above given different DV lengths, when designing a turbo-roundabout, its individual elements should be determined on the basis of an analysis of the swept paths of the DVs anticipated for traffic in the location/region. The optimum geometric design of the roundabout will then be achieved and safe passage of the DV through the roundabout will be ensured. However, all the existing design guidelines listed in Table 1 [5,15,16,19,24,27,28,32] apply to roundabouts with approaches oriented to each other at a right angle. Similar comments can be noted with regard to the publications shown in Table 1, concerning the analysis of the driving corridors of selected design vehicles and, consequently, the lane widths of the turbo-roundabout and the entry and exit radii [24,25,29,30,33,34].

The above literature review has shown that the existing design guidelines lack the information that shaping of turbo-roundabout geometry is also allowed in the case of curvilinear approaches oriented to each other at other than right angle. Such cases of "non-ideal" orientation of approaches are not uncommon or unusual in design practice. In fact, it could be argued that cases of curvilinear approaches oriented to each other at other than right angles are fairly common in design practice.

This article presents a case study of the design of a large *Basic* turbo-roundabout with a 0.7 m wide raised separation lane, with curvilinear approaches oriented to each other at an angle different than a right angle, taking the above into account. Based on the traffic surveys carried out, the two DVs recorded in the counts and the DV recommended in the European Directive [12] were selected, and their swept path analyses were performed. Section 3 describes the method of analysis for the design of roundabout geometry with reference to the roundabout parameters recommended in the Dutch guidelines [5], analysing the swept paths of the actual DVs predicted to move through the designed roundabout and the swept path of the DV recommended in [12] of approx. 16.5 m length. The next section discusses the results obtained and presents conclusions about the need for wider circulatory lanes and for larger entry and exit radii for turbo-roundabouts with curved approaches oriented to each other at a non-right angle, taking into account different design vehicles. The last section formulates conclusions as regards designing a turbo-roundabout with curvilinear approaches oriented to each other at a non-right angle.

2. Materials and Methods

2.1. Study Area

A road intersection on the outskirts of Szczecin, Poland (Figure 1), was selected for the analysis of the Basic roundabout design with curvilinear approaches oriented to each other at a non-right angle. The existing signalised intersection is a three-approach structure with the main approaches oriented west and east. Both these approaches are curvilinear, with roundabout exit lanes oriented at an acute angle to the side approaches. The south approach, currently a side one, has a very wide splitter island, as a high-speed tramway [38] was planned at the location in the future, and the island was to accommodate tramway stops for residents to be constructed in parallel with the development of residential areas over time. Because the current intersection does not have a north approach, this article assumes a case study analysis and proposes a north approach with an 8 m-wide splitter island in accordance with the current Polish design guidelines for conventional roundabouts [39]. Considering that most of the above-mentioned design guidelines for turbo-roundabouts assume the use of splitter island widths of 2–3 m [5,15,16,19,24,27,28,32] and taking into account the detailed swept path analyses described in [34], related to offsetting the roundabout entry lane relative to the approach axis, a roundabout with varying widths and different shapes of the splitter islands at each approach was chosen specifically for the analyses described in this article.

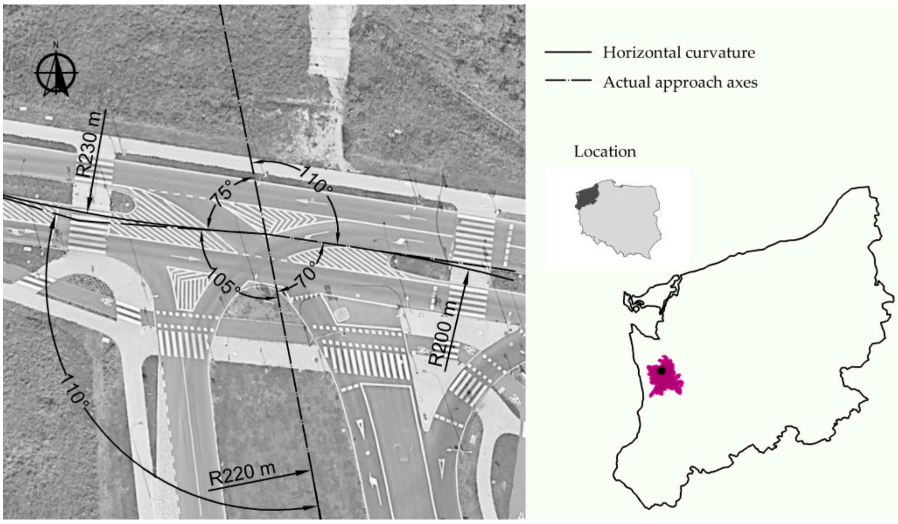


Figure 1. The alignment of the approach axes at the location selected for the described analyses of the proposed turbo-roundabout. Source: authors' elaboration against the background of the satellite photograph from z [40].

Considering the north–south direction of the planned dual carriageway, the north and south approaches were assumed to be the main ones for the purpose of analysing the turbo-roundabout geometry. The west and east approaches would be the side approaches. Furthermore, taking into account the parameters of the existing streets, it was assumed that a large turbo-roundabout of the *Basic* type with the parameters recommended in the Dutch guidelines [5] should be chosen for the analyses (Table 2).

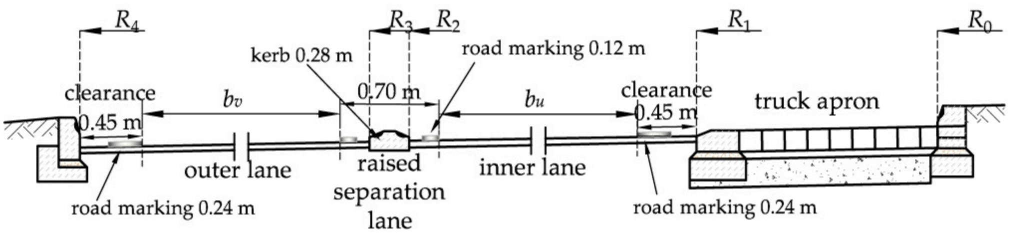


Figure 2. Lane widths and distances between edge lines in a turbo-roundabout. Source: own work.

Table 2. Standard design values for *Basic* turbo-roundabouts according to Dutch guidelines [5].

Main Elements of a Transverse Cross-Section of the Roundabout	Mathematical Designation	Radius and Measurement in m
Fastest path speed for a passenger car in km/h	v	40
Radii		
Inner radius of the inner lane	R_1	20.00
Outside radius of the inner lane	R_2	24.90 [1]
Inner radius of the outside lane	R_3	25.20 [2]
Outside radius of the outside lane	R_4	29.90
Curve lane divider entry	R_t	12
Curve lane divider exit	R_a	14
Widths		
Overrun area (truck apron) width ($R_1 - R_0$)		5.00
Raised separation lane between driving lanes		0.70
Width, inside lane	b_u	4.25
Width, outside lane	b_v	4.05
Shift of inner arc centres along the translation axis (stakeout: R_2, R_3, R_4)	Δv	5.15
Shift of outer arc centres along the translation axis (stakeout: R_0, R_1)	Δu	4.75

[1] In Poland—24.91 m (see Figure 2); [2] In Poland—25.19 m (see Figure 2).

The input design of the roundabout is shown in Figures 2 and 3. In Poland, the width of the road marking on the raised separation lane is 0.12 m, and the edge line width is 0.24 m. The width of the raised curb on the raised separation lane is 0.28 m. Figure 3 shows the initial staking scheme for the new Basic type turbo-roundabout prepared according to the parameters given in Table 2. In addition, the radii of the arcs set out from the four set-out points located on the translation axis are colour-coded in Figure 3.

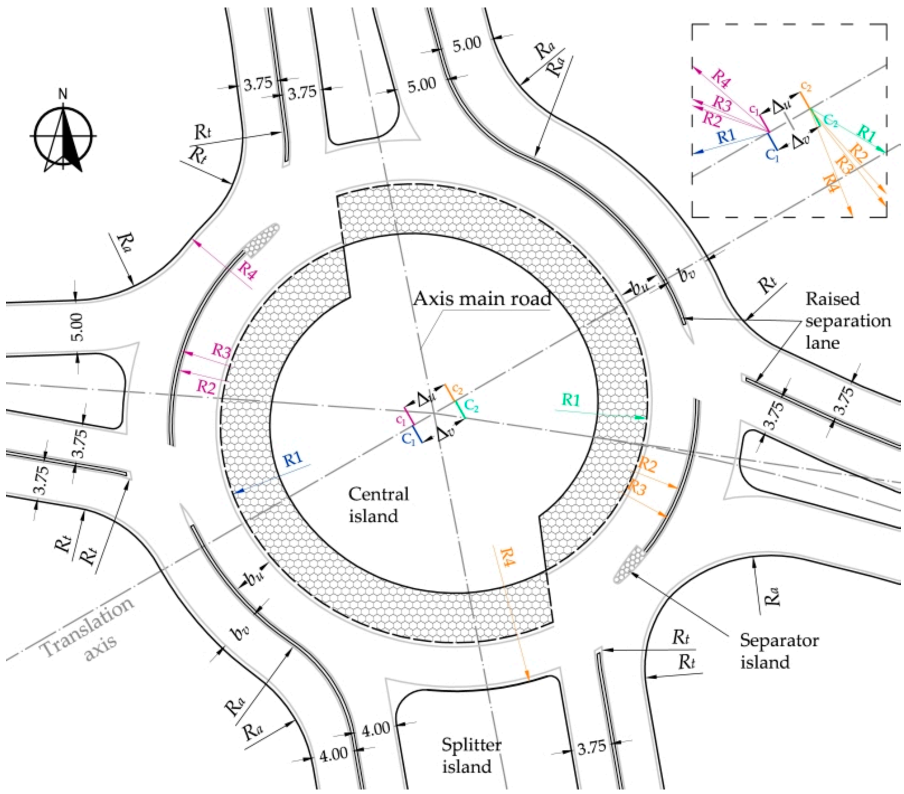


Figure 3. Turbo block of a standard turbo-roundabout *Basic* adjusted to the entries when the main traffic flow is north–south (units in m). Source: own work.

