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Problems of ensuring traffic flow on a Basic turbo roundabout with non-standard curvilinear entries (a case study)

Abstract: With ever-increasing motorisation and the desire for greater traffic safety, conventional roundabouts and turbo roundabouts are being designed. Turbo roundabouts provide greater traffic safety than conventional roundabouts due to the segregation of traffic at the entries and on the roadway. In the design of a turbo roundabout, the usual roundabout principles recommended in Dutch guidelines can be applied. However, these apply when the roundabout entrances are directed perpendicularly to each other, which is not always possible. This paper undertakes an analysis of the traffic flow on a *Basic* turbo roundabout with curvilinear entries directed at an angle other than a right angle to each other. A junction in a built-up area located on the outskirts of Szczecin was selected for analysis as a case study. In the first phase of the turbo roundabout design, the recommended roundabout parameters given in the Dutch guidelines were adopted for a roundabout with a 0.7 m wide separation lane. After preliminary swept path analysis of the accepted design vehicles, it became necessary to design the entries individually due to their curvilinear nature and angle. The analysis of the swept paths provision at the *Basic* turbo roundabout with a non-standard orientation of the curvilinear entries shows that wider lanes and larger corner radius than recommended in the Dutch guidelines should be used. Higher angle splitter island should also be considered.

Keywords: Turbo-roundabout; Raised lane dividers; Swept path analysis; Curvilinear entries; Fastest-path speeds

Introduction

With the continuously increasing economic progress and growing traffic intensity, primarily related to capacity and traffic safety issues, communication systems and intersections are designed to ensure the expected objectives. Among other solutions, a turbine roundabout is one such solution. The first turbine roundabout was built in the Kingdom of the Netherlands in 1996. The designer and originator of the first turbine roundabout was L.G.H. Fortuijn [18, 33]. The idea for the turbine roundabout arose from the analysis of increasing the capacity of two-lane roundabouts while ensuring greater traffic safety, resulting from the elimination of side collisions that can occur when changing lanes. The turbine roundabout ensures: no need to change lanes within the roundabout, no need to yield to vehicles traveling on more than two lanes, and low speed on the roundabout roadway due to separation lanes with a raised curb of 7 cm height. The concept of the turbine roundabout involves associating individual relationships with their counterparts, similar to the relationships on a conventional single-lane roundabout. In Dutch guidelines, several types of turbine roundabouts were introduced, which should meet four basic principles [3, 34]:

a) At entries with high traffic intensity, there should be two lanes, separated by a separation lane and clearly marked relations using signage,
b) On the roundabout roadway, clear traffic separation should be implemented using a separation lane, eliminating the need to change lanes,
c) On the roundabout roadway, the direction of traffic must be ensured and clearly marked, consistent with the applied signage and traffic separation at the entries to the roundabout, so that the driver occupies the appropriate lane before entering the roundabout,
d) From the outer lane, one can turn right at the nearest exit or proceed straight, and from the inner lane, one can only turn left or proceed straight.

If at any roundabout at least one of the above principles is not adhered to, such a roundabout is not a turbine roundabout but a partially turbine roundabout (in Dutch – Partiële turborotonde) [3]. If a separation lane with a raised curb is not implemented on the roundabout and traffic segregation is performed only using horizontal markings, such a roundabout is called a "look-a-like" according to Dutch guidelines [3].

Since 1996, several hundred turbine roundabouts have been built worldwide according to various design principles (globally, according to data from [2], by December 2021, 676 roundabouts had been built, of which 396 were in the Kingdom of the Netherlands and 82 in Poland). Considering that the first turbine roundabouts were built in the Kingdom of the Netherlands, the basis for their design were the principles outlined in Dutch publications [11, 18, 33]. The majority of publications related to turbine roundabouts are associated with the assessment of capacity or traffic safety [4, 18, 19, 21, 23, 24, 25, 26, 28, 39]. There are also many publications on the design principles of turbine roundabouts or the assessment of their operation, which cover: traffic simulation analysis, capacity analysis, assessment of lane widths on the roundabout roadway and at entries with various configurations of reference vehicles, as well as the location of separation lanes and the placement of separation islands. Taking the above into account, several countries have supplemented their design guidelines for turbine roundabouts with additional provisions, which are briefly summarized in Table **1**.

The above considerations represent only a part of what a designer should take into account when designing a turbine roundabout. The issue of the conformity of the roundabout geometry with the existing vehicle fleet is current and closely related to sustainable development, as the goal of road system planning is to enable the greatest possible mobility of people while ensuring environmental care. In the design process, this goal requires designers to be continuously ready to make compromises, leading to the continuous improvement of design principles.

The literature review presented indicates a lack of analyses and guidelines for designing roundabouts with curved entries. In Dutch guidelines, turbine roundabouts are recommended to be designed only in cases where entries are directed perpendicularly to each other and have a straight alignment. However, in design practice, other entry orientations are also encountered, and there is a need to implement a turbine roundabout due to the necessity to increase capacity or improve traffic safety. Taking the above into account, this article presents a case study of designing a large Basic-type turbine roundabout with curved entries directed relative to each other at non-right angles. Initially, a research area was selected, and reference vehicles were defined. Due to the actual conditions of curved entries and the magnitude of forecasted traffic intensities, a large roundabout was selected for analysis. For the designed roundabout, the recommended parameters from the Dutch guidelines [33] were adopted as the initial parameters, and a Basic-type roundabout was designed. The conducted capacity analysis revealed that the traffic corridors of the selected reference vehicles were not maintained. Considering the above, iterative corrections were made at individual entries to ensure traffic corridors. After several iterations, the set goal was achieved: through subsequent lane widenings on the roundabout roadway, adjustment of entry curvatures, and correction of the separation island location, traffic corridors were ensured on the designed roundabout. Based on the performed capacity analyses, conclusions were formulated regarding the design of a Basic-type turbine roundabout with curved entries directed relative to each other at non-right angles.

Table 1. Summary of the characteristics of basic recommendations and introduced additions in the process of designing turbine roundabouts

