sustainability

Article

An Analysis of Turbo Roundabouts from the Perspective of Sustainability of Road Transportation

Jan Petru * and **Vladislav Krivda**

Department of Transport Constructions, Faculty of Civil Engineering, VSB-Technical University of Ostrava, 708 00 Ostrava-Poruba, Czech Republic; vladislav.krivda@vsb.cz
* Correspondence: jan.petru@vsb.cz

Abstract: The designs of turbo roundabouts vary among countries and undesirable and potentially dangerous situations can occur for vehicles passing through the roundabout. In this article, we focus on an analysis of one of the problems within sustainable road transportation, i.e., the geometric layout of turbo roundabouts. First, we review the Czech and foreign regulations and describe the design procedures for turbo roundabouts. Studies that have been performed in the Czech Republic and abroad (the Netherlands, Slovenia, Poland, Germany, Hungary, etc.) are described. We evaluate the geometric layout of turbo roundabouts, the effectiveness of construction adjustments at the entrance to the roundabout, and an analysis of the physical separation of lanes. We present procedures and methods for measurements and assessments, which are used for evaluating the effectiveness of the geometry of a turbo roundabout. Finally, conclusions for the given hypotheses are given, as well as the importance of geometric elements (shape of the turbo roundabout, physical separation of lanes, the spike, etc.) for the actual passage of vehicles through the turbo roundabout. Furthermore, we discuss how these elements influence the safety of road traffic, the sustainability of road transportation, and the emergence of potentially dangerous situations.

Keywords: road transport; turbo roundabout; geometry; physical separation; element of spike; traffic safety

Citation: Petru, J.; Krivda, V. An Analysis of Turbo Roundabouts from the Perspective of Sustainability of Road Transportation. *Sustainability* **2021**, *13*, 2119. https://doi.org/10.3390/su13042119

Academic Editor: Seungjun Roh

Received: 30 November 2020
Accepted: 4 February 2021
Published: 16 February 2021

1. Introduction

Transportation is an inseparable part of the world, from the simplest methods used in the past (so-called nonmotorized land transport, i.e., transportation in wagons, using animals, carriers, rickshaws, etc.), through to conventional types of transportation used nowadays (road, rail, water, and air), to space transportation. Each type of transportation requires an appropriate technical base, a so-called mobile base (i.e., means of transport) and a stable technical base (i.e., transport infrastructure and equipment). These bases must coexist so that they do not negatively influence each other, and thus form a comprehensive, functioning, and long-term sustainable system. An example related to the focus of this study is the design of intersections (roundabouts); if the dimensions or geometric layout of an intersection are such that motor vehicles have difficulty passing through the intersection safely, dangerous situations may occur (i.e., traffic conflicts [1–5] or even accidents [6,7]). For example, an intersection with a small corner radius can be a problem, if it forces a driver who is turning right to enter the opposite direction when exiting the intersection. Drivers of ordinary vehicles, as well as drivers of oversized cargoes could encounter problems while passage through the intersection [8,9]. There are so-called backbone routes in road networks, for the transport of various large machine parts, construction machinery, etc. On such a route there is often an intersection (e.g., a roundabout), however, which does not contain elements for the passage of large cargoes.

The capacity of an intersection is often unsatisfactory. The simplest solution seems to be to reconstruct the intersection into an intersection with better dimensions, and thus increase its capacity; however, this does not always happen, and if it does, it is often at the expense of traffic safety [10,11]. Microsimulation traffic models [10,12] are suitable means for evaluating the capacity of an intersection solution, which complement traditional capacity calculations and often are reliable for pointing out possible problems.

Another possible solution is to reconstruct the intersection into a different type of intersection. Uncontrolled intersections are frequently reconstructed into roundabouts. There are many types of roundabouts, from standard single-lane ones, to turbo roundabouts, and other special types (double, "hamburger", etc.) (see examples [13–15]). As previously mentioned, reconstruction of an intersection often involves building an intersection with larger dimensions, which is not always appropriate, or sometimes is even impossible.

The abovementioned consideration is only part of what a designer must take into account when designing intersections. This issue is very closely related to sustainable transportation, or to sustainability in general [16–20], because new and larger transportation construction is not endlessly possible and it is always at the expense of our environment, which also has its limits. The primary goal of a traditional approach to transportation planning is to enable the greatest possible mobility of the population. However, we see the negative impacts of this way of planning around us every day in terms of a worsened environment, accident rates, etc. As mentioned in the Introduction, transportation is an inseparable part of humanity, and therefore it is necessary to find a sustainable compromise.

This issue is also related to the proper design and construction of transportation structures. In this article, we deal with a specific type of intersection, i.e., turbo roundabouts (see Figure 1).

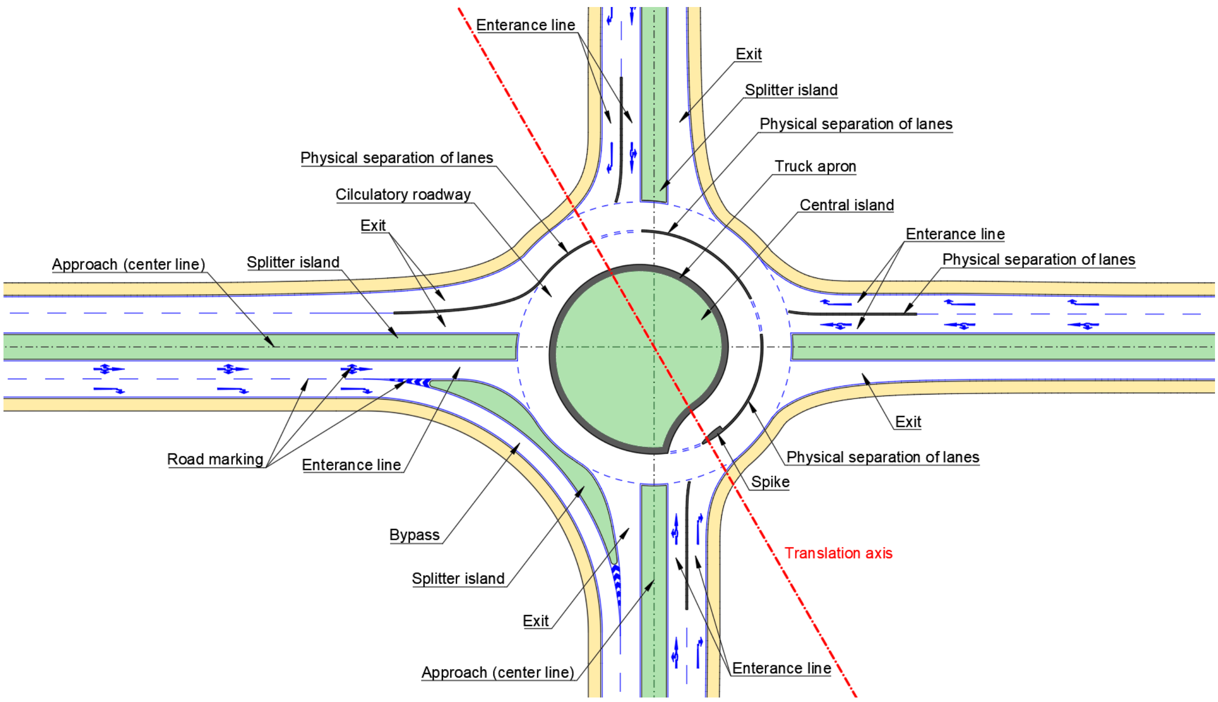

Figure 1. A turbo roundabout.