2.2. Design Vehicles and Swept Path

Selecting a design vehicle (DV) is an important element of the roundabout design. This can be done in a number of ways: (a)—adoption of the DV determined in the guideline documents applicable in a given country, (b)—at intersections to be converted into turbo-roundabouts, particularly in the suburbs, adoption of the DV predicted at the intersection in question based on traffic count results, or (c)—on planned new roundabouts, adoption of a DV appropriate for the intersecting streets or roads. On the intersection selected for the study described in this article, traffic surveys were carried out over a period of one week [41]. Based on the results of surveys performed, forecast traffic was estimated in a time horizon of 20 years. Traffic volumes on the planned fourth north approach were assumed to be the same as at the south approach. The results of the traffic volume forecast on the basis of the traffic surveys made are shown in Table 3.

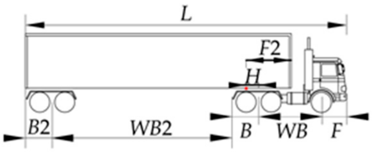
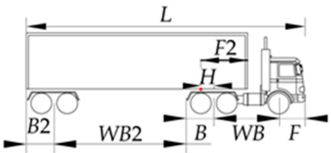
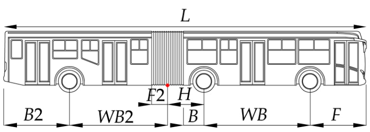
Table 3. Magnitude of estimated forecast traffic volumes. Source: own.

Approach	Volume of Traffic by Vehicle Category, veh./h					
	O	D	C	CP	A	Ap
North	683	28	–	2	–	22
South	683	28	–	2	–	22
Western	441	80	4	5	7	18
Eastern	630	19	8	5	7	18

Legend: O—passenger cars, D—commercial vehicles, C—heavy goods vehicles, CP—tractor-semitrailer units, A—buses, Ap—low-floor articulated buses.

The parameters of the design vehicles adopted for the analysis are shown in Table 4. When selecting DVs, the width of the vehicles was also taken into account, as it mainly affects swept path width. All DVs selected for analysis were 2.55 m wide, which is the width of vehicles recommended by the European Directive [12].

Table 4. Parameters of the selected DVs. Source: own elaboration—data based on the values of vehicle parameters included in the program Cad Tools [42] (units in m).

Design Vehicle Data	Vehicle Details									
	L	*MWTA* [1]	*MABS* [2]	*F*	*WB*	*B*	*WB2*	*B2*	*H*	*F2*
DV1 	16.76	17.7	70	0.91	3.81	1	10.82	1.22	0	0.91
DV2 	13.87	20.3	70	0.91	3.81	1	7.7	1.45	0	0.91
DV3 	17.967	38.3	50	2.65	5.95	1.2	2.997	3.37	3	0.8

[1] Max wheel turning angle, °. [2] Max angle between segments, °.

Just a few passages of tractors with two-axle semitrailers DV2 (13.87 m long) and dozens of passages of articulated buses DV3 were recorded during the survey period. The above-mentioned vehicles were assumed to be design vehicles for the intersection under consideration, taking this into account. However, given the mandatory importance of the analyses described here, for a turbo-roundabout in the general sense, the longer tractor-semitrailer unit recommended in the [12,22] was selected as the third design vehicle DV1. An analysis of the swept paths of the selected vehicles was carried out using the CadTools 1.1 software [42], in which a tractor with a two-axle semitrailer DV1 has a length of 16.76 m, which means it is slightly longer than the recommended length of 16.50 m [12,22].

Figure 4 shows the relevant elements of the swept path analysis for the selected DVs. Analysis of the swept path width shows that DV1 has the widest swept path at the same turning angle (Figure 4a). On the other hand, the analysis of vehicle trajectories reveals that the track of the right rear wheels of DV1 is most distant from the front wheel axis trajectory (Figure 4a), and the left trajectory of the DV3 envelope is most distant from the front wheel axis trajectory (Figure 4c), which is due to the articulated bus's largest front overhang length of all the DVs analysed, *F* = 2.65 m, in this case (Table 4). This is an important consideration in turbo-roundabout geometry design analyses, as some design guidelines recommend that bus sweat paths should not encroach on the truck apron, as overcoming the height difference at the curb can cause undesirable sensations and discomfort to passengers [29]. At the same time, it is allowed for bus wheels to overrun the separator island and mountable apron area, which is incomprehensible, as the recommended elevation of the part of the separator island is 7 cm [1,30] (Figures 3, 5 and 6, p. 60). The curb elevation at the interface between the truck apron and the circulatory carriageway is 7–10 cm according to Dutch guidelines [5,10,11], while in other design guidelines, it varies from 2 to 4 cm. Taking the above into account, this article assumes that when conducting swept path analysis special attention will be paid to the wheel paths and the DV envelope path in order to meet the above requirements, to ensure that DV wheels do not encroach on the raised curbs and to ensure collision-free simultaneous movement of vehicles in adjacent lanes with no swept path overlap.

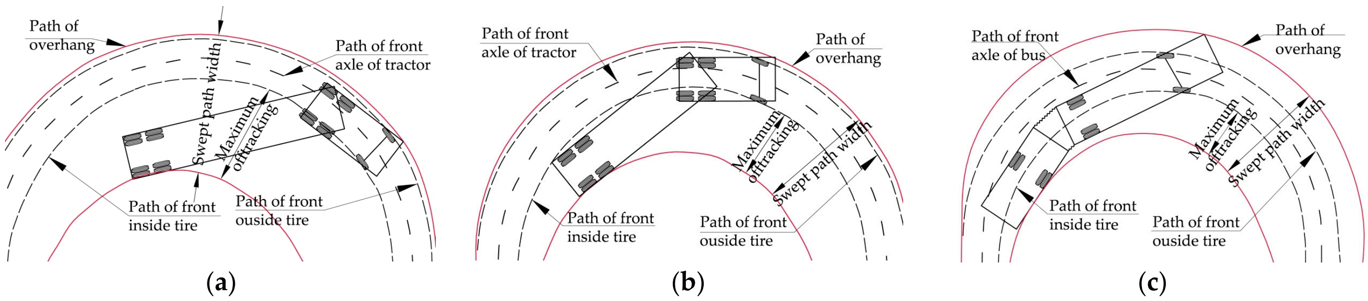


Figure 4. Turning characteristics of selected design vehicle: (**a**) DV1; (**b**) DV2; (**c**) DV3. Source: own work.

For comparative purposes, Figure 5 shows the swept paths of the selected DVs in the right-hand direction with an angle of 70° and 90° between neighbouring approaches. An analysis of the swept-path widths shows that considerably more lane width is needed on non-perpendicular approaches. An in-depth analysis of the widths of the swept paths of the selected DVs revealed in the case of perpendicular approaches, the outer lane width recommended in the guidelines [5] does not accommodate swept paths of any of the analysed DVs, a mountable apron should be designed from the start at each entry and exit (Figure 5). If the angles are less than 90°, the mountable apron areas will be considerably larger, as at sensitive spots, the widths of the swept paths are much larger than the outer lane width of 4.05 m recommended in the guidelines [5] (Figure 5).