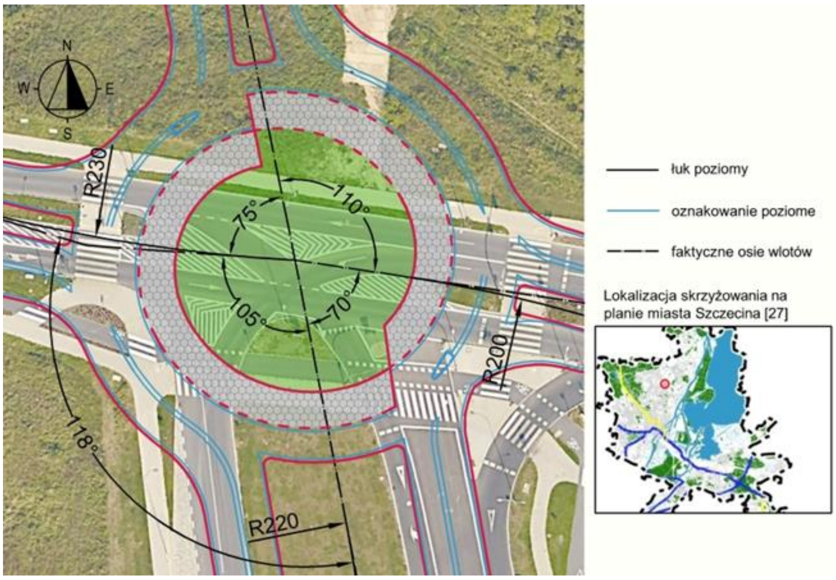
[11, 33]	The basic types of roundabouts were defined. Their design was presented step by step. The principles of classic turbine roundabouts were defined. Two basic design assumptions were formulated: - first - the inlets should be directed perpendicularly to each other, second - passenger cars cannot drive onto the islands and separation lanes and the passable part of the roundabout.
[18, 22, 23, 28, 32]	It was recommended that conventional multi-lane roundabouts be equipped with a spiral movement imitating the movement on turbo roundabouts. Various types of road markings were introduced on the roundabout carriageway, without the need for a separation strip with a raised curb.
[8]	Following preliminary analyses of the length of the standard vehicles used in New Zealand (i.e. 17.9 m long with four axles at the rear), which is longer than the Dutch guidelines (16.5 m with three axles at the rear), the Report proposed corrections to the position of the separation island. The design recommendations allowed both entry onto the separation island and onto the trafficable part of the roundabout when turning left. The publication also analysed the traffic corridors of standard vehicles when the standard vehicles were travelling simultaneously on both lanes in straight-ahead and in a combination of left-hand and straight-ahead traffic. However, simultaneous straight-ahead and right-hand turns were omitted from the analyses, as the vehicle entering the inner lane of the roundabout drove, as intended, on the surface of the separation island.
[9]	With the adopted basic parameters of a turbine roundabout according to the Dutch guidelines [33], the necessary widths of traffic lanes on the roundabout roadway were analyzed depending on the adopted reference vehicles, i.e. a 9.14 m long truck, a 12.36 m long bus and a 15.5 m long tractor-trailer. Considering that in the USA turbine roundabouts are built without separation lanes with a raised curb, the authors took into account only the width of the segregation line equal to 0.3 m instead. The publication analyzed the minimum widths of traffic lanes in relation to the three above-mentioned reference vehicles on partially turbine roundabouts of the following types: Basic, Egg and Knee (roundabout: mini, small, medium and large).
[39, 40]	Many modifications to the shape of the impassable part of the roundabout were proposed, introducing a circular impassable part, and various versions of "flattening" roundabouts were proposed, thanks to which they could be used in traffic systems with limited space.
[13, 14, 29, 36]	The publications analysed various locations of the separation island in relation to the provision of traffic corridors for authoritative vehicles (16.5 m long with three axles at the back) and showed certain inaccuracies in the marking of the traffic part of the roundabout and the resulting marking errors within the range of up to 5 cm. The studies took into account Croatian and Serbian marking rules and assumed the width of both strips equal to 0.5 m, instead of the width of 0.45 m proposed in the Dutch guidelines. Based on the analysis of the traffic corridors of the accepted authoritative vehicles, the following was proposed: - the use of corrected turboblock parameters, depending on the type of roundabout and the assumed output diameter. - the use of variable rounding radii at the entrance and exit of the roundabout, instead of the 12 m proposed in the Dutch guidelines, as well as the use of basket curves with radii in the range of 25 - 33 m.
[15]	Conclusions from previous studies [13, 14] have shown that existing roundabout design procedures, in which trajectory analyses are performed at the end of the design process, contain certain flaws and omissions that may lead to unsatisfactory roundabout geometry, i.e. low capacity, small improvement in traffic safety, low driving comfort and high construction costs. In situ verification studies were performed with respect to the hypothetically formulated new design proposals, confirming the initial hypotheses.

[26]	Various country-specific designs of turbo roundabouts were considered, with particular emphasis on the conditions of entry to the roundabout. The analyses primarily considered the geometric layout of the turbo roundabout elements (i.e. the shape of the turbo roundabout, lanes and separation islands), ensuring physical separation of traffic on the lanes, and the effectiveness of the proposed innovative changes in the entry part (including the use of basket bends), compared to the recommendations included in the design guidelines applicable in other countries.
[5]	A different shape of the separation island was proposed if a separation strip is used on the roundabout and it was recommended to use a 0.6 m wide separation strip. It was also proposed to transform existing conventional two-lane roundabouts into turbine roundabouts with a 1–2.5 m wide driving section, marked out as a shift of part of the roundabout along selected axes. These roundabouts can be designed with separation strips with a raised curb or they can be part-turbo roundabouts without separation strips but with the lane separation applied by means of horizontal marking lines.

Characteristics of the Selected Research Area

Considering that in design practice not all intersections have entries directed at right angles and that they cannot always be appropriately adjusted to this requirement, an intersection with curved entries located in Szczecin (Fig. 1) was chosen as the research area. In the study [6], a Basic-type turbine roundabout was designed at the specified location, assuming that the main entries were directed north and south. It was assumed that the designed northern entry would be part of the planned bypass for the Warszewo and Bukowe estates. At the current three-entry intersection with traffic signals, the main entries are the western and eastern entries. The existing Wkrzańska Street, with a gravel surface, currently serves as a public exit leading to the few residential buildings and does not effectively constitute a northern entry. In the initial land development plans [30], tram lines were planned to be designed at the southern entry, which is why a wide divider lane was designed. However, this tram line concept did not find further implementation in the current land development plan [31]. Taking the above into account, a wide divider lane was left at the southern entry [6], and at the northern entry on the planned bypass, a divider lane width of 4 m, used on two-lane streets, was adopted. At the western and eastern entries, curved separating islands were implemented. Pedestrian crossings and bicycle paths were ultimately planned at all entries, but these are not considered in this article.

The assumptions formulated in the design guidelines [8, 29, 32, 33, 36] recommend designing turbine roundabouts with entries directed at right angles to each other. However, in design practice, these conditions are difficult to achieve, and the design of a turbine roundabout should, in reality, take the actual road conditions into account to the maximum extent. Considering the above, a location with highly varied entries to the roundabout (Fig. **1**) was selected for analysis. The northern entry is traditionally directed toward the center of the roundabout at a right angle. The southern entry has a portion adjacent to the roundabout directed at a right angle, but further along the entry is a curved section with a radius of 220 m (the beginning of the curve is approximately 60 m from the center of the intersection). The western entry is curved and has two opposing horizontal curves; the apex of the first curve with a radius of 230 m is approximately 30 m from the center of the intersection, and the end of the curve is at the center of the intersection. Further along the western entry is a second horizontal curve with a radius of approximately 890 m. The axis of the western curved entry is directed at angles of 105° and 118° relative to the main entry axes. The eastern entry is also a curved entry, and the beginning of the curve with a radius of 200 m is located 15.5 m from the center of the intersection. The axis of the eastern entry is directed at an angle of 110° relative to the main entry axes.