Turbo roundabouts, as reported by the current research, are generally considered to be safe [11,21,22]. An important element is the capacity of the turbo roundabout [11,22–25]. They are considered to have more capacity than single-lane roundabouts, but some may have less capacity than two-lane roundabouts [22,23]; however, they are safer than two-lane roundabouts. There are also traffic conflicts or accidents in turbo roundabouts [5,20,26]. Another aspect to be considered in the design of turbo roundabouts is their sustainability, including their influence on the environment, in particular, their life cycle assessment (LCA) [27] and the influence of emissions at turbo roundabouts in urban areas [28,29].

A specific element of turbo roundabouts is the physical separation of lanes and whether these lanes should be separated or not [13,15,22,23,30]. In addition, the influence of the geometry of the turbo roundabout on safe passage of vehicles through it and the influence of physical separation on traffic safety [22,30] should be considered. Another specific element is the representation of traffic signs, including how signs should inform road users for safe passage through the turbo roundabout [3,23,31,32].

Because turbo roundabouts are still evolving as traffic and transportation infrastructures change, there are more and more questions to be answered. The development and design elements also differ significantly among countries, where the turbo roundabout design takes place separately for each area. For the reasons mentioned above, we conducted our study on 105 turbo roundabouts in Europe (the Czech Republic, Luxembourg, Hungary, Germany, the Netherlands, Poland, Austria, Slovenia, and the UK) from 2014 to 2019 [5]. The aim of the research was to analyze the regulations for designing turbo roundabouts and the geometric design elements, as well as traffic signs, and to determine the behavior of drivers in a given type of turbo roundabout to identify conflict situations and analyze their causes. For example, whether these conflicts were caused only by the mistakes by drivers who did not follow traffic rules, or whether they were caused by inappropriately designed building elements of the given turbo roundabout. The main goal of the study was to optimize the design of a turbo roundabout and to determine if following all the design parameters in the existing regulations would avoid errors in the design of a turbo roundabout.

In this paper, our aim is to, first, review the European regulations for the geometric design of turbo roundabouts for the professional public and to confirm the hypothesis that correctly designed turbo roundabouts could partially contribute to road sustainability. If the geometrical and building elements of a turbo roundabout are correct, traffic on it should be smoother and safer. This would help to achieve the required capacity, to ensure a minimum number of traffic conflicts or accidents, and to reduce negative influences on the environment.

2. An Analysis of Regulations for the Design of Turbo Roundabouts

From the point of view of sustainable and safe transportation, an understanding of the design procedures of a turbo roundabout is essential. The regulations in this area differ among European countries, and therefore it is necessary to analyze individual regulations and design procedures in detail. Our findings focus on the initial approach for designing a sustainable transport infrastructure from the perspective of the coexistence of individual transports and the impact on the environment, the evaluation of effectiveness of individual procedures, and possible recommendations for adjustments to increase the effectiveness of this type of roundabout.

We chose countries that have had experience designing turbo roundabouts (the Czech Republic, The Netherlands, Slovenia, Germany, Croatia, and Serbia) for the analysis. The analysis of regulations summarizes the findings regarding regulations for the design of a turbo roundabout from the perspective of individual elements of the roundabout (geometry, central island, physical separation, verification of swept paths, etc.).

2.1. Design Vehicles

The individual elements of an intersection and, subsequently, the intersection as a whole must enable the passage of a relevant design vehicle [31–42]. The choice of the design vehicle and its swept path have a major influence on the geometry of a turbo roundabout [43] and should be based on the composition of the traffic flow (personal vehicles, trucks, etc.) and on the percentage share of the given vehicle types within the total traffic flow of the area where the intersection is located.

The design parameters of a vehicle affect its subsequent behavior when verifying the swept paths. The width and length of a vehicle affect the resulting curve; the front and rear overhang, the distance of the individual axles, the wheelbase, etc. also influence the final design. The usage of a design vehicle is guaranteed to achieve more accurate results for the design of a turbo roundabout for vehicle passage with the most unfavorable parameters. Figure 2 shows a design vehicle; an example of technical data for chosen countries is shown in Table 1.

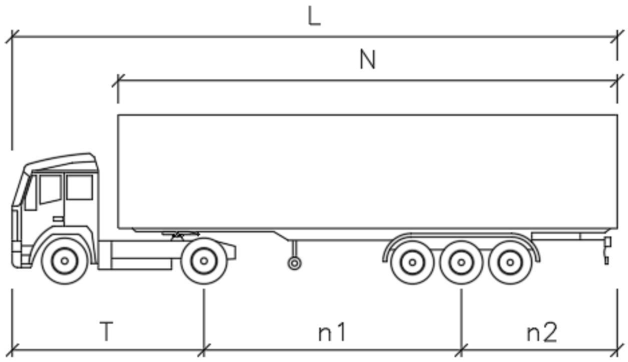

Figure 2. A design vehicle for the verification of swept paths on a turbo roundabout.

Table 1. The parameters of design vehicles for individual countries.

Feature	Design Vehicle						
	Czech Republic	**The Netherlands**	**Slovakia**	**Slovenia**	**Germany**	**Croatia**	**Serbia**
Overall length L (m)	16.50	16.50	16.50	16.53	16.53	16.50	15.40
Vehicle width d (m)	2.50	2.55	2.50	2.50	2.50	2.50	2.50
Semitrailer length N (m)	13.61	13.60	13.61	13.60	13.60	13.60	12.20
Truck length T (m)	4.50	4.50	4.50	4.50	4.50	4.50	4.50
The length between axles n1 (m)	7.78	7.80	7.78	7.78	7.78	7.97	7.15
Overhang n2 (m)	4.25	4.20	4.25	4.25	4.25	4.20	3.75

2.2. A Turbo Block

The basic design of the geometry of a turbo roundabout is the so-called turbo block (Figure 3), which is a set of lines used for the design of lanes on the circulatory roadway. The turbo block is formed by mutually adjoining arcs of given radii. Their points of connection and mutually rotated centers lie on the rotated translation axis. A turbo roundabout can consist of one, two, or three lanes on the circulatory roadway, as can be seen from Figure 3. A new lane is created at the entrance and is adjacent on the inside to the continuous lane of the circulatory roadway. New lanes are proposed at the main entrances in the traffic-dominant directions of traffic flows (i.e., flows with higher traffic intensities). The direction of the dominant flows, thus, becomes the basic criterion for choosing a suitable type of turbo roundabout.

The analyzed regulations differ significantly in the construction approach for turbo roundabouts. In some documents, the turbo block is defined by predetermined dimensions, other documents do not provide information about the parameters (templates) of the turbo block.

The Czech Republic, the Netherlands, Slovakia, Slovenia, Croatia, and Serbia are among the countries that have regulations that determine the parameters for the turbo block, whereas Germany is among the countries with regulations where there is no turbo block.