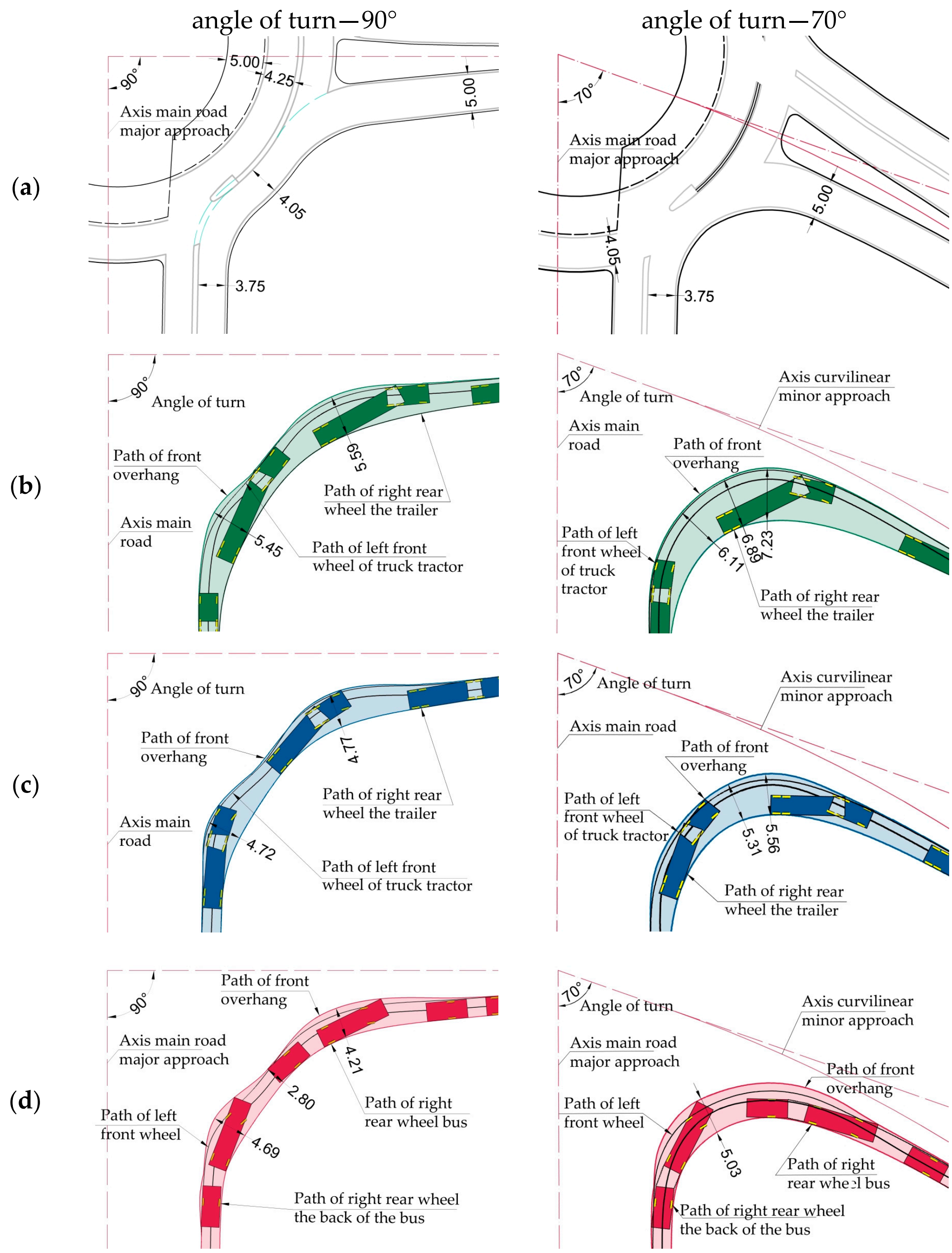


Figure 5. Minimum turning paths for the design vehicle during right turn at 70° and 90° angles: (**a**) fragment of the geometry of selected approaches; (**b**) swept path of design vehicle DV1; (**c**) swept path of design vehicle DV2; (**d**) swept path of design vehicle DV3 (units in m). Source: own work.

2.3. Methods

Considering the above-described problems with ensuring swept paths of design vehicles are accommodated on a roundabout with curvilinear approaches intersecting at non-perpendicular angles, a method of analysis shown in Figure 6 was adopted. The Basic turbo-roundabout shown in Figure 3, designed in accordance with guidelines [5], was a starting element in the design. An iterative procedure was used, at first, swept paths of DV2 and DV3 recorded during surveys were analysed, and next, the analysis of the swept path of DV1 recommended by the European Directive [12] followed (Figure 6—Stage I).

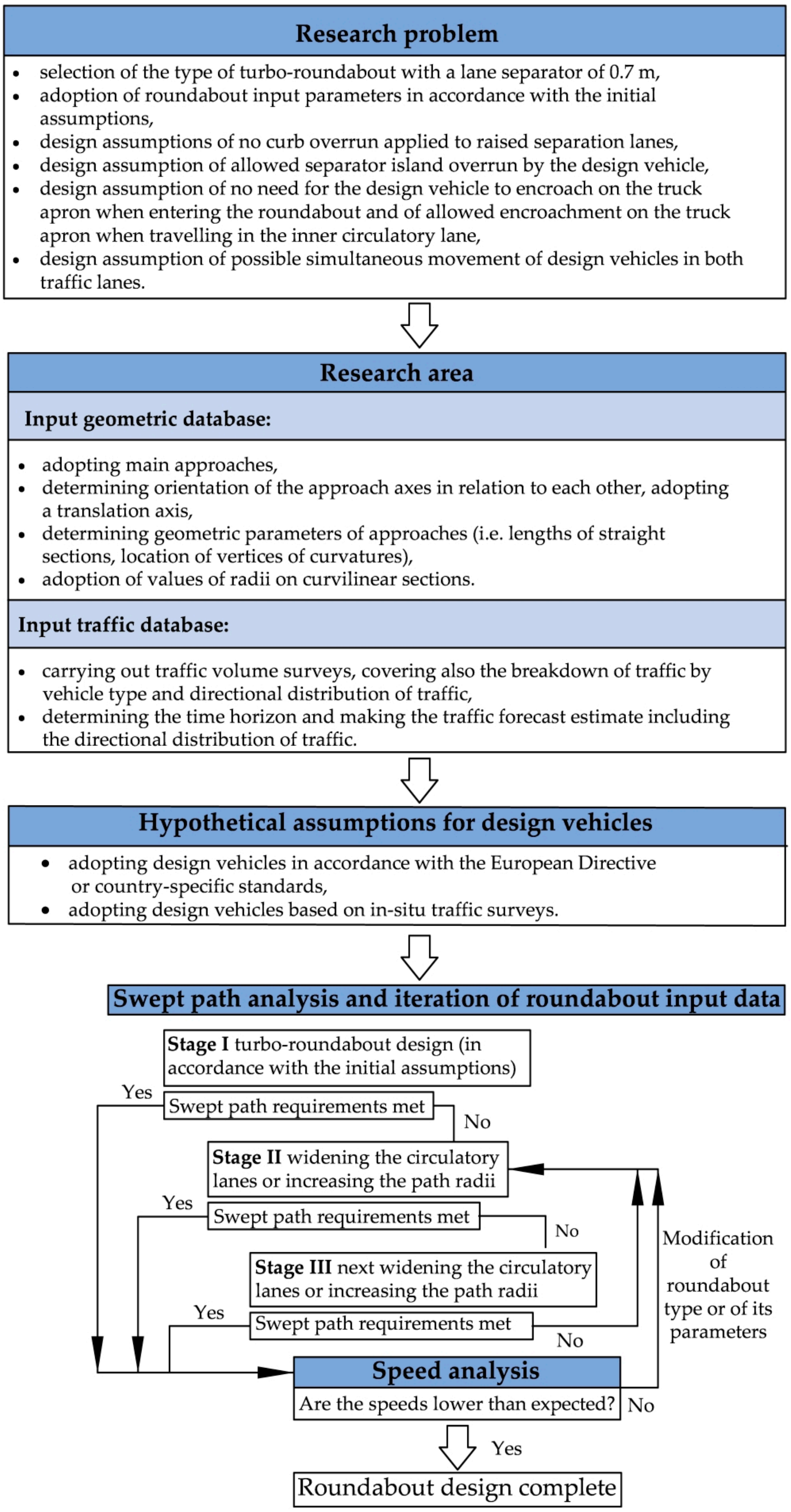


Figure 6. Step-by-step analysis method. Source: own work.

Where the swept path requirement was not satisfied, circulatory lanes were gradually widened. Where swept paths were accommodated within circulatory lanes, and DVs would overrun raised separation lane at the entries and exits, the respective entry and exit radii were increased (Figure 6—Stage II and Stage III). Stages II and III were completed to meet the swept paths requirements for the DVs selected. The completely designed turbo-roundabout, in the final stage of turnabout geometry design, was analysed in terms of the speed of a passenger vehicle travelling along the fastest path through the roundabout. The design of the roundabout was accepted as final if the swept paths requirements for the DVs were met and if the speed of the passenger car travelling along the fastest path did not exceed the 40 km/h allowed for this type of roundabout in the Dutch guidelines [5].

2.4. Fastest Path Passenger Car Speed Analysis

One of the important analyses decisive for the correct design of the roundabout geometry is also an analysis of the speed of a passenger car moving through the roundabout along the fastest path allowed by its geometry [43]. For roundabout design, it is assumed, according to [13], that the fastest possible path is through movement. This is the smoothest and flattest route a passenger car can take through a roundabout (traversing through the entry, around the central island, and out the exit) in the absence of other traffic and ignoring all lane markings [29,43]. In accordance with the recommendations given in [5,14,19,29], the speed on the fastest path through the roundabout is determined for the straight-ahead movement. It is calculated from the Equation (1) [4,13,28,29]:

$$v = 7.4\sqrt{R} \tag{1}$$

where v = fastest path speed (km/h) and R = fastest path radius (m).