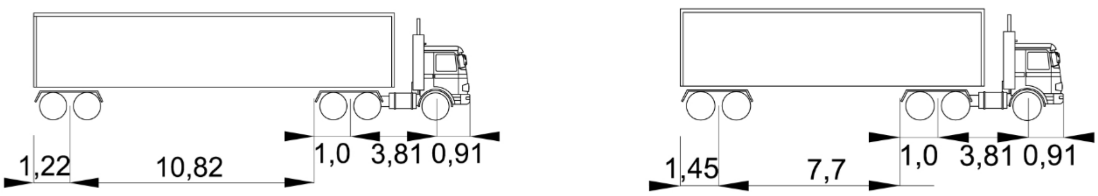
1. Visualization of the geometry of the inlets on the planned Basic type turbine roundabout against the background of a satellite image from Google Earth [20] (Source: authors' study)

Characteristics of the Adopted Traffic Conditions and Reference Vehicles

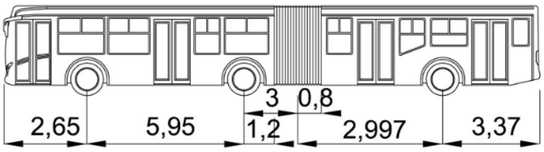
The next step was to select reference vehicles. Analogous to the content in publications [8, 9, 13, 14, 15, 32], various reference vehicles considering the traffic specifics in the selected research area were adopted in the analyses. According to design principles, turbine roundabouts should ensure uninterrupted passage for reference vehicles. Reference vehicles significantly influence the geometry of the turbine roundabout [4, 9, 38]. Taking the above into account, the selection of reference vehicles should consider the existing vehicle fleet in a given region/country and the projected vehicle type structure at a given roundabout. The initial templates for reference vehicles are provided in [11], i.e., a two-axle tractor unit with a three-axle trailer, 16.5 m in length. This vehicle complies with the European Commission Directive [12] and is the most commonly encountered tractor unit in Europe [1]. The current Polish guidelines [34] also recommend adopting this vehicle as a reference. After analyzing the above recommendations and data obtained from in situ measurements regarding vehicle categories, it was determined [6] that the longest truck at the selected intersection was a tractor unit with a two-axle trailer approximately 14 m in length (Fig. **2b**), and the longest articulated bus operating at all existing entries was an 18 m-long bus (Fig. **3**). However, considering the guidelines [11, 12, 34], the tractor unit presented in Fig. **2a** was also included in the analyses. The capacity analyses presented in this article were performed using computer software [7], which only included a tractor unit with a two-axle trailer slightly over 16.5 m in length. Its basic parameters are shown in Fig. **2a**.

a) PM1 – length 16.76 m, maximum steering angle – 17.7˚, maximum angle between tractor and trailer 70˚

b) PM2 – length 13.87 m, maximum steering angle – 23˚, maximum angle between tractor and trailer 70˚

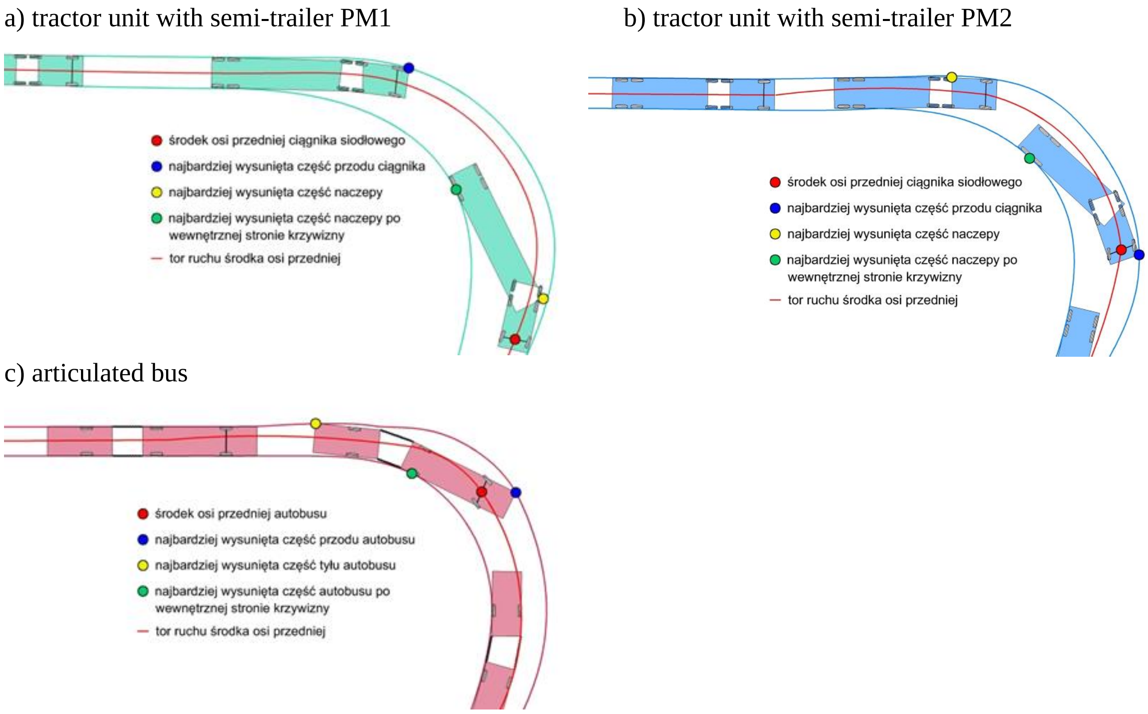


2. Accepted reference vehicles – tractor units with semi-trailers PM1 and PM2



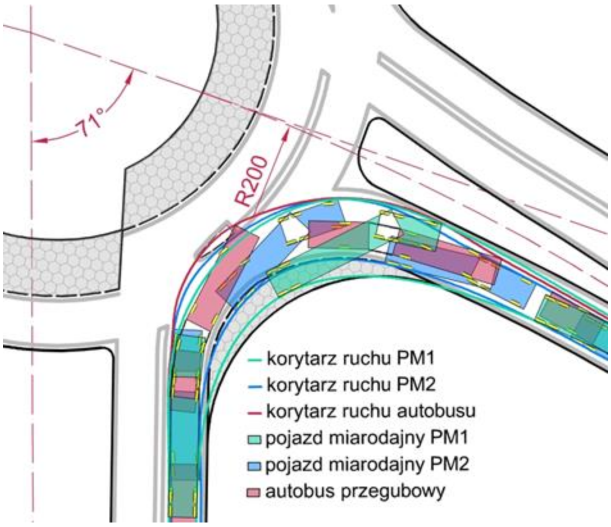
3. The reference vehicle adopted was an articulated bus with a length of 17.967 m, maximum steering angle of the wheels – 28.3˚,
maximum steering angle of both parts of the articulated bus 50˚

To determine the final traffic corridors, traditional movement trajectories of the most extended parts of the reference vehicles are used, as shown in Fig. **4**. In Fig. **4**, in addition to the standard movement trajectories of the most extended points of the vehicles, the movement trajectory of the front axle center is also presented.