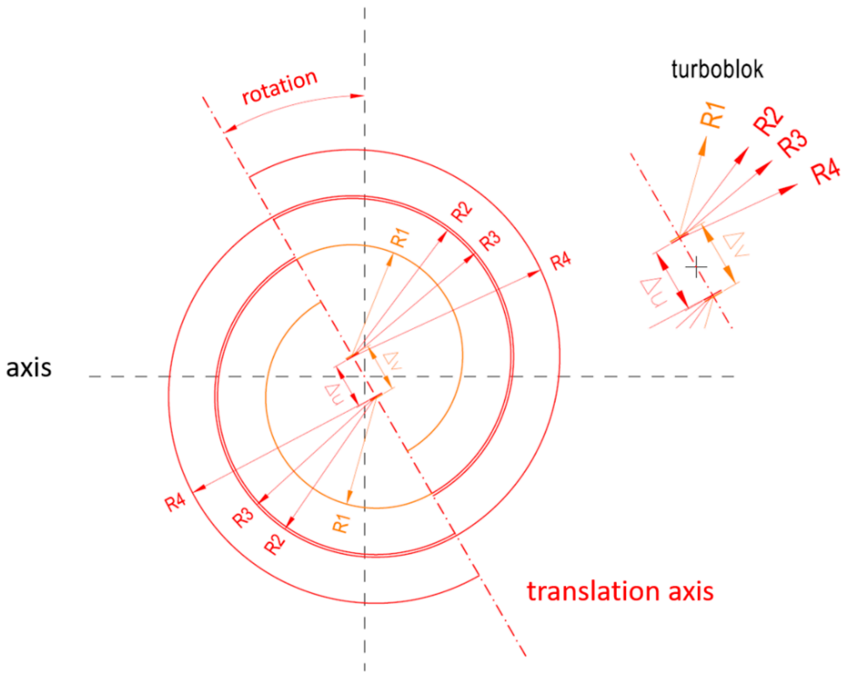

Figure 3. The basic geometric arrangement of the turbo block.

The basic geometric arrangement of the turbo block is shown in Figure 3. The turbo block consists of two spirals, which represent the edges of the lanes (road). The individual spirals consist of four semicircles of different radii. These radii increase gradually (from R1 to R4). The centers of these radii lie on the so-called translation axis. The arcs, R1 and R2, represent the inner and outer edges of the inner lane L1 on the circulatory roadway, while the arcs, R3 and R4, represent the inner and outer edges of the outer lane L2 on the circulatory roadway.

At the beginning of the inner lane L1, an extension is made, which gradually decreases towards the end of the lane. This extension is achieved precisely by designing four centers of circular arcs located on the translation axis. The centers of the individual arcs have various positions on the translation axis. The arcs on the right side of the translation axis have centers above the general center of the turbo roundabout, and the arcs on the left side have centers below the general center of the turbo roundabout. The distance between these centers of arcs is called the offset from the translation axis. The deflection of the arcs is, then, the distance from its center to the general center of the turbo roundabout; at the same time, this value is equal to half the offset along the translation axis. For the continuous spiral, it is necessary for the offset along the translation axis to be equal to the change in radius. Not with all regulations it is about continuous spiral. Ideally, the offset along the translation axis is equal to the width of the lane [44].

The physical separation of the lanes is achieved with the help of 0.30 m wide elements (concrete curbs, assembly parts, setts, etc.).

An example of a comparison of turbo block parameters in relation to the size of the turbo roundabout from the analyzed regulations is shown in Table 2. The table shows the dimensions of the turbo block elements for countries that have extensive experience with the design of turbo roundabouts, i.e., the Netherlands, Slovenia, Serbia, Croatia, Slovakia, and the Czech Republic. As can be seen in the Czech Republic, the dimensions of the turbo block, the turbo roundabout signs, and the categorization according to the outer diameter differs significantly from other regulations. The German regulations do not define the parameters of the turbo block, for these reasons they are not listed in the table.

Table 2. The dimensions of a turbo block processed on the basis of the analysis of the regulations for designing turbo roundabouts.

Dimension of Elements of a Turbo Block of a Turbo Roundabout (in Meters)												
Label	**Small**		**Small**	**Standard**		**Small Standard**	**Middle**		**Standard**	**Large**		**Large**
Outer diameter	47.35	47.45	<56.0	49.95	49.90	56.00–60.00	55.35	55.45	60.00–65.00	64.55	64.65	>65.0
Element	NL SI RS	HR SK	CZ	NL SI RS	HR SK	CZ	NL SI RS	HR SK	CZ	NL SI RS	HR SK	CZ
R1	10.50	10.45	10.50	12.00			15.00	14.95	15.00	20.00	19.95	20.00
R2	15.85		17.85	17.15		18.975	20.00		21.55	24.90		25.95
R3	16.15		18.15	17.45		19.275	20.30		21.85	24.90		26.25
R4	21.15	21.20	24.55	22.45		25.525	25.20	25.25	27.85	29.90	29.95	31.90
L1	5.35	5.40	8.30	5.15		7.70	5.00	5.05	7.10	4.90	4.95	6.25
L2	5.00	5.05	6.40	5.00		6.25	4.90	4.95	6.00	4.70	4.75	5.65
Δv	5.75		8.60	5.35	5.30	8.00	5.15		7.40	5.15		6.55
Δu	5.05		6.70	5.05	5.00	6.55	4.95		6.30	4.75		5.95

R1, the radius of the outer edge of the central island; R2, the radius of the inner edge of the physical separation of lanes; R3, radius of the outer edge of the physical separation of lanes; R4, radius of the outer edge of the circulatory roadway; L1, width of the inner lane of the circulatory roadway with the edge of carriageway markings; L2, width of the outer lane of the circulatory roadway with the edge of carriageway markings; Δv, distance between the outer points on the translation axis; Δu, distance between the inner points on the translation axis. Abbreviations of states (geographically): NL, The Netherlands; SI, Slovenia; RS, Serbia; HR, Croatia; SK, Slovakia; CZ, Czech Republic.

According to Dutch regulations [37], the design of a turbo roundabout should always start by choosing a turbo block with respect to its suitability for the area and in terms of vehicle speed. The optimal value of the inner radius depends on the dimensions of the dividing islands of the approach centerline. For an island width of 3 m, the optimal value of the inner radius is 12 m. For dividing islands of 7 m width, this value increases to 15 m [45]. The use of smaller inner radii is only recommended in places with significant space constraints and the usage of larger inner radii when traffic characteristics require it. In the Slovenian [38] and Serbian regulations [40], a turbo roundabout with an inner radius is classified as a roundabout of "regular" size. In the Croatian regulations [41], a roundabout of "regular" size has a radius of 12 m and is the most frequently used typed of roundabout. The Slovak regulations [44] recommend a 12 m radius and 15 m at the exit of the roundabout. The Czech regulations [31] recommended value of the corner of the roundabout at the entrance is 12 m, and the exit consists of a compound arc with radius of arcs 2:1:3 (R = 40, 20, and 60 m).

On the basis of the values from Table 2, it is obvious that almost all the above stated dimensions of regulations from the Netherlands, Slovenia, and Serbia differ by 0.05 m from the regulations from Croatia and Slovakia. This difference results from the different widths of the outer lane on the circulatory roadway of the roundabout. The edge of carriageway markings is 0.45 m wide (possible is also 0.40 m) in the Netherlands, Slovenia, and Serbia, while, in Slovakia and Croatia, the edge of carriageway markings is 0.50 m wide. The inner markings are the same width, i.e., 0.20 m. We further analyze the fundamental difference in the size of the widths of individual lanes on the circulatory roadway in the Czech Republic. The individual widths can be seen in Figure 4.