For turbo-roundabouts, the radii of curvature of vehicular paths at the entry, at the circulatory carriageway, and at the exit from the roundabout should have the same value. Considering the above, the most effective assumption was to adopt the radius applied to the inner and outer lanes of the circulatory carriageway.

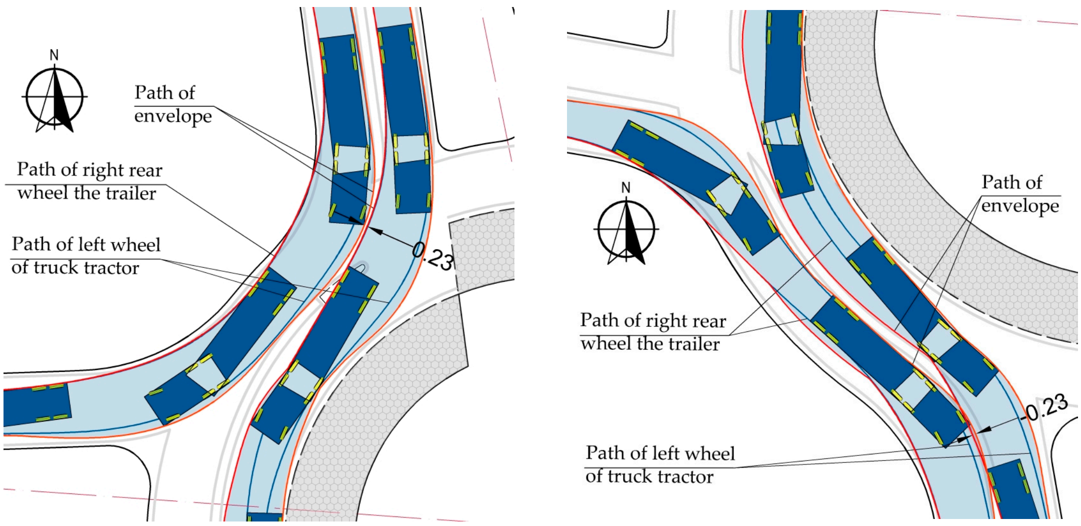
3. Results

3.1. An Analysis of Vehicle Swept Paths on the Basic Turbo-Roundabout with Standard Geometry Parameters

In the first step, the authors analysed the swept path accommodation on the turbo-roundabout designed according to the parameters recommended in guidelines [5] (Stage I), given in Table 2.

Figure 7 shows selected sections of the swept paths of DV2, being the shortest of the analysed design vehicles. The other DV2 swept paths are shown in Appendix A (Figure A1). An analysis of the DV2 swept paths on the north approach shown in Figure 7a demonstrated that a mountable apron should also be designed there, as the right wheels of the semitrailer encroached outside the outer curb line of the roundabout carriageway. Additionally, no safe distance was kept between the swept paths of the two DVs travelling in parallel, Figure 7a—a distance of 0.23 m. An analysis of the wheel paths of DV2 showed that both vehicles overran the lane separator when entering the circulatory carriageway. An analysis of the DV2 swept paths at the west approach shown in Figure 7a demonstrated that a mountable apron was also needed in this area and that the circulatory lanes should be widened here as the vehicle wheels overran the lane separator. In addition, the exit radii are too small, as the swept paths of DV2s simultaneously exiting the circulatory carriageway overlap. The above observations indicate the need for wider circulatory lanes and larger entry and exit radii. In Figure 7, the thick red line marks the edges of the swept path, and the thick blue line marks the sensitive paths of DV2 wheels.

Similar conclusions as regards the overlap of the paths of two vehicles simultaneously travelling in adjacent lanes can be drawn for other DV2 and DV3 movements shown in Appendix A (Figures A1–A3). Taking the above into account, for DV1, only swept paths during right turn movements are shown in Figure A4 in Appendix A in an attempt to demonstrate how large the mountable aprons at all entry and exit areas should be. An analysis of the swept paths of the chosen DVs in the case study described here, included in Appendix A (Figures A1–A4), showed that in addition to the necessary mountable aprons at all entries and exits wider circular lanes and entry and exit radii significantly larger than these recommended in the Dutch guidelines [5] are also needed.



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

Figure 7. Analysis of the swept paths of the shortest design vehicle (DV2): (**a**) north entry; (**b**) west entry (units in m). Source: own work.

3.2. An Analysis of the Swept Paths on a Basic Turbo-Roundabout after the Widening of Circulatory Lanes

Taking into account the results of the swept paths analysis given in Section 3.1, iteratively widened circulatory carriageway lanes were adopted first in Stage II. In line with the adopted method of analysis shown in Figure 6, both circulatory lanes were gradually widened by increments of 0.05 m until both DV2 and DV3, confirmed in traffic volume surveys, stopped overrunning lane separators. Once the design lane width was achieved, larger entry and exit radii were also applied. The final roundabout parameters obtained as a result of the iterative analysis are shown in Table 5.

Table 5. An analysis of the modified parameter values of the *Basic* turbo-roundabout after the widening of circulatory lanes. Source: own work.

Main Elements of a Transverse Cross-Section of the Roundabout		Mathematical Designation	Radius and Measurement in m
Radii			
	Outside radius of the inner lane	R_2	25.10
	Inner radius of the outside lane	R_3	25.40
	Outside radius of the outside lane	R_4	30.20
	Curve lane divider entry	R_t	12 or 14
	Curve lane divider exit	R_a	16
Widths			
	Width, inside lane	b_u	4.35
	Width, outside lane	b_v	4.55

In accordance with the conclusions of the publication [25], for a bus approximately 12 m long, the width of the inner circulatory lane of a large roundabout should be 4.74 m, and for a tractor-semitrailer unit approximately 15.5 m long, the width of the inner circulatory lane should be 4.98 m. For the outer circulatory lane of a large roundabout, according to [25], in the case of a bus approximately 12 m long, the recommended width is 4.74 m, and for a tractor-semitrailer unit approximately 15.5 m long, the width of the lane should be 4.98 m. The differences in traffic lane widths given in the publication [25] and in Table 5 are, firstly, due to the different lengths of tractor units analysed and, secondly, due to the fact that the vehicles are allowed to overrun the truck apron in accordance with the design guidelines applicable in Poland [22,23,39], as illustrated in Figure 8. Figure 8 shows the swept paths for all right- and left-turning movements and two swept paths for selected left-turn movements, illustrating the aforementioned differences resulting from the fact that the vehicles are allowed to overrun the truck apron. With the above assumptions, the resulting circulatory lane widths are sufficient in terms of satisfying the DV2 swept path requirements. Entry radii are another problem to be addressed. In the case in question, the slightly increased entry and exit radii adopted, as summarised in Table 4, result in the DV2 wheels overrunning the road marking lines on lane separators and in occasional encroachment on the road marking lines applied at the outer edge of the circulatory carriageway. Only at the south approach do the right wheels of DV2 overrun the outer curb, and, therefore, a mountable apron must be provided in this area.

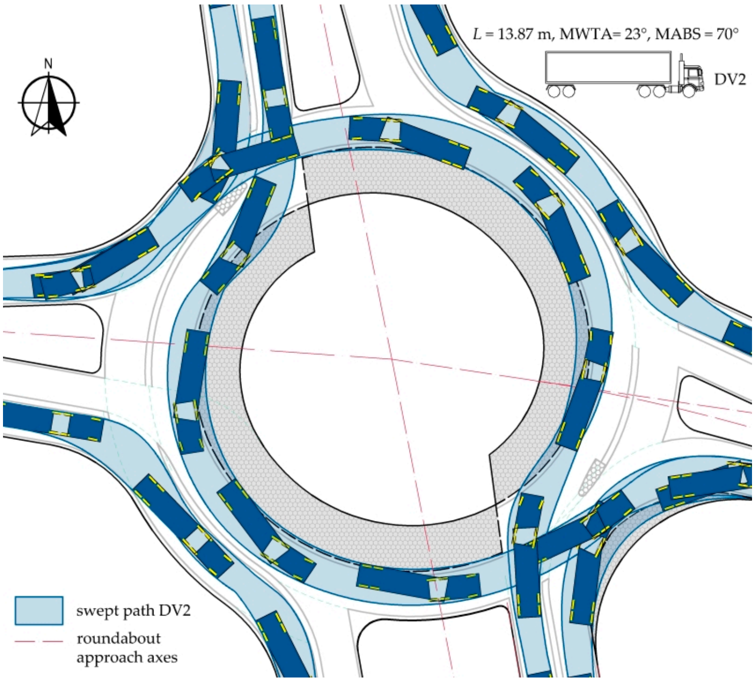


Figure 8. Selected swept paths of DV2 following a change in the roundabout geometry that involved primarily widening the circulatory lanes. Source: own work.