4. Traffic corridors and traffic trajectories of the most advanced points of the adopted reference vehicles: a) PM1; b) PM2; c) articulated bus

Fig. **5** presents an example comparison of the traffic corridors of the analyzed reference vehicles in the context of a right turn at the most curved corner of the analyzed roundabout, to demonstrate the differences in their areas and confirm the necessity of conducting capacity analyses in the design process concerning different reference vehicles. Similar research assumptions were also adopted in publications [8, 9], with the only difference being that in the analyses described in the New Zealand guidelines [8], the analysis concerned the differences in traffic corridors of tractor units adopted in the Dutch guidelines, which are shorter than those encountered in New Zealand. In publication [9], different traffic corridors were compared: trucks without trailers, regular buses, and tractor units with trailers. Depending on the analyzed reference vehicle, different lane widths were recommended for various types of Basic, Egg, and Knee turbine roundabouts concerning four different initial diameters. The detailed analysis of traffic corridors presented in Fig. **5** indicates that at the most curved corner of the analyzed roundabout, the traffic corridor of the articulated bus occupies a significantly larger area on the roundabout roadway in the context of a right turn, and tractor units PM1 and PM2 occupy a larger area on the outer part of the roundabout than the traffic corridor of the articulated bus. The largest area on the paved surface is occupied by vehicle PM1 due to the smallest steering angle of the wheels.



5. Comparison of traffic corridors of the analyzed reference vehicles on the most curved corner of the analyzed turbine roundabout

Research Assumptions Adopted in the Capacity Analysis Performed in the Design Process

In publications [8, 19, 33], it is recommended to design all entries of a turbine roundabout as straight segments in plan view and directed at right angles to each other. Unfortunately, this assumption cannot always be ensured, as the roundabout design must refer to the actual road situation and should not constitute a significant economic barrier, requiring substantial land occupation, demolition of existing buildings, etc., solely due to the right-angle orientation of entries. Considering the above, this article selected a location with highly varied individual entries for analysis, both in terms of their orientation relative to each other at angles other than right angles and in terms of entry curvature.

The recommended lane widths included in the Dutch guidelines [33] consider the traffic corridors of the standard reference vehicle, provided in [12]. Additionally, it was allowed that, exceptionally, the wheels of the reference vehicle may slightly exceed the separation lanes but must not drive on the curbs located on the separation lanes. These assumptions were also confirmed in other publications [4, 16, 29, 36]. Furthermore, the aforementioned guidelines assumed that it is rare for reference vehicles to simultaneously travel on both lanes of the roundabout roadway. Publications [8, 9, 13, 26] also drew attention to these conditions of possible simultaneous driving on both lanes. Additionally, they highlighted slight differences in reference vehicle dimensions and the necessary adjustments of separation lane parameters on the roundabout roadway and entries due to the too narrow lane widths on the roundabout roadway. In the analyses described in this article, traffic conditions confirmed during site visits were adopted, where buses and tractor units with trailers or two articulated buses simultaneously traveled on both lanes. Considering the above, the simulations accounted for the simultaneous driving of the adopted reference vehicles on both lanes. This assumption constituted a significant research condition, particularly concerning curved entries.

The above assumptions allow for comparing the obtained results of the necessary widths of both lanes on the roundabout roadway not only concerning the reference vehicles adopted by the authors (Figs. **2** and **3**) but also reference vehicles analyzed in publication [9] (i.e., a bus approximately 12.5 m long and a tractor unit with a 15.5 m-long trailer) or those in publications [13, 26], referring to a tractor unit typical for a given country.

Another assumption concerned the width of separation lanes. In the guidelines [33, 29, 36] and in publications [4, 13, 14, 15, 16, 24, 25, 39, 40], a separation lane width of 0.7 m was adopted. Additionally, the Dutch guidelines [33] recommend a separation lane width of 1 m but do not recommend other lane widths. In the analyses described in publications [9, 32], considering that in the USA, turbine roundabouts were built without separation lanes with raised curbs, a separation lane width of 0.30 m was adopted with the simultaneous assumption that the movement trajectory of the outermost wheel would be located 0.30 m from the edge of the separation lane. This assumption, concerning traffic corridors, effectively constituted "theoretical" separation lane widths of 0.9 m. In this article, a separation lane width of 0.7 m was adopted for the research analyses. Considering the widths of the horizontal marking lines applicable in Poland and the possible curbs to be applied, it was assumed that they would slightly vary the internal parameters of the separation lane and the internal and external safety lanes, the so-called "strips," on the roundabout roadway.

The last assumption concerned the orientation of the traffic corridor when entering the internal lane of the turbine roundabout. In publications [8, 9, 13, 14, 15], it was assumed that a reference vehicle entering the roundabout from the internal lane at the entry does not enter the traversable part of the roundabout and only occasionally drives over a small portion of it. Moreover, in the analyses presented in publications [8, 9, 13, 14, 15], varying distances of the outer edge of the traffic corridor from the edge of the separation lane or the edge of the horizontal marking line were adopted. These differences were mainly related to the width of the horizontal marking lines, which slightly differed in various countries. However, the basic cross-section of the roundabout roadway and the dimensions of individual roundabout elements were always maintained. Considering the above, the initial parameters of the turbine roundabout (regarding the recommended lane widths and separation lane) analyzed in this article were adopted based on the Dutch guidelines [33]. Additionally, it was assumed (similar to the aforementioned cases) that the reference vehicle should not drive on the separation lane but may drive on the separation island, provided it does not interfere with the traffic corridor on the adjacent lane.

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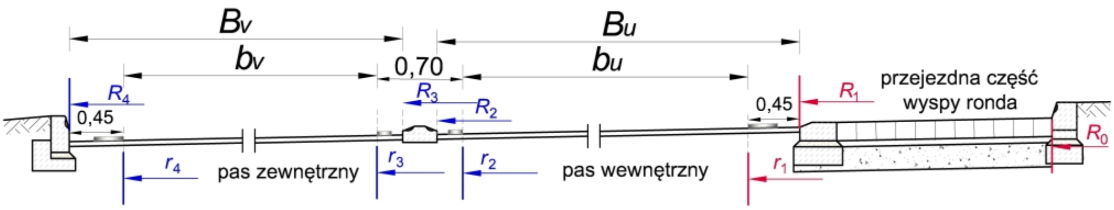
Adopted Methodology for Designing a Turbine Roundabout with Curved Entries Oriented Relative to Each Other at Non-Right Angles

Taking into account the previously outlined characteristics of the research area and traffic conditions, as well as the aforementioned research assumptions, the following roundabout design methodology was adopted, primarily based on traffic corridor analysis. Initially, the large turbine roundabout parameters provided in the Dutch guidelines [33] were adopted as the starting parameters. The adopted roundabout parameters are compiled in Fig. **6** and Table **2**. After performing the capacity analysis, it was assumed that all changes to the roundabout parameters would be made iteratively, primarily based on the analysis of traffic corridors of selected reference vehicles, aiming to ultimately obtain a roundabout with ensured capacity. However, the roundabout design must ensure not only capacity but also traffic safety, which, in addition to a reduced number of collision points, should result from the expected lower speeds achievable on the fastest travel routes, i.e., when driving straight.