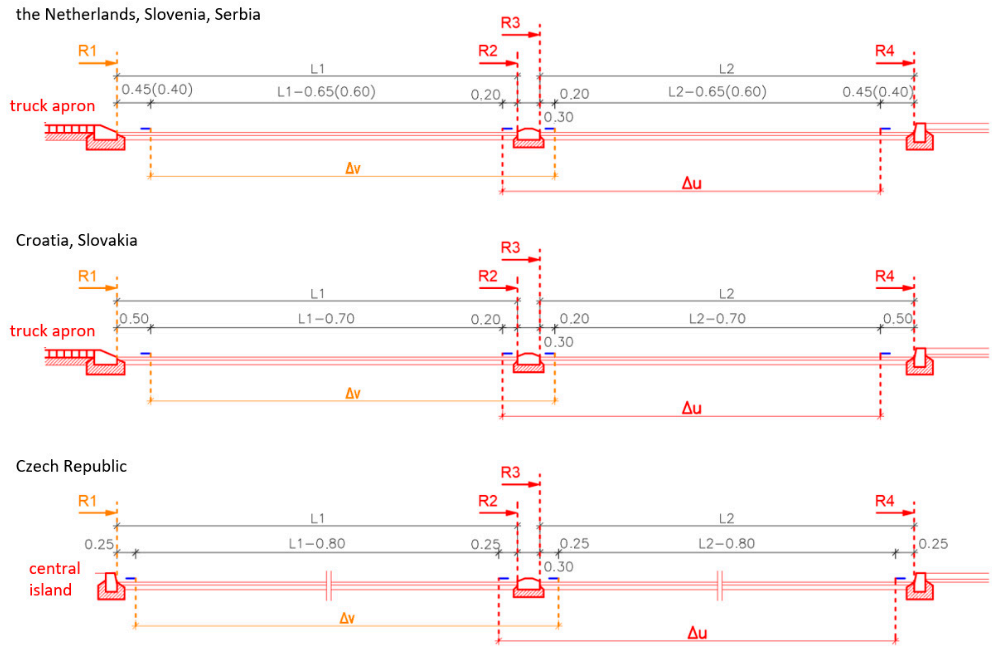

Figure 4. A comparison of width layout of a turbo roundabout on the basis of the dimensions of turbo block.

Most documents recommended a width of 5.25 m for a lane on the circulatory roadway. This width should represent the value of the standard width of a lane in the circulatory roadway of a single-lane roundabout. In the Netherlands, a turbo roundabout is considered to be a single lane due to the physical separation of lanes [46].

As previously mentioned, the turbo block should be designed so that the individual radii of the arcs on both sides of the translation axis touch, that is, the inner radius of the lane on one side of the translation axis continues smoothly on the other side [47]. The turbo blocks based on the regulations from the Netherlands, Slovenia, and Serbia do not fully meet this requirement. The parameters of the turbo block include a 0.05 m offset of circular arcs on the translation axis (Figure 5). In the regulations from Croatia, Slovakia, and the Czech Republic, this offset is excluded by using 0.05 m wider outer edges of the markings. The circular arcs overlap on the translational axis.

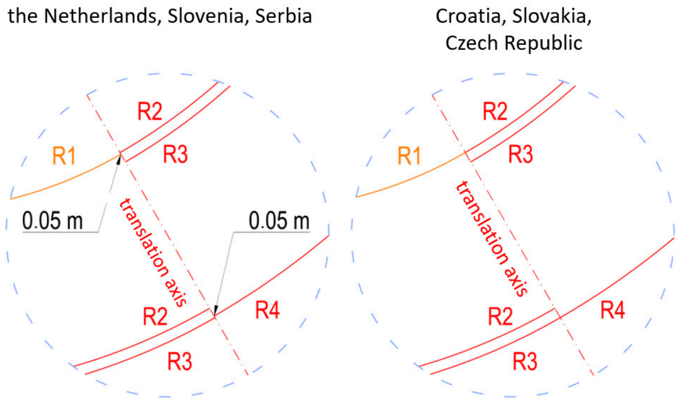

Figure 5. The difference in design of the geometry of arcs on translation axis in individual countries.

An analysis of European regulations describing the turbo block shows that the Dutch, Slovenian, and Serbian regulations recommend rotor and star-shaped turbo roundabouts. The parameters for these variants are given only in the regulations from the Netherlands. According to the German regulations [39], a turbo block consists of three pairs of circular arcs (R1, R2, R3) and only two centers on the translation axis (Figure 6).

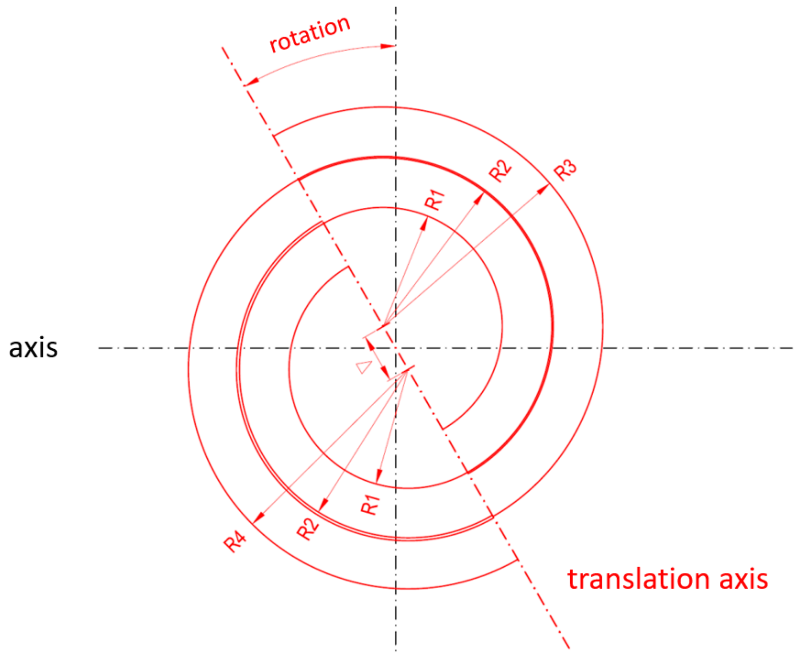

Figure 6. A turbo block according to the German regulations.

The recommended position of the translation axis is given as "five minutes to five" for the intersection of four approach centerlines and "ten after eight" for the intersections of three approach centerlines. The first center represents the centers of the arcs on one side of the translation axis and the second center represents the centers of the arcs on the other side of the translation axis. As a result, the width of the lanes on the roundabout is constant. The German regulations for turbo roundabouts [39] do not provide turbo block parameters with predetermined dimensions. According to the regulation, the width of the circulatory roadway depends on the diameter of the turbo roundabout and on the design trajectory of the vehicle. The recommended values for turbo roundabouts range from 45 to 70 m and the width of the lane on the circulatory roadway should be from 5.0 to 6.0 m. The position of the translation axis should be determined interactively in relation to the position of the approaches of the turbo roundabout and the vehicle path (passage of a vehicle through the turbo roundabout).

After creating the turbo block, other remaining elements of turbo roundabouts can be designed including a central island, lanes on the approach centerline of the turbo roundabout, a dividing strip, traffic islands, etc. The definitions of the elements differ from one regulation to another. The same elements are named differently and have different purposes. Different dimensions are assigned to them and the definition of their geometry differs significantly.

2.3. Central Island

The central island of a turbo roundabout consists of a truck apron and a central island area (Figure 7). According to the Dutch regulations [37], the truck apron of the island allows passage of vehicles longer than 22 m through the inner lane of the circulatory roadway. The recommended width of the truck apron is 5.00 m. In the Croatian [41], Slovenian [38], and Serbian regulations [40], the truck apron is defined as an area on which only special emergency vehicles and ordinary vehicles in an emergency can stop. The recommended width of the truck apron is from 2.0 to 2.5 m. In the Slovak technical regulations [44], the paved part is intended for a smoother passage of heavy trucks and the width of the truck apron is from 2.0 to 2.5 m. In the Czech regulations, the truck apron is not a necessary part of the turbo roundabout and is seldom designed, especially for the passage of large vehicles [31].