If a given roundabout is not expected to be used by longer tractor-semitrailer units in the future, then the parameters of a roundabout with curvilinear approaches intersecting at non-perpendicular angles, as summarised in Table 4, ensure optimum land take and satisfy the DV2 swept path requirement.

Given that the traffic volume survey results confirmed the passage of articulated buses for all movements, another swept path analysis was carried out for DV3 (Figure 9). In the case in question, the successive iterative widening of traffic lanes was not analysed, but the final roundabout geometry designed for DV2 was used as a basis for the analysis. A detailed DV3 swept path analysis demonstrated that a mountable apron needed to be designed only on the south approach for right-turning movement. As regards the widened circulatory lanes, it can be concluded that they ensured safe distances between the paths of DV3s simultaneously travelling in both lanes on the circulatory carriageway and through the entries and exits. The wheels of this design vehicle did not overrun raised separating lanes.

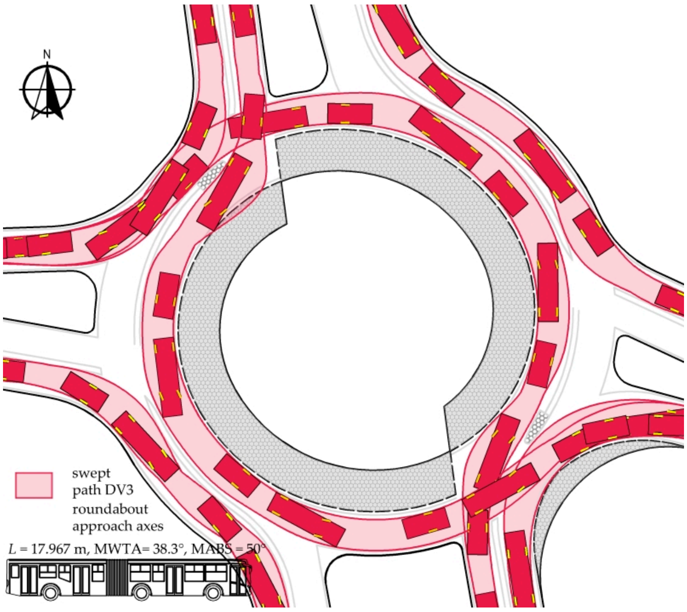


Figure 9. Selected DV3 swept paths following a change in the roundabout geometry that involved primarily widening the circulatory lanes. Source: own work.

Only at the north approach, with a narrower splitter island designed specifically for the analyses described in this article, was a certain inconvenience observed, consisting of the encroachment of the swept path on a small area of the truck apron at the entry to the roundabout. Considering the above, Figure 10 shows the swept path of the DV3 traffic entering the roundabout from the inner lane, taking into account the selected wheel paths. A detailed analysis of the path of DV3's left wheels indicates that the wheels do not overrun the truck apron, the recommendations given in the guidelines [5] are met. Similarly, the right wheels of DV3 do not overrun the separator island or the edge of the road marking lines on the raised separation lane.

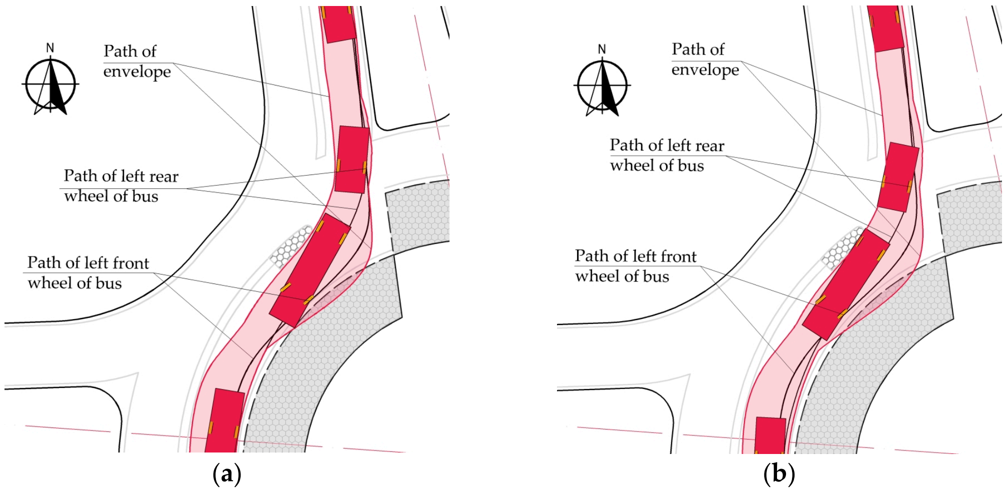


Figure 10. DV3 swept paths at the entry to the roundabout from the north approach leg: (**a**) left-turning movement; (**b**) straight-ahead movement. Source: own work.

Summarising both analyses of the DV2 and DV3 swept paths, it can be concluded (Figures 8 and 9) that if these are the only DVs at the roundabout, the parameters of the turbo-roundabout given in Table 4 meet their swept paths requirements and ensure safe movement for both vehicles.

However, taking a broader view of the problem of designing a turbo-roundabout with curvilinear approaches intersecting at non-perpendicular angles, the above-described roundabout design should also satisfy the swept path requirement for the DV1, which is 16.5 m long. It should be mandatory to analyse the parameters of a turbo-roundabout with non-standard approaches rather than focus only on the described case study, taking the above into account, in the given example on the swept paths of the design vehicles recorded in traffic volume counts.

Considering the above remark, Figure 11 shows the swept paths of the DV1 tractor-semitrailer unit, as recommended in the European Directive [12]. A thorough analysis of DV1 swept paths revealed that, unfortunately, the swept path requirement for the DV1 was not satisfied at the turbo-roundabout designed according to the parameters summarised in Table 4 (Figure 11). The first observation is that it is necessary to design mountable aprons at all entries and exits due to the small values of the entry and exit radii. Additionally, when entering the roundabout from the inner lane, due to the small lane separator radii, the swept path of DV1 bypasses the separator island and, without encroaching on the raised separation lane, overruns the truck apron. Further, when travelling in the inner lane of the roundabout during left-turning movements, despite the fact that the left wheels of the semitrailer overrun the truck apron, the right wheels of the tractor unit still encroach on the lane separator. The DV1 swept path analysis indicates that, to address this problem, it is necessary to widen the outer lane of the roundabout and to significantly increase the entry and exit radii.

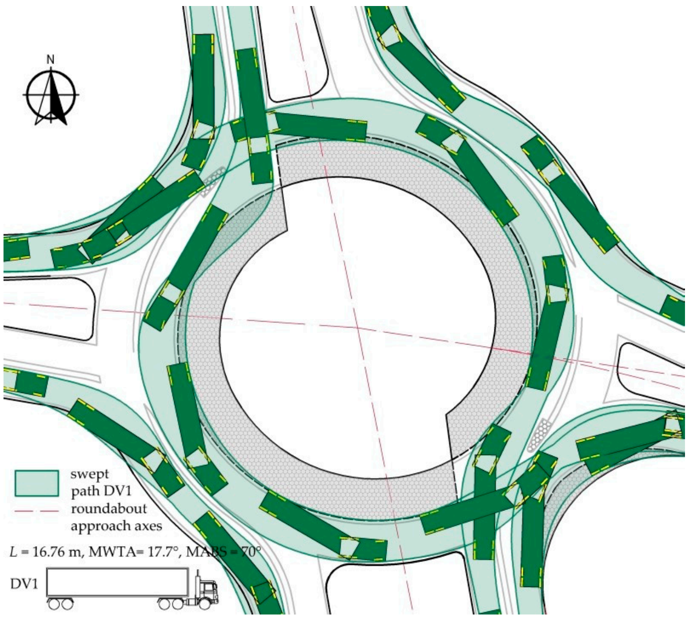


Figure 11. Selected swept paths of DV1 following a change in the roundabout geometry that involved primarily widening the circulatory lanes. Source: own work.

3.3. An Analysis of the Swept Paths on the Basic Turbo-Roundabout following Changes in the Roundabout Parameters

Taking into account the observations described in Section 3.2, regarding the need for the provision of mountable apron areas on all approaches, lane separator and road marking line encroachments, and considering the research conclusions formulated in publications [24,25,29,33,34], successive iterations as regards the outer lane widths and the values of the entry and exit radii were applied in the swept path analyses described in this article in Stage III. The geometry of the roundabout was designed as follows: (a) First, the outer circulatory lane was incrementally widened until the DV1 swept path requirement for right-turning movements from the side approaches was satisfied, which means the vehicle path no longer encroached on the road marking lines; (b) next, the edges of the splitter islands were adjusted by iterative specification of the entry and exit radii. Eventually, after several iterations, a significantly increased outer lane width and varying larger entry and exit radii were proposed. The new parameters of a turbo-roundabout with curvilinear approaches at non-perpendicular angles are summarised in Table 6. The swept paths of the tractor-semitrailer unit, DV1, are shown in Figures 12–14.