Fig. **6** presents the general designations of the analyzed roundabout parameters and the radii of tangent curves from various points located on the translation axis, according to the adopted tangential drafting technique described in [11, 18, 33]. Table **2** additionally presents the parameters obtained during successive capacity analyses of reference vehicles and the resulting widening of the internal or external lanes, as well as corrections to the radii of entry curvatures. Additionally, the widths of the horizontal marking lines P-7a (0.24 m) and P-2a

(0.12 m) applicable in Poland, as well as the width of the curb used in Poland on the separation lane equal to 0.28 m, were taken into account.



6. Proposed roundabout parameters according to Dutch guidelines [33], on a Basic type turbine roundabout with a 0.7 m wide separation strip

Analysis of Ensuring Traffic Corridors on a Basic-Type Turbine Roundabout Designed According to Dutch Guidelines with a 0.7 m Separation Lane

First, the traffic corridors in the context of right turns were examined. The obtained traffic corridors for PM1, PM2, and the articulated bus confirmed that the outer lane was too narrow at all entries and that chamfers should be applied regardless of the entry orientation and its curvature (Fig. **7**). Additionally, all reference vehicles traversed the separation island and the separation lanes at the entries and exits. Considering the multitude of analyses concerning the analyzed reference vehicles, Fig. **7** only presents selected traffic corridors for reference vehicle PM1 in right turn contexts and reference vehicle PM2 in straight-through contexts from the main entries. The analysis of the remaining traffic corridors, in left turn contexts from all entries and straight-through contexts from the secondary entries, showed that all analyzed reference vehicles on the roundabout roadway exceeded the edges of the separation lane and the horizontal markings on the outer edge of the roundabout, indicating that both traffic lanes on the roundabout roadway were too narrow. These conclusions confirm the findings from the studies published in [9]. The analysis of traffic corridors at the entry to the roundabout from the internal lane, however, showed that due to the curvature of the entries and their relative orientations, they encroached upon the adjacent lane, confirming that the recommended rounding radii of 12 m for the separation lane at the entries, as stated in the guidelines [11, 33], were too small. These observations confirmed the conclusions from the studies described in [13], especially since, in the analyzed case, the entries were curved and not oriented at right angles relative to each other.

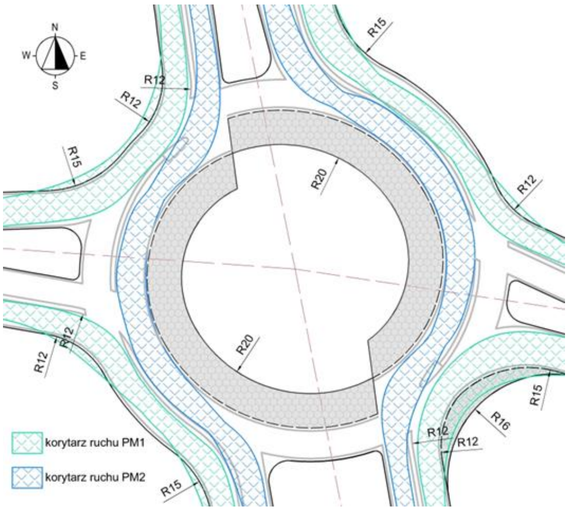
Analysis of Ensuring Traffic Corridors on a Basic-Type Turbine Roundabout After Widening the Traffic Lanes on the Roundabout Roadway

Taking into account the above observations and conclusions, the first iteration was performed by widening the internal lane by 0.10 m and the external lane by 0.30 m. Unfortunately, the traffic corridor analysis did not show significant improvement, as the traffic corridors still exceeded the edges of the separation lanes on the roundabout roadway and at the entries. Considering the above, an additional widening of the external lane was adopted (Table **2**), and appropriate bends were applied to the ends of the separating islands at a slope of 1:10 (at the northern, western, and eastern entries), allowing for smoother entry onto the roundabout roadway from the internal lane. To avoid chamfers, larger rounding radii were also applied to the entries and exits (Table **2**). These corrections ensured the traffic corridors for reference vehicle PM2; however, reference vehicle PM2, when entering the roundabout from the internal lane at the northern and southern entries, traversed the traversable part of the roundabout (Fig. **8**). Entering the traversable part of the roundabout from the internal lane is not recommended in the Dutch guidelines [33], but it is permissible for tractor units with trailers in the guidelines [8, 26, 29, 36].

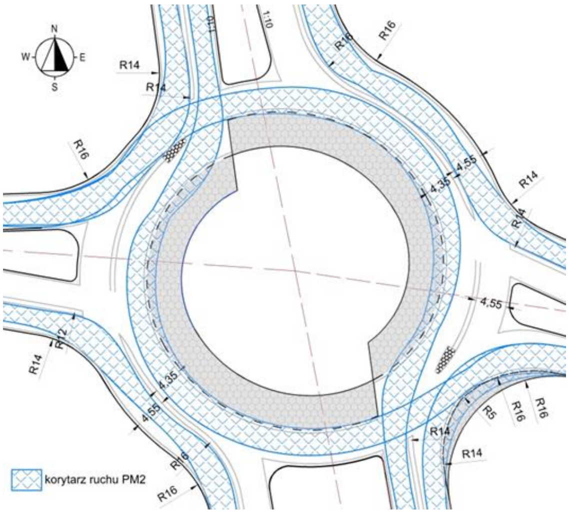
Table 2. Summary of subsequent iterations of the geometry parameters of the Basic type turbine roundabout