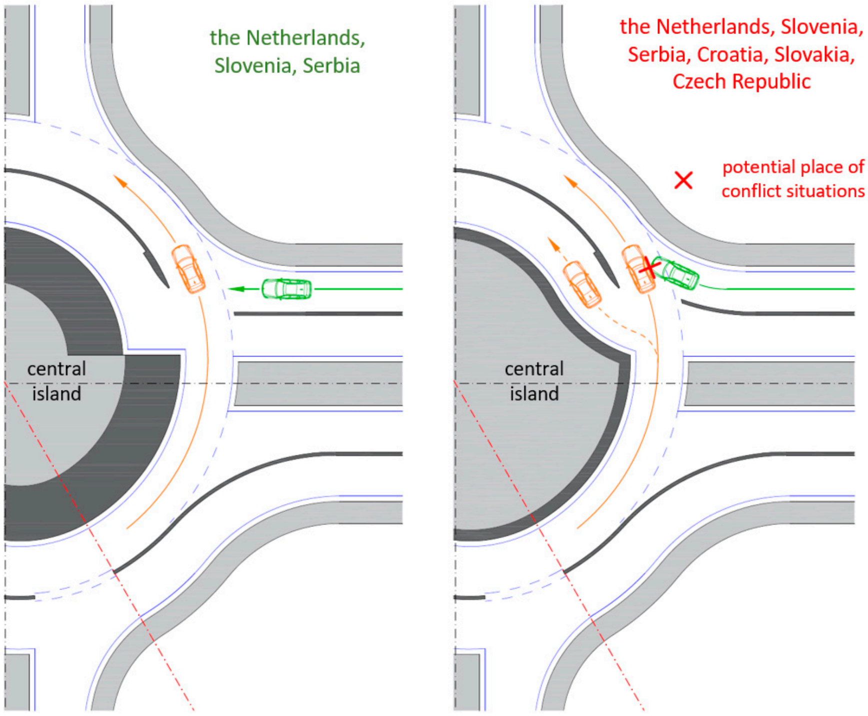

Figure 7. The beginning of the central island. (**right**) Flat; (**left**) Spiral.

Regulations also vary considerably in the parameters of the central island. In the Netherlands, traffic signs are placed here. They reduce the view of the opposite approach in the direction of travel. This is a requirement for the safety of roundabouts. According to the Croatian, Slovenian, and Serbian regulations, this element is irrelevant. In the German regulations, the central island is an important element of a turbo roundabout, but its parameters are not given. In the Slovak regulations, the central island of a turbo roundabout has no function, and it represents a redundant space. However, it should be designed to prevent a direct view through the turbo roundabout. The Czech regulations state that if a part or all of the central island is outside the field of view, its height arrangement is solved at that point so that it prevents a view through the roundabout from the approach crossing the turbo roundabout [31].

The beginning of a central island can be flat or spiral (Figure 7). In the Netherlands, it was first implemented as a spiral. In the new regulations, it is also recommended as flat, as the spiral is ambiguous for drivers coming to the entrance of the turbo roundabout Consequently, it can lead to a potential traffic conflict on the circulatory roadway of the turbo roundabout. The Croatian, German, Slovak, and Czech regulations have all examples designed as spiral. In the Slovenian and Serbian regulations, both types of the beginning of the island are listed, i.e., flat and spiral. Apart from the Czech and Slovak regulations, other regulations do not provide more detailed information on the design of the spiral beginning of the central island.

2.4. An Approach Centerline of a Turbo Roundabout

According to the analysis of the Dutch regulations, the approach centerlines should form an angle of 90° with each other (due to the driving of long vehicles). It should be noted that 90° entrances to a turbo roundabout are very difficult to plan. Achieving the required angle in the case of reconstructions of existing two-lane roundabouts with significant space restrictions is almost unrealistic. Furthermore, the approaches should be designed so that the speed of the car during the passage through the turbo roundabout does not exceed the maximum recommended value [45]. According to the German regulation, the approaches should intersect at the geometric center of the roundabout, but it is not defined at what angles.

Many European regulations state detailed instructions for the verification of the vehicle passage through a roundabout. The main parameters defining vehicle passage are the width of the entry and exit lanes, the width of the dividing islands, and the radii of the corner of the turbo roundabout. All these parameters should be chosen on the basis of the size of the roundabout, the relevant design trajectory of the vehicle, and the required speed of driving through the roundabout.

The width of the entry and exit lanes to a turbo roundabout is not precisely defined in many regulations (the Netherlands, Croatia, Slovenia, Slovakia, Serbia, and the Czech Republic). The regulations refer to other regulations for the design of roads, local roads, legislation, etc.

Dividing islands on the approaches of a turbo roundabout have, in the regulations, also different roles and definitions of geometry. In the Netherlands, the minimum width of the dividing island is 2.50 m; in the Croatian, Slovenian, and Serbian regulations, this value is 2.0 m; the German regulations do not have recommendation.

The radii of the entrance to a turbo roundabout have previously been mentioned. In the Czech regulations [41], the recommended value of the corner of the turbo roundabout at the entrance is 12 m and the exit is formed by a compound arc with a ratio of arcs of 2:1:3 (R = 40, 20, and 60 m).

2.5. Physical Separation of Lanes

According to Slovenian experts, countries can be divided into two groups with respect to designing turbo roundabouts [48], i.e., countries where physical separation of lanes is used (see Figure 8) and countries where physical separation of lanes is avoided. The main reason why these countries have fewer satisfactory experiences with turbo roundabouts is that "traffic signs do not prevent lane change" [48]. The author of [49] claimed that the use of physical separation of lanes is unacceptable due to the requirements for safety of motorcycles, winter service and maintenance, and that the absence of these elements does not have a major impact on the safety and capacity of a turbo roundabout. Regulations from the Netherlands, Croatia, Slovenia, Serbia, Slovakia, and the Czech Republic recommend implementation of physical separation of lanes. For turbo roundabouts in cities, the use of a specially designed "spike" is recommended, which should prevent unacceptable driving and enable the passage of long trucks through the turbo roundabouts (Figure 8).

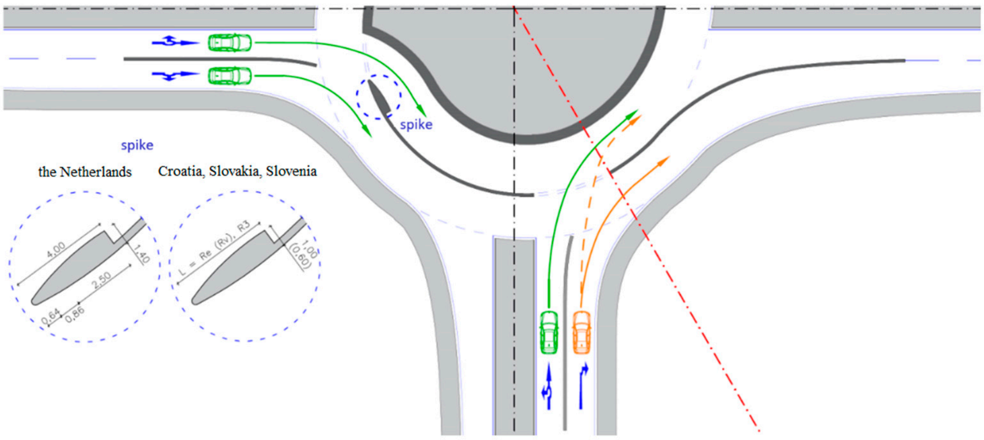

Figure 8. Physical separation of lanes and the definition of the shape of a "spike".

In the Netherlands, a spike has fixed dimensions [49], while other countries (Croatia, Slovenia, and Slovakia) do not have a defined length, rather the length depends on the radii used and the swept path of the vehicle. This element is not defined in the Serbian, Czech, and German regulations.