Table 6. Summary of the modified parameter values of the *Basic* turbo-roundabout after the widening of the outer circulatory lane and the change of the entry and exit radii. Source: own work.

Main Elements of a Transverse Cross-Section of the Roundabout	Mathematical Designation	Radius and with Measurement in m
Radii		
Outside radius of the outside lane	R_4	31.35
Curve lane divider entry	R_t	14, 22, 25 [1]
Curve lane divider exit	R_a	16, 28 [2]
Radius of raised separation lane at entry		22, 25 [3]
Radius of raised separation lane at exit		28 [4]
Widths		
Width, outside lane	b_v	5.30 [5]

[1]—entry radii increased following the analysis of the swept path of DV1. [2]—exit radii increased following the analysis of the swept path of DV1. [3]—radii of lane separator at entry increased following the analysis of the swept path of DV1. [4]—radii of lane separator at exit increased following the analysis of the swept path of DV1. [5]—final width of the outer lane obtained when meeting the DV1 swept path requirement.

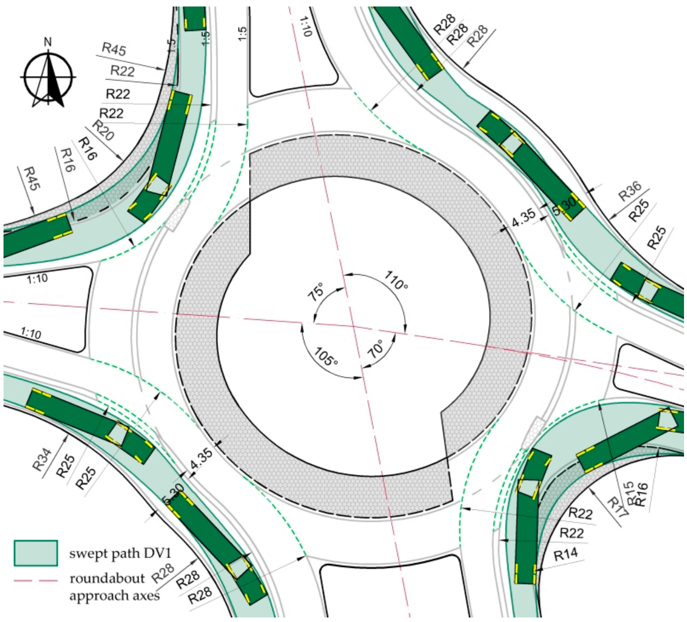


Figure 12. DV1 swept paths for right-turning movements (units in m). Source: own work.

Based on the analysis of the swept paths for right-turning movements from side approaches shown in Figure 12, it can be definitely concluded that the adjusted shapes of splitter islands, the increased entry and exit radii and the increased width of the outer circulatory lane ensure a safe passage of the design vehicle, DV1 through the roundabout. In the case in question, the swept paths of DV1 were analysed on the part of the outer lane, on the right-turning section from the side approaches.

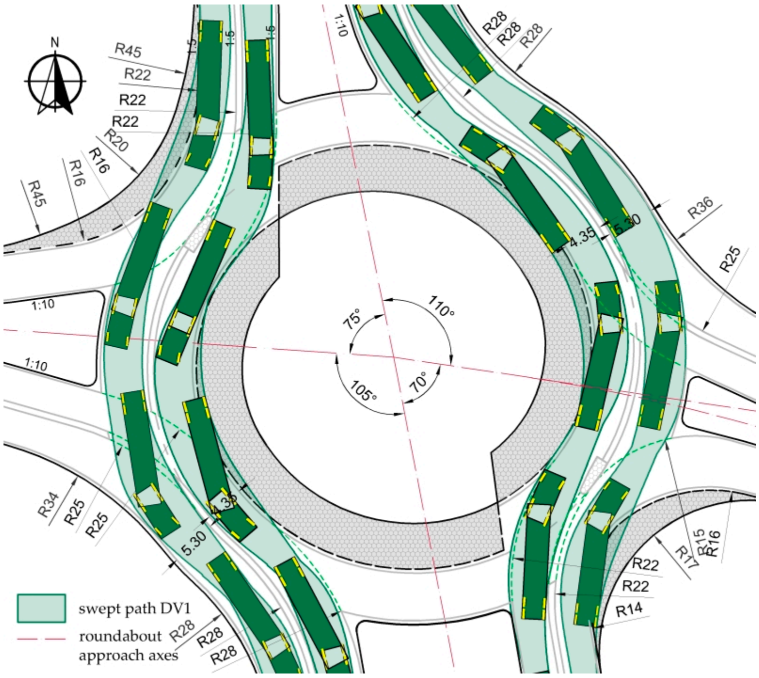


Figure 13. DV1 swept paths for the straight-ahead movements from the main approaches (units in m). Source: own work.

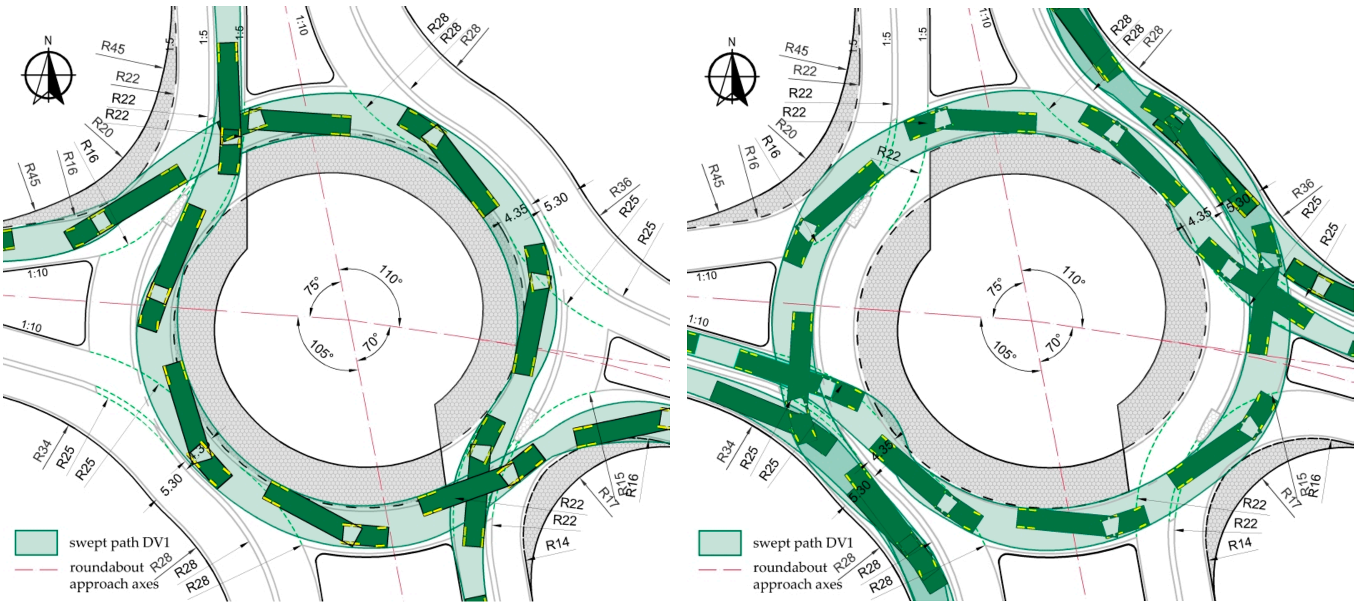


Figure 14. Swept paths of DV1: (**a**) for left-turning movements from the main approaches; (**b**) for right- and left-turning movements from the side approaches (units in m). Source: own work.

Another DV1 swept path analysis for the remaining parts of the outer lane was carried out for straight-ahead movements from the main approaches (Figure 13). Additionally, in this case, the widened outer lane satisfied the DV1 swept path requirement, which proved particularly important for passing along the splitter islands on the side approaches and at the exit from the roundabout. As for the swept paths in the inner circulatory lane, it was proven that there was no need to increase the width of the inner lane. More important for accommodating design vehicle swept paths in the inner lane are increased entry and exit radii and modified splitter island shapes.

Similar conclusions as regards the width of the outer lane at the left turn can be drawn based on the analysis of the swept paths shown in Figure 14.

4. Discussion

When comparing the increased width of the outer lane with the conclusions formulated by Chan and Livingston in [25], it was found that when designing a turbo-roundabout with curvilinear approaches intersecting at non-perpendicular angles, there was clearly a need to analyse DV swept paths. This width cannot be adopted as an obligatory value for all roundabout design cases, as can be done for approaches oriented to each other at right angles (90°). It is so because, for curvilinear approaches, the shape of the splitter islands needs to be individually designed to match the curvature of a given approach.