The main elements of the cross-section of a normal Basic type turbine roundabout		Width of selected elements, [m]:			Applied radius, [m]:		
Another iteration of the roundabout parameters:		***1[1]***	***2***	***3***	***1[1]***	***2***	***3***
The radius of the curb face of the impassable part of the roundabout	R_0				14,85	14,85	14,85
Width of the passable part of the roundabout ($R_1 - R_0$)		5,15	5,15	5,15			
The radius of the curb face ending the passable part of the island	R_1				20,00	20,00	20,00
P-7b Line width		0,24	0,24	0,24			
P-7b Line edge radius	r_1				20,45	20,45	20,45
The width of the inner lane measured between the inner edge of the trafficable part of the roundabout island and the inner edge of the separator, $B_u = b_u + 0{,}21 + 0{,}45$	*Bu*	4,91[2]	**5,01**	5,01			
Inner belt width $b_v = (r_2 - r_1)$	b_u	4,25	**4,35[4]**	4,35			
P-2a Line edge radius	r_2				24,70	**24,90**	24,90
P-2b Line width		0,12	0,12	0,12			
The radius of the inner face of the stone curb	R_2				24,90	**25,10**	25,10
Width of the stone curb on the separation strip		0,28	0,28	0,28			
The radius of the external face of a stone curb	R_3				25,20	**25,40**	25,40
P-2b Line width		0,12	0,12	0,12			
P-2b Line Edge Radius	r_3				25,40	**25,60**	25,60
The width of the outer lane between the outer edge of the separator and the outer edge of the roundabout carriageway, $B_v = b_v + 0{,}21 + 0{,}45$	*Bv*	4,71[3]	**5,21**	**5,96**			
Outer lane width $b_u = (r_4 - r_3)$	b_v	4,05	**4,55[5]**	**5,30[6]**			
P-7b Line Edge Radius	r_4				29,45	**29,75**	**30,90**
P-7b Line width		0,24	0,24	0,24			
Radius of the curb face in the outer diameter of the roundabout	R_4				29,90	**30,20**	**31,35**
Rounding radii used							
Radius of the separation strip at the inlet					12	**12, 14**	**22, 25**
Radius of the separation strip at the outlet					14	**14, 16**	**28**
The radius of rounding the edge of the road at the entrance					12	**14**	**14, 22, 25**
Rounding radius of the road edge at the exit					14	**16**	**16, 28**
Distance between pivot points measured along the translation axis for staking arcs							
Outer rays: R_2, R_3, R_4, i r_2, r_3, r_4	Δ_v	5,15	5,15	5,15			
Internal rays: R_0, R_1 i r_1	Δ_u	4,75	4,75	4,75			

1) Values of the appropriate widths and radii adopted according to the Dutch guidelines [33]
2) 2) According to the publication [9], in the case of a bus of approx. 12 m in length, the lane width should be 4.74 m on a large roundabout, and in the case of a tractor-trailer of approx. 15.5 m in length, the width of the inner lane should be 4.98 m.
3) 3) According to the publication [9], in the case of a bus of approx. 12 m in length, the lane width should be 4.74 m on a large roundabout, and in the case of a tractor-trailer of approx. 15.5 m in length, the width of the outer lane should be 4.98 m.
4) 4) The extension of the inner lane width by 0.10 m adopted in this article.
5) 5) The extension of the outer lane width by 0.50 m adopted in this article.
6) 6) The final width of the outer lane obtained while maintaining the PM1 vehicle traffic corridor.

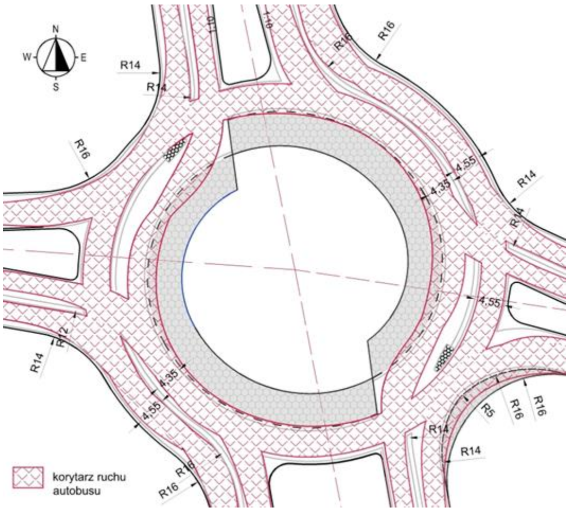


7. The first step of the analysis of trafficability at a roundabout designed according to the dimensions recommended in the Dutch guidelines [33] (Source: authors' study)



8. The second step of the analysis of the passability of selected PM2 vehicle routes after widening the lanes on the roundabout and increasing the radii at the entrance and exit (Source: authors' study)

Similarly, the traffic corridors for the articulated bus at all entries when entering from the internal lane occupied a portion of the traversable part of the roundabout (Fig. **9**). Fig. **9** presents all relationships of the articulated bus and connects all corridors. A detailed analysis of the traffic corridors revealed that, in right turn contexts at the roundabout entry from all entries, the traffic corridor exceeded the edge of the separation lane, indicating that the rounding radius at the entries was too small. Similarly, a detailed analysis of the articulated bus's traffic corridor when entering the roundabout from the internal lane showed that it entered the traversable part. According to the Dutch guidelines [33], heavy vehicles may slightly traverse the traversable part when driving on the internal lane of the roundabout roadway but should not do so when entering the roundabout. However, for articulated buses, this should not be allowed, as any entry into the traversable part may cause undesirable sensations for passengers due to the need to navigate height differences (between the internal lane and the traversable part). Unfortunately, with the adopted parameters for the end of the separating island and the application of too small a rounding radius at the entry from the internal lane, the traffic corridor for the articulated bus occupied a portion of the traversable part. Considering the above, in this case, larger bends of the separating island from the entry axis and the application of larger rounding radii at the roundabout entry should be adopted, which would allow avoiding the widening of the internal lane and prevent entry into the traversable part. Similarly, applying larger rounding radii at the entries and exits would result in smoother relationships and allow avoiding further widening of the external lane without encroaching upon the separation lane.



9. The second step of the analysis of the passability of an articulated bus after widening the lanes on the roundabout and increasing the radii at the entrance and exit (Source: authors' study)

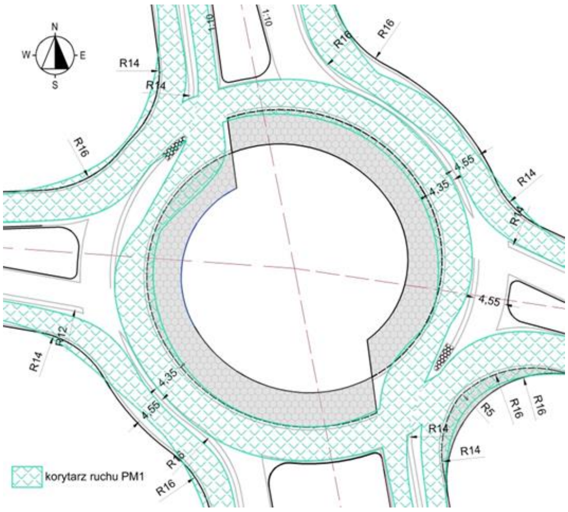
Final Capacity Analysis of Traffic Corridor PM1 at All Entries in Right Turn Contexts

The final capacity analysis of traffic corridor PM1, at all entries in right turn contexts, showed that the traffic corridors were outside the outer diameter of the roundabout, indicating that chamfers should be applied at all entries and exits (Fig. **10**). Additionally, in several locations within turn contexts, the traffic corridors for PM1 exceeded the separation lane. However, further widening of the traffic lanes would result in excessively wide lanes, which would not positively impact traffic safety, as it would inadvertently encourage passenger car drivers to increase speeds or overtake, which is unacceptable.