2.6. Geometry Check

After designing all elements of a turbo roundabout, it should be checked and, here, the analyzed regulations also differ. Regulations from the Netherlands, Croatia, Slovenia, Serbia, Slovakia, and the Czech Republic use some of the following analyses for the final design: an analysis of the swept paths of the design vehicle; an analysis of the fastest trajectory of the vehicle; and an analysis of the speed of the vehicle at the entrance, on the circulatory roadway and at the exit of the turbo roundabout. If these analyses show negative results, the geometry of the designed turbo roundabout must be adjusted.

In the German regulations, the basis for defining all elements of a roundabout is the analysis of the passage of the vehicle (swept paths). The difference between the German regulation and the other analyzed regulations is the fact that the fastest trajectory of the vehicle through the turbo roundabout is not required. The design procedure described in this regulation may lead to higher speeds through the turbo roundabout; however, the speed can be regulated by traffic signs in this case. These design procedures are mainly used for turbo roundabouts located in places with significant spatial limitations, where it is not often possible to rebuild the elements of the roundabout (increase in diameter).

2.7. An Analysis of Other Regulations

The regulations of other European countries were also analyzed. Full versions of documents for designing turbo roundabouts were not available for some countries, and therefore these countries were not included in the analyses.

For example, in the UK, there are numerous roundabouts, which are not a traditional design, but a modification of the horizontal traffic signs on the circulatory roadway in the form of a spiral. Other countries, such as Belgium, Italy, Hungary, and Poland have designed turbo roundabouts following the Dutch or Slovenian regulations.

2.8. Partial Conclusions from the Analysis of the Regulations

The analysis of regulations for designing turbo roundabouts showed that they differ in several aspects such as the number of variants, information about relevant structural elements, dimensions of a turbo block and other elements, the definition of the design, and the input and output parameters for checking the design.

Despite these differences, some regulations have a common basis (i.e., they are based on the same regulation) and they define the procedure for creating a turbo roundabout. These are, in particular, the design procedure for a turbo block, the subsequent analysis of the speed of the vehicles and the analysis of the route (swept paths). This approach to design procedures is highly dependent on a follow-up check. If the subsequent check of the design is not performed properly, there is a risk of designing an excessive or an inadequate turbo roundabout. Giving a designer some freedom to consider satisfactorily evaluated elements in the design, may ultimately be fundamental for proper functioning of a turbo roundabout.

First, we analyzed regulations for evaluating the effectiveness of a turbo roundabout that, subsequently, have a major impact on the safety and sustainability of transport infrastructure. We also considered different designs of a turbo block; an evaluation of the physical separation of lanes, including the design of the spike; an analysis of the fastest vehicle trajectory; and an evaluation of the swept paths based, among other things, on the performed measurements of existing turbo roundabouts in Europe. The observed elements of 105 turbo roundabouts were analyzed.

3. Evaluation of the Effectiveness of Turbo Roundabouts

3.1. Geometry

In order to evaluate the effectiveness of a turbo roundabout, it is necessary to know its geometric design which has a fundamental influence on its use, i.e., traffic safety, the capacity of the roundabout, the effectiveness itself, and the subsequent sustainability of traffic.

In the previous section, the geometry of a turbo roundabout was analyzed, especially from the point of view of regulations for designing in the Czech Republic and abroad (the Netherlands, Slovenia, Slovakia, Croatia, Germany, etc.). An important aspect of the geometry is the detection of conflict situations [5], which occur on already existing turbo roundabouts. Measurements were performed on 105 turbo roundabouts in European countries. The acquired data were used for analysis of conflict situations and analysis of regulations for design, the design of geometry, and its effectiveness can be adequately evaluated.

The effectiveness of a turbo roundabout was evaluated by comparing two sets of regulations for the design procedures of turbo roundabouts. The first set of regulations is the Slovak regulations [44], which are based on regulations from the Netherlands [37] and Slovenia [38]. The Slovak regulations are one of the newest sets of regulations for turbo roundabout design with almost the same parameters as the abovementioned regulations (see Table 2). The second set of regulations is the Czech technical regulations [31].

3.1.1. Design of a Turbo Roundabout: Parameters of a Turbo Block

When choosing the design parameters of a turbo roundabout, it is necessary to proceed from the largest dimension of vehicles that will pass through the turbo roundabout. For example, the following describes the design procedures for a “standard” turbo roundabout [44] (which has the same dimensions of turbo block elements R1 to R4 within the foreign regulations) and a “small standard” turbo roundabout [31] (based on the same radius R1 as the “standard” one and there is the smallest difference in the width of the lanes L1 and L2, and the distance between the points on the translation axis Δu and Δv from the point of view of the relation to the size of the outer diameter) (the comparison of dimensions of the turbo block elements for individual regulations are given in Table 2):

Step 1: Translation axis

In the first step, it is necessary to determine the angle of the approaches to the turbo roundabout. The ideal design is for the approaches to be perpendicular to each other, i.e., to form an angle of 90°. The angle of 90° is determined, in particular, in the Dutch regulations [37]. The translation axis, which forms an angle of 30° is drawn into the layout prepared in advance (which is the recommended value of the diversion of the translation axis). The distances between the outer points Δv and the inner points Δu are indicated on the translation axis. This procedure is the same for both regulations. They differ only in the distance of the points on the translation axis (Figure 9).

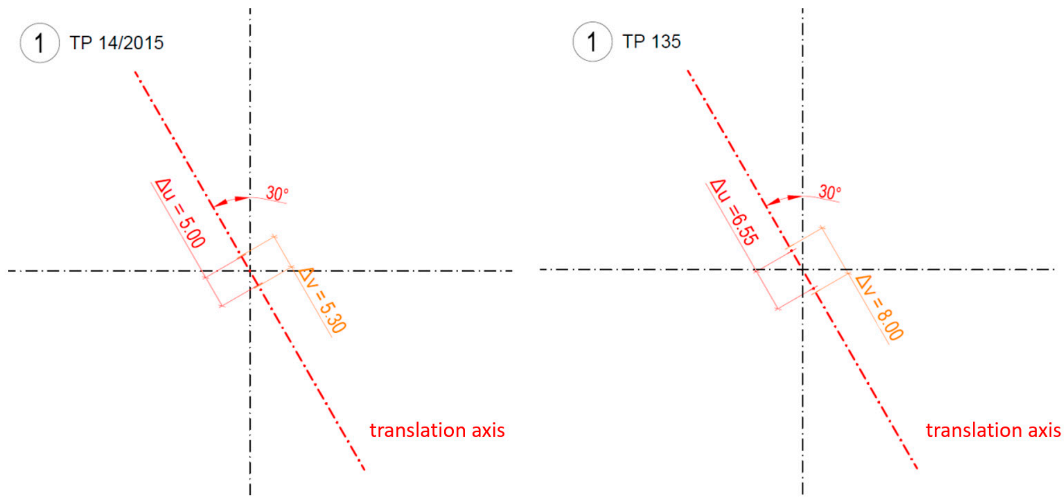

Figure 9. A translation axis and the distance between the outer and inner points. (**left**) The Slovak regulations; (**right**) The Czech regulations.

Step 2: A turbo block

Then, the individual radii are indicated so that the edge lines connect to each other and form a spiral. During the creation, the radius R1 is plotted from the centers with a mutual distance Δv, while the radii R2, R3, and R4 are plotted from the centers with a mutual distance Δu. The values are stated in Table 2. This construction ensures that the arcs with radius R1 connect to an arc with radius R2 on one side of the translation axis. Arcs with radii R3 and R4 are connected on the other side of the translation axis. The drawn turbo block is shown in Figure 10. This procedure is again identical for both sets of regulations.