Neither can the entry and exit radii be mandatorily specified in a given case, as proposed in [29] or recommended in the Czech design guidelines [32] for roundabouts with perpendicular approaches. For curvilinear approaches, the approach curvature and the three related parameters have a significant influence on the accommodation of the swept path of the chosen design vehicle. The three parameters are the shape of the splitter island, entry and exit radii and the widths of the circulatory carriageway lanes on the roundabout for the specific movements.

The above conclusions and swept path analyses presented in Sections 3.2 and 3.3 demonstrate the need for necessary analyses of the swept paths of the design vehicles chosen. Furthermore, the swept path analyses also need to consider the country-specific recommendations as to whether it is allowed for the wheels of the design vehicle to overrun the truck apron or not, as design guidelines developed in various countries vary on this issue.

Based on the analysis of the swept paths of an articulated bus as presented in Section 3.3, it can be concluded that for these design vehicles, in addition to the path occupancy analysis, it is important to investigate the wheel paths, especially the paths of the vehicle's left wheels, which should not overrun the curb line between the truck apron and the circulatory carriageway. This is particularly important in countries where the curb at the interface between the truck apron and the carriageway is raised by 7–10 cm above the roundabout carriageway level [5,10,11].

The final element of the analysis of the roundabout geometry designed in the design process should be an analysis of the speed of a passenger car on the fastest path vehicle speed. According to [4,13,14,17,29,43], the average passenger car width is 2 m. Therefore, British guidelines on conventional roundabouts recommended [43] that the fastest path through a roundabout should be so drawn that the vehicle following it would maintain a distance of at least one metre between its centreline and any curb or edge at the entrance to the roundabout around the centre island and at the exit from the roundabout. The same principles are reiterated in more recent guidelines [17]. On the other hand, the American guidelines of 2000 [13] on conventional roundabouts, recommended that the fastest path through the roundabout should be drawn at a distance of at least 1.5 m from the critical lines at the entrance to the roundabout, around the central island and at the exit from the roundabout, and only at the approaches and exits at a distance of 50 m from the outer edge of the roundabout should it be drawn at a distance of 1 m from these lines. Considering the necessity of providing safe lateral clearance at the roundabout and the conclusions of the research formulated in publications [29,34], the authors of this article also adopted the 1.5 m distance from the sensitive edges.

Therefore, it was assumed in this article (taking into account the widened circulatory lanes) that in both traffic lanes at the entry to the roundabout from the main approaches, the two fastest vehicle paths through the roundabout would be drawn for the straight-ahead movement (Figure 15). Two fastest vehicle paths with radii RI and RII from the main approaches (Figure 15a) and one fastest vehicle path RI from the side approaches (Figure 15b) were analysed in the inner lane. The fastest vehicle paths with radii RIII and RIV were also drawn from the main approaches in the outer lane.

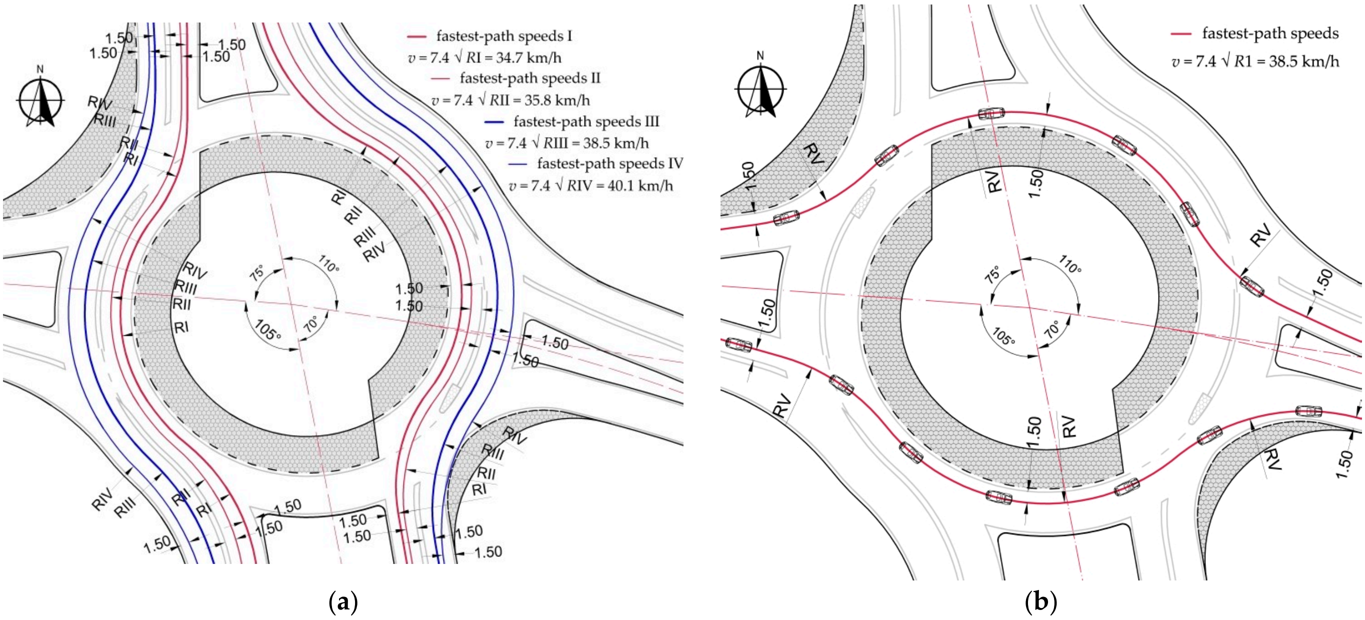


Figure 15. Fastest vehicle paths through the roundabout: (**a**) from the main approaches; (**b**) from the side approaches (units in m). Source: own work.

Given that this is a big roundabout, maximum vehicle speeds on it should not exceed 40 km/h according to Dutch guidelines [5]. An analysis of the speed values calculated from Equation (1) (Table 7) and summarised in Figure 15 revealed that in almost all cases, the speeds were less than 40 km/h, except for one passage along the outermost path. Still, even in this case, the 40 km/h speed level was exceeded by less than 1%. Therefore, following an analysis of the speed data shown in Figure 15, it can be concluded that the geometry of the turbo-roundabout with curvilinear approaches intersecting at non-perpendicular angles is correct and that widened lanes and increased entry and exit curve radii ensure traffic safety as exemplified by the turbo-roundabout in question.

Table 7. Values of the radii determined on the fastest paths through the roundabout. Source: own work.

Location	Feature (Radii: R_1, R_2, R_3 and R_4—see Figure 3)	Measurement in m
Inner lane, entry from the main approaches	RI = R_1 [1] + 0.45 [2] + 1.5 = 20.00 + 0.45 [2] + 1.5 RII = R_2 [3] − 0.21 [4] − 1.5 = 25.10 − 0.21 − 1.5	21.95 23.39
Outer lane, entry from the main approaches	RIII = R_3 [5] + 0.21 [4] + 1.5 = 25.40 + 0.21 + 1.5 RIV = R_4 [6] − 0.45 [7] − 1.5 = 31.35 − 0.45 − 1.5	27.11 29.40
Inner lane, entry from the side approaches	RV = R_1 [1] + Δv [8] + 0.45 [2] + 1.5 = 20.00 + 5.15 + 0.45 + 1.5	27.10

[1] R_1 from Table 2—20.00 m. [2] Clearance—0.45 m (see Figure 2—inner edge line offset). [3] R_2 from Table 5—25.10 m. [4] Raised separation lane—width 0.7 m, width curb—0.28 m, (see Figure 2); (0.7 − 0.28)/2 = 0.21 m. [5] R_3 from Table 5—25.40 m. [6] R_4 from Table 6—31.35 m. [7] Clearance—0.45 m (see Figure 2—outer edge line offset). [8] Δv—from Table 2—5.15 m.

5. Conclusions

The following conclusions can be drawn on the basis of the results of analyses of vehicle-swept paths on a turbo-roundabout with curvilinear approaches oriented non-perpendicular to each other:

- Any design of a turbo-roundabout should include the swept paths analysis and the speed analysis for a passenger car travelling along the fastest path through the roundabout in order to verify the correctness of its geometric design essential for ensuring traffic safety;

- The swept path analysis should be a basis for the adjustment of the basic parameters of a turbo-roundabout with curvilinear approaches at a non-right angle;
- In every case, the process of turbo-roundabout design should involve a strict selection of possible design vehicles on the basis of traffic surveys conducted at the location in question, as their parameters significantly influence the roundabout geometry parameters and, consequently, the required land take area;
- The use of only the 16.5 m-long design vehicle in each roundabout design case has a significant effect on the circulatory lane widths and on the so-called "opening width" of the roundabout;
- In the case of curvilinear approaches oriented non-perpendicular to each other, detailed vehicle-swept path analyses should be carried out on each approach and for each movement, as the approach geometry parameters depend on its curvature,
- for curvilinear approaches, a swept path analysis for the movements using the inner lane should be carried out in the first step, and the vehicle swept paths for movements using the outer lane should be examined next;
- Given the positive effects of the widening of both circulatory lanes, further analyses of the swept paths should be carried out accordingly for all entries and exits and the values of splitter island and raised separation lane curvature radii and outer curb radii should be adjusted accordingly to the curvature of the respective approach;
- On approaches oriented to each other at ca. 70–75°, the necessity of installing a large mountable apron should be taken into account. Its size will depend on the width of the designed splitter island;
- If the design provides for 3 m-wide splitter islands, as recommended in the guidelines, and even if straight approaches are designed, there is a need for significant deflection of the edge of the splitter island and the traffic lanes at the entry to the roundabout to satisfy swept path requirements, i.e., to ensure that wheels of the travelling vehicles overrun neither the truck apron nor the raised separation lanes;
- In the case of curvilinear approaches oriented to each other at the angle of ca. 105–120°, installation of the mountable apron may be avoided if larger curve radii are used.