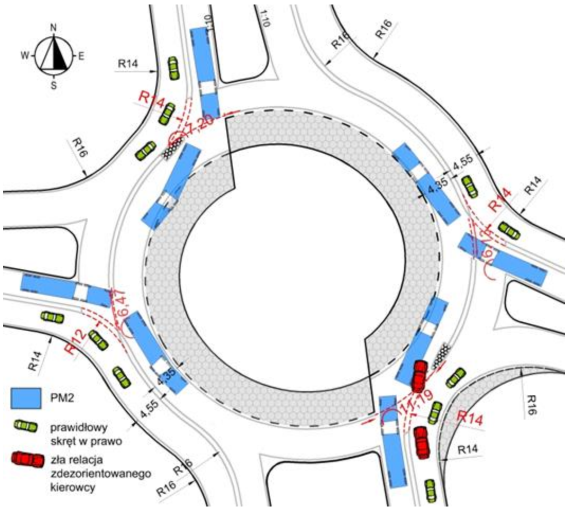
The observed shortcomings were inconsistent with the initial assumptions regarding the prohibition of reference vehicles entering the traversable part and the separation lane. Furthermore, further widening of the internal lane could lead to excessive widening of the so-called "openness of the entry to the internal lane" on the roundabout roadway [9, 13, 26]. The obtained widths of the entry to the internal lane after widening the traffic lanes on the roundabout roadway are presented in Fig. **11**. After geometric corrections, it was found that, at the southern entry, the increased width of the entry to the internal lane could confuse the driver and enable undesirable behavior on the turbine roundabout. However, it should be emphasized that the placement of the separation islands was correct and in accordance with the roundabout design principles, meaning that they were located where the separation lanes on the roundabout roadway connected with the "theoretical extension" of the separation lanes from the main entries (the parameters of the "openness of the entry" are highlighted in red in Fig. **11**).

Analysis of Ensuring Traffic Corridors on a Basic-Type Turbine Roundabout After Changing the Rounding Radii of Entries and Exits

Based on the conclusions from the studies described in publication [13], regarding entries directed at right angles and potentially slightly offset separation island axes, it follows that in similar cases, larger rounding radii for entries and exits should be applied. This approach allows avoiding chamfers and ensures traffic corridors without further widening of the roundabout roadway lanes. Such an approach was implemented in the next iteration of the discussed turbine roundabout case. The parameters adopted in the next iteration are compiled in Table 2 (changed values are highlighted in bold). However, it should be noted that further parameter changes may negatively impact traffic safety, as they involve widening lanes and the "openness of the entry" to the internal roundabout lane.

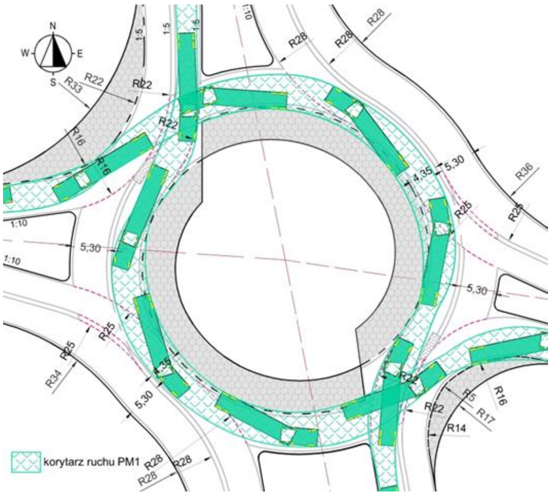


10. The second step of the analysis of the passability of selected PM1 vehicle routes after widening the lanes at the roundabout and increasing the radii at the entrance and exit (Source: authors' study)

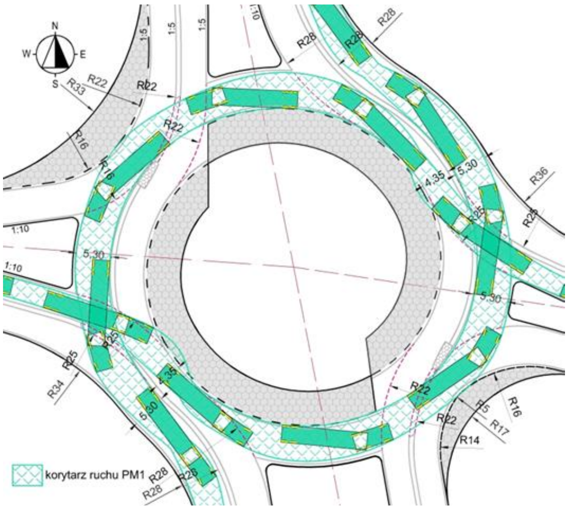


11. Entry widths to the inner lane of the turbine roundabout after widening the lanes on the roundabout and increasing the radii at the entrance and exit (Source: authors' study)

The analysis of traffic corridors presented in Figs. **12–14** showed that after widening the external lane on the roundabout roadway, increasing the bending of the entry lanes to the roundabout, and changing the rounding radii of entries and exits, all traffic corridors for PM1 were ensured. According to guidelines [11, 32, 33], in cases of significant "openness of the entry" to the internal lane, directional arrows should be repeated on the entry lanes to the roundabout to prevent undesirable driver behaviors. Considering the significantly widened external lane, in accordance with guideline [10, 11, 32], after designing the roundabout geometry, it is mandatory to check the speeds on the fastest travel route, i.e., in straight-through contexts.



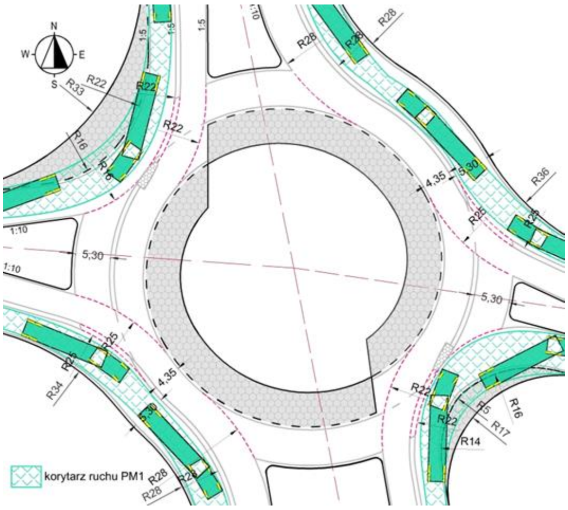
12. The third step of the analysis of the PM1 vehicle movement corridors – left-hand relations from the main inlets – after correcting the inlets and widening the outer lane at the roundabout (Source: authors' study)



13. The third step of the PM1 vehicle movement corridor analysis – left-hand relations from side inlets – after correction of inlets and widening of the outer lane (Source: authors' study)

The above conclusions confirm that for curved and non-right-angle-oriented entries, not only significant widening of the roundabout roadway lanes should be applied, but also appropriate bends in the entries and larger rounding radii for entries and exits should be adopted. The final corrected dimensions of selected critical roundabout parameters are presented in Figs. **12–14**.