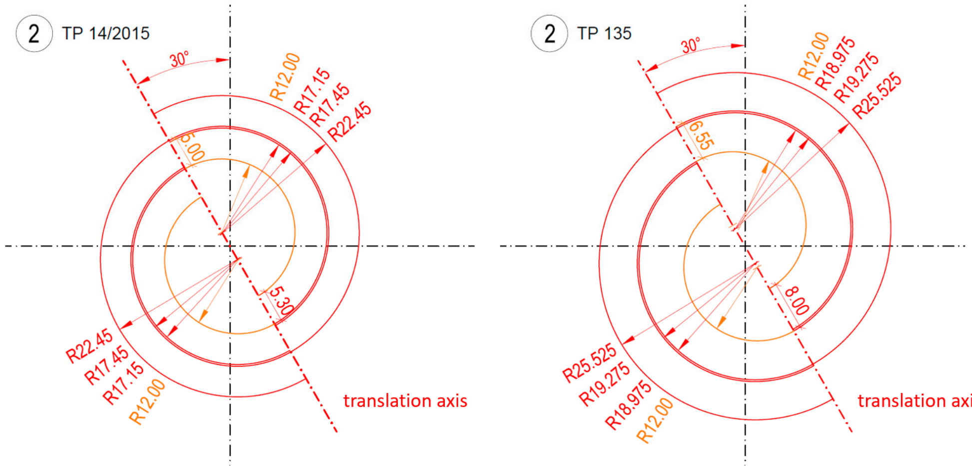

Figure 10. The representation of turbo blocks for individual regulations. (**left**) Slovak regulations; (**right**) The Czech regulations.

Step 3: Determination of the width of the traffic lanes

The width of the traffic lanes depends on the speed achieved on the designed turbo roundabout, and also on the choice of the type of the design vehicle for which the turbo roundabout is designed. The choice also depends on the locality in which the turbo roundabout is designed and according to which regulations it is designed. For comparison of the effectiveness, traffic lanes (on the main and secondary approaches of the turbo roundabout) were designed with the same width of traffic lane (Figure 11). The difference that is evident in the design lies in the different width of the edge of carriageway markings of the turbo roundabout according to individual regulations [31,44].

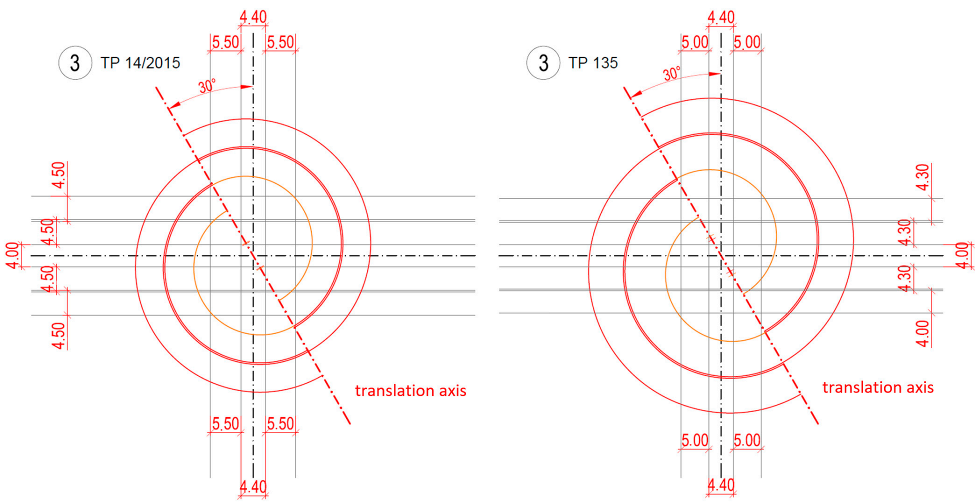

Figure 11. The representation of the width of the traffic lanes in the turbo roundabouts. (**left**) The Slovak regulations; (**right**) The Czech regulations.

Step 4: Adjustment of the geometry

In this step, the entrances to the turbo roundabouts are adjusted. In the Slovak regulations [44], the traffic lanes are cut at the outer circles of the turbo block. The Czech regulations [31] change the rotation of the translation axis. The translation axis forms an angle of 39.20° after the rotation of the entire turbo block. According to the author of the regulations [31], this is the optimal angle (this angle can be changed according to effectiveness) and the calculation for changing the angle is not part of the regulations [31]. As part of the evaluation of the effectiveness of the turbo roundabout, an inappropriate change in geometry, in this step, could affect the speed of the passage of the vehicle through the turbo roundabout, or has an influence on the safety of traffic. Furthermore, according to the Czech regulations [31], it is suitable to make a slight deviation of the traffic lane at the entrance and exit (approximately 5°–10° towards the axis of the approach) points of connection of the approach to the roundabout circulatory roadway. This would ensure deceleration of the vehicles approaching the circulatory roadway and it would facilitate passage of large vehicles (Figure 12). Although according to [31] this adjustment should have a positive effect on the capacity of the turbo roundabout, it is not entirely specified how to construct this angle (at what distance). This element can have an influence on the geometry of the passage.

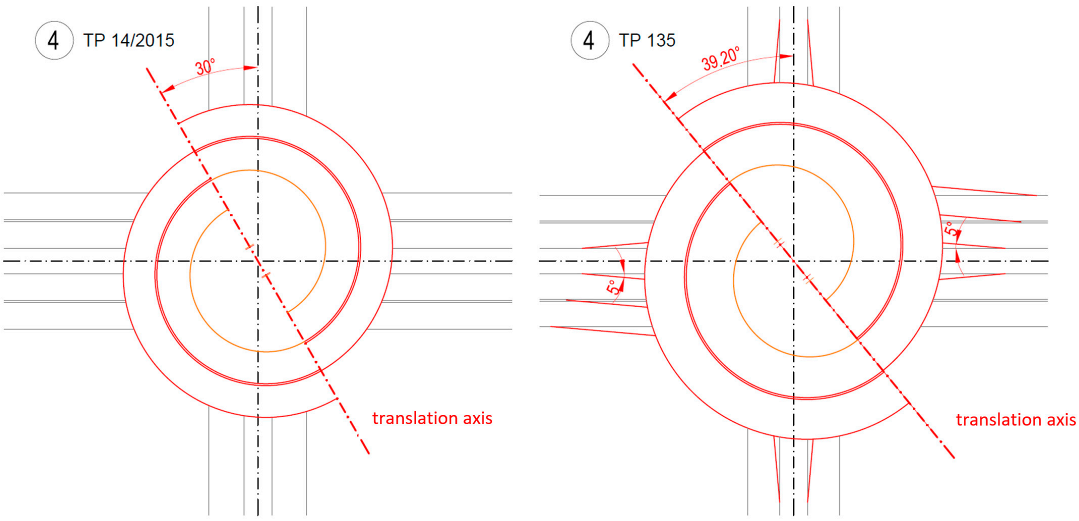

Figure 12. The adjustment of the entrance to the turbo roundabout. (**left**) The Slovak regulations; (**right**) The Czech regulations.

Step 5: Radii at the entrances and exits to and from the turbo roundabout

The evaluated regulations fundamentally differ in the adjustments of radii at the entrances to and the exits from turbo roundabouts (Figure 13). The Slovak regulations [44] recommend similar radii at entrances and exits to/from the turbo roundabouts, the same as regulations from the Netherlands [37] and Slovenia [38], i.e., a radius of 12 m at the entrance and 15 m at an exit. Furthermore, traffic signs are added, and the element of a spike is designed. The design of the spike according to the Slovak regulations [34] is shown in Figure 14. The radii R2 and R3, indicated in Figure 14, are the radii of the inner and the outer edges of the physical separation of the lanes, respectively. The radius Rv is the radius of the inner edge of the extension of the part of the physical separation. Ru is the radius of the continuous line (shifted radius Rv). Radius RT1 is the radius of the line separation at the entrance to the inner lane of the circulatory roadway.