An additional practical contribution of the analyses described in our article is the possibility of supplementing the existing design guidelines for turbo-roundabouts, as well as introducing additional recommendations to new guidelines being developed in countries that still do not have the regulations for the design of roundabouts in place. The analyses in this article have shown that each curvilinear approach more distant from the right angles should be individually considered. The initial steps of designing the approach should take into account the parameters recommended in the guidelines, followed by mandatory check of the swept paths for final characterization of approach's parameters. The design guidelines should, however, allow for the design of curvilinear approaches oriented to each other, not at right angles, where swept path indication and analysis should be mandatory. This condition must be included in the guidelines, as some curvilinear approaches found in real life have significant site constraints that make it impossible to design them other than at right angles to each other.

Author Contributions: Conceptualisation, A.B.S.; methodology, A.B.S.; formal analysis, A.B.S. and W.B.; data curation, W.B.; writing—original draft preparation, A.B.S.; writing—review and editing, A.B.S.; visualisation, A.B.S. and W.B.; supervision, A.B.S. 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.

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

Appendix A

Design of a turbo-roundabout in accordance with the parameters listed in Table 2.

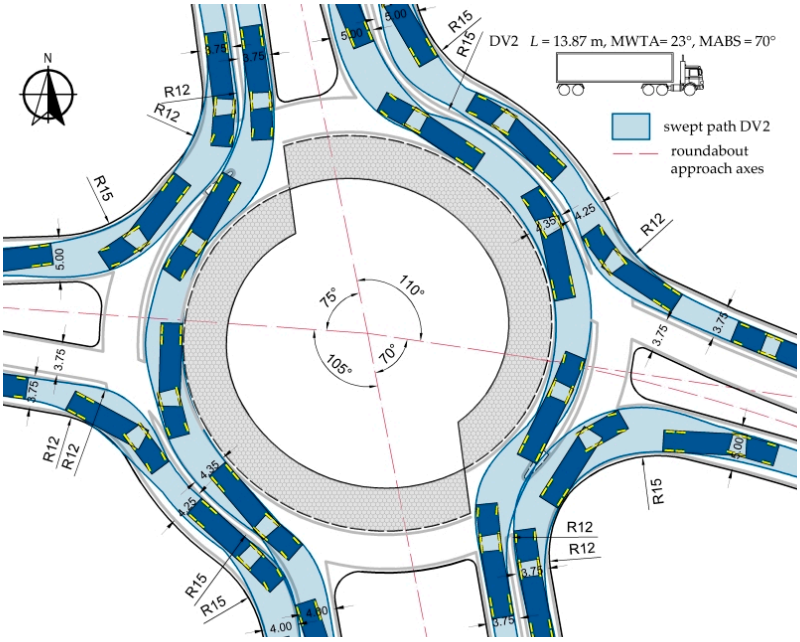


Figure A1. Selected swept paths of DV2—right-turning movement and straight-ahead movement—north and south approach (units in m). Source: own work.

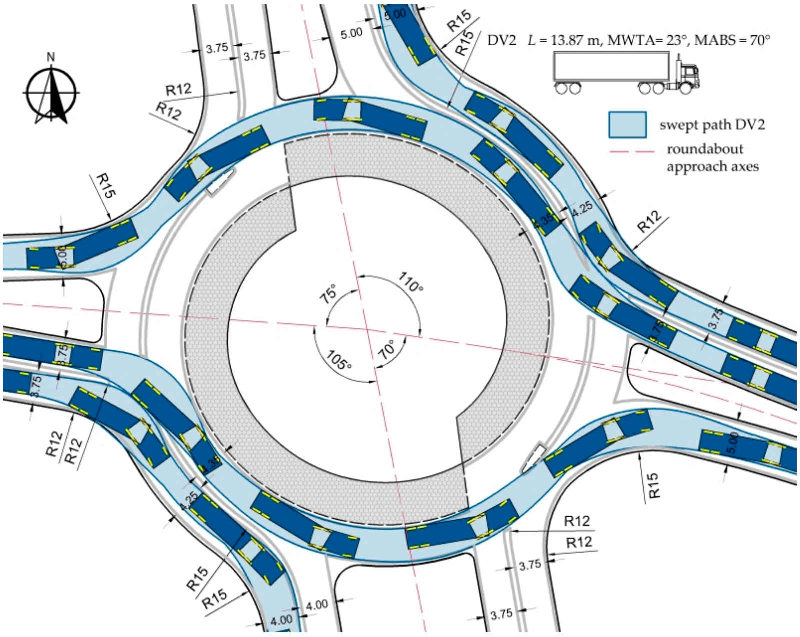


Figure A2. Selected swept paths of DV3—east and west approach (units in m). Source: own.

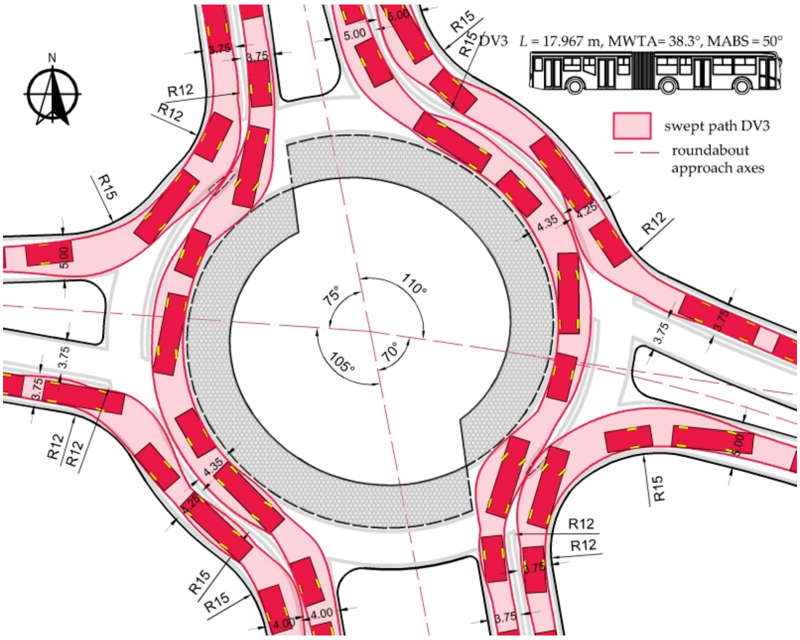


Figure A3. Selected swept paths of DV3—right-turning movement and straight-ahead movement—north and south approach (units in m). Source: own work.

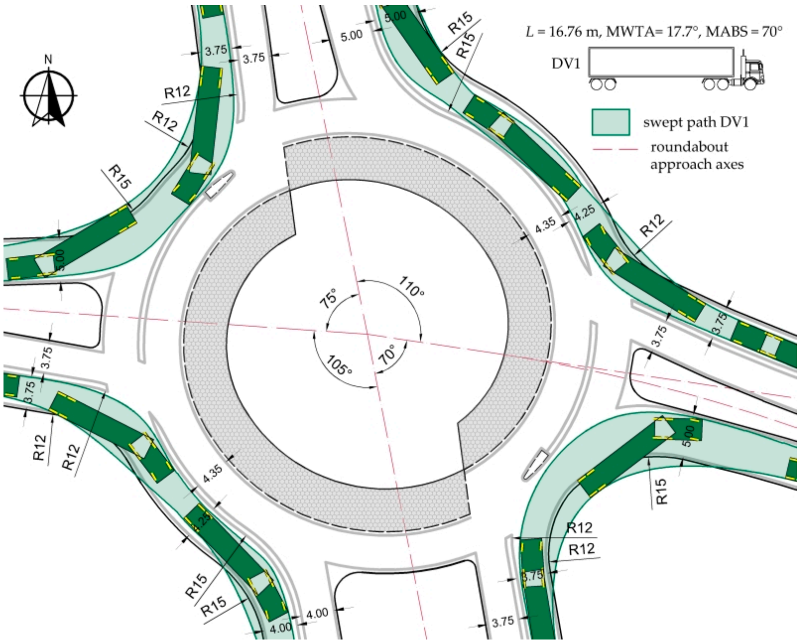


Figure A4. Selected swept paths of DV1—right-turning movement and necessity mountable aprons (units in m). Source: own work.

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