Based on the conducted capacity analyses, it can be stated that the lane widths on the roundabout roadway with curved and non-right-angle-oriented entries should be individually selected during the design process based on the traffic corridors of selected reference vehicles. This conclusion also arises from a detailed analysis of the recommended lane widths in publication [9] concerning various reference vehicles on different types and kinds of turbine roundabouts. A similar conclusion can be drawn from comparing the rounding radii for entries and exits recommended in publication [13] and those applied to the analyzed roundabout. In the case of a roundabout with curved entries oriented relative to each other at non-right angles, the rounding radii for entries and exits should be selected based on the analysis of specific traffic corridors (Figs. **12–14**), rather than obligatorily using the rounding radii values recommended for classical turbine roundabouts with straight, right-angle-oriented entries.



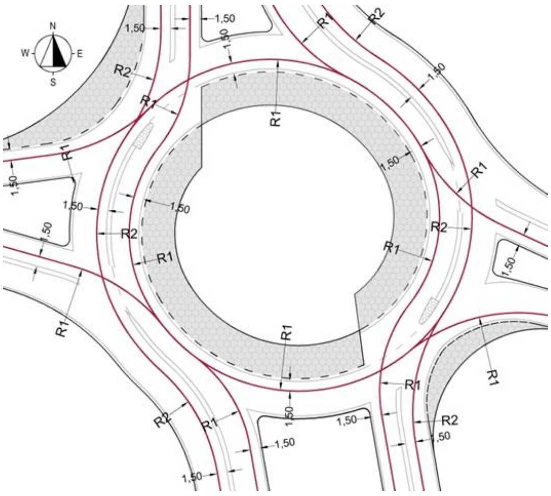
14. The third step of the analysis of the PM1 vehicle movement corridors – relations to the right – after correcting the entries and widening the outer lane at the roundabout (Source: authors' study)

Speed Analysis in Straight-Through Contexts on the Geometrically Corrected Turbine Roundabout

Considering the widened traffic lanes on the roundabout compared to the recommended widths provided in the Dutch guidelines [33] (Table **2**), it is mandatory to check the estimated speed values on the designed roundabout on the fastest travel route. Given that the analyzed roundabout is large, the design speed on it is set to 40 km/h, in accordance with [33, 37]. The speed analysis on the fastest travel route on the analyzed roundabout with curved and non-right-angle-oriented entries was performed according to the recommendations described in [10, 11, 32]. The speed analysis determined by the geometry of the designed roundabout relates to the possible fastest travel route into the roundabout, traversing the roundabout, and exiting it. This is the smoothest travel route through the roundabout referenced to a passenger car, assuming the absence of other vehicles moving on the given roundabout. The fastest travel route through the roundabout is usually determined in straight-through contexts but can also be determined in left or right turn contexts [32]. It must be emphasized, however, that designing the fastest travel route through the roundabout does not reflect expected speeds but rather indicates "theoretical" speeds necessary to verify the correctness of the designed roundabout. Actual speeds achieved on a given roundabout depend on factors such as the vehicle's suspension system, acceleration and deceleration, friction coefficient, transverse slope of the traffic lane, weather conditions, the individual skills and characteristics of the driver, and the tolerance of the driver and passengers to gravitational forces.

Considering the curved and non-right-angle-oriented entries, it was adopted, in accordance with the recommendations described in [32], that the distance of the fastest travel route is 1.5 m from the edge of the separation lane and from the applied horizontal marking line on the internal lane near the separation islands and traversable part, as shown in Fig. **15**. According to the recommendation for designing the fastest travel route through a roundabout for a passenger car, as stated in guidelines [17, 32, 33], the radii of entry into the roundabout, traversing the roundabout, and exiting the roundabout (R1 on the internal lane and R2 on the external lane) are the same, and the three arcs at the connection point share the same tangent. In further analyses, the relationship provided in the Dutch guidelines [33] was used, and it was estimated that the speed on the internal lane was 34.7 km/h and on the external lane 38.1

km/h, meaning that in each case, the speeds were lower than the design value of 40 km/h adopted for large roundabouts [33, 37]. The obtained speeds practically confirm that the designed roundabout has correctly adopted parameters and that the widening of the roundabout roadway lanes did not excessively increase the speed of a passenger car traveling along the fastest travel route. The Dutch guidelines [33] recommend that if the design speed is exceeded at any entry or context, chamfers should be designed to reduce the entry speed. In the analyzed roundabout case, such an exceedance of the design speed was not observed, and the three entries analyzed were still curved with sufficiently small arc radii, so the speed on the approach to the roundabout was practically limited.



15. The process of constructing the geometry of the fastest route through the analyzed roundabout (Source: authors' study)

Conclusions

Based on the conducted case study analysis of a turbine roundabout with curved entries oriented relative to each other at non-right angles, the following conclusions can be formulated:

– The analysis of traffic corridors on the designed turbine roundabout with curved entries, according to the design principles formulated in the Dutch guidelines, showed that for curved entries, adjusted parameters based on the analysis of traffic corridors of selected reference vehicles should be applied.
– The proposed method of iteratively changing selected roundabout parameters based on capacity analyses resulted in an optimal roundabout geometry design in terms of capacity and land occupation.
– The applied iterative principles for determining individual roundabout parameters at each design stage allowed for ensuring traffic corridors first on the internal lane and then on the external lane, indicating the necessity of a phased design approach.
– The original phased design approach of the roundabout and the adoption of changes to individual roundabout parameters starting from the interior and ending with the external boundaries of the roundabout, along with phased traffic corridor analysis, allowed adapting the roundabout design to the actual road situation with highly varied curved entries oriented relative to each other at non-right angles.
– In cases where entries are oriented relative to each other at an acute angle of approximately 70–75°, it is necessary to apply significant chamfers and larger bends of the separating island edges and traffic lanes at the roundabout entry. With an obtuse angle of approximately 105–120°, chamfers may not be necessary, and instead, larger rounding radii between both entries should be applied.

– Based on the conducted capacity analysis concerning three different reference vehicles with distinct characteristic parameters considered in turn contexts, it was demonstrated that traffic corridor analysis should be conducted concerning the vehicles intended to operate on the given roundabout, and not always only concerning the standard tractor unit with a 16.5 m trailer, as this may result in significantly greater land occupation and substantial widening of the roundabout roadway lanes, which can adversely affect traffic safety, especially with large "openness of the entry" to the roundabout.
– By adopting reference vehicles other than the tractor unit with a 16.5 m trailer in capacity analyses, based on traffic measurements and forecasts for future operations, more economical turbine roundabout solutions with curved entries oriented relative to each other at non-right angles can be achieved, and appropriate road signs informing about permissible vehicles can be applied.
– The conducted case study of the selected roundabout demonstrated that for curved entries oriented relative to each other at non-right angles, the roundabout design should primarily be based on the capacity analysis of selected reference vehicles and adjust the basic roundabout parameters accordingly.
– An additional practical contribution of these studies is the possibility to introduce corrections in existing turbine roundabout design guidelines, as well as to include additional recommendations in new guidelines being developed in countries that still lack their own regulations regarding the design of this type of roundabout.

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