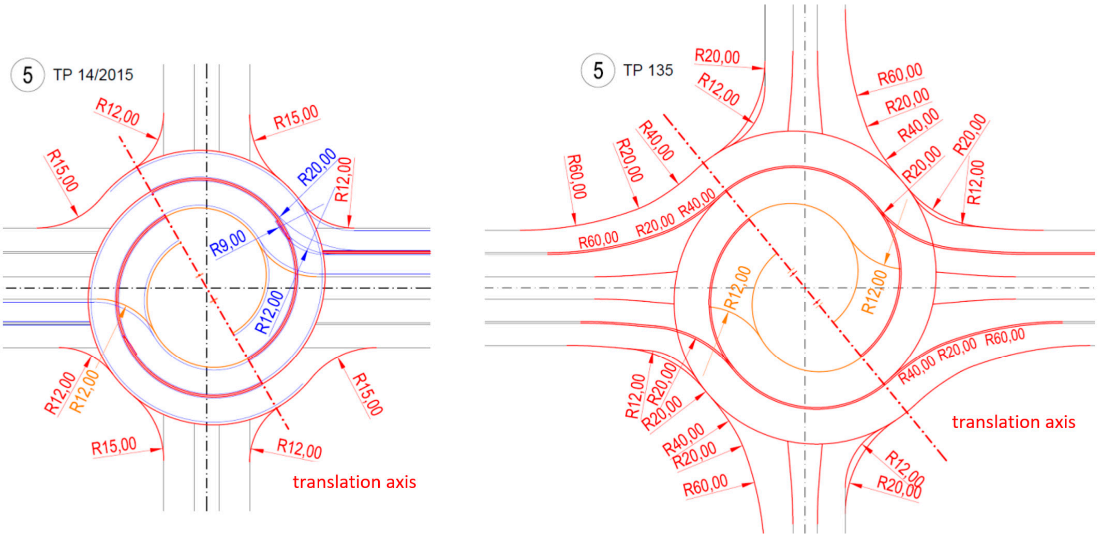

Figure 13. Design of radii at the entrances and exits to/from a turbo roundabout. (**left**) The Slovak regulations; (**right**) The Czech regulations.

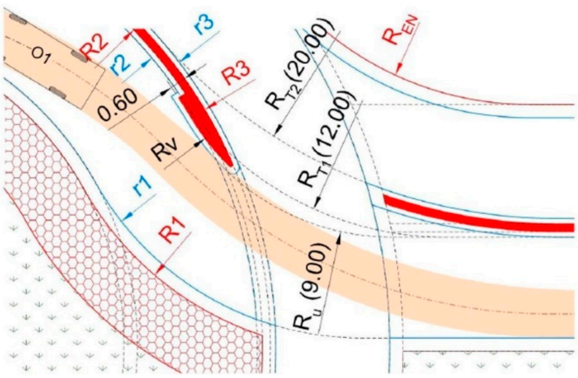

Figure 14. Design of spike according to TP 15/2015 [34].

According to the Czech regulations [31], the design is supplemented by compound arcs with radii R1, R2, and R3 = 2:1:3 (20, 30, and 60 m). When designing a "small" turbo roundabout, there may be problems with drawing a compound corner (it is not possible in some cases to draw it due to the size of the turbo roundabout and the connection to an individual radius); designers may have difficulty drawing it, or they may design it inappropriately. The compound arc significantly increases the speed of vehicles at the exit of the turbo roundabout. In the case of a pedestrian crossing or a place for crossing, etc. is designed at the exit, this geometric design may have a significant influence on traffic safety.

Step 6: The final design

In the last step, the geometry of the turbo roundabout is adjusted, truck aprons are added, and the design of horizontal traffic signs is realized (Figure 15). For both sets of regulations, the modification of the central island is implemented as a spiral. The regulations do not specify, in more detail, the entrance to the turbo roundabout from the side road, and thus the adjustment of the physical separation of lanes (required maximum/minimum width of the gap for the entry of the vehicle). Figure 16 shows designs for comparison, which were drawn according to individual regulations, and then connected. The design according to the Slovak regulations is shown in red and the design according to the Czech regulations is shown in black.

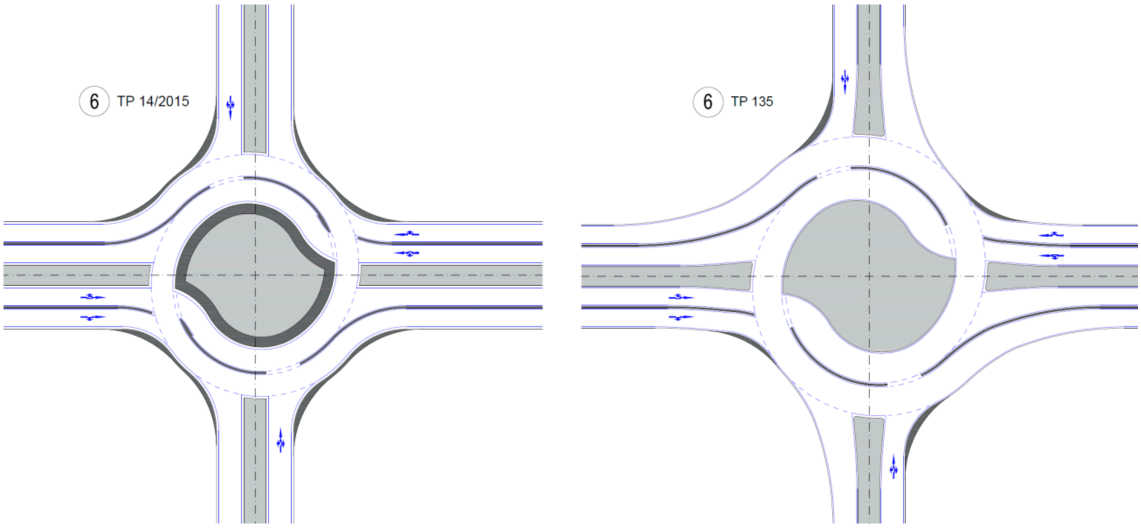

Figure 15. The final designs of a turbo roundabout according to individual regulations. (**left**) The Slovak regulations; (**right**) The Czech regulations.

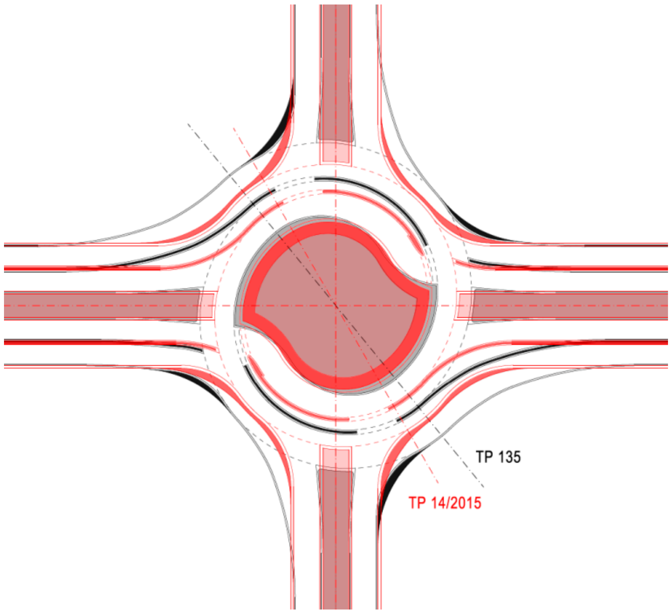

Figure 16. Connection of final designs drawn according to individual regulations. (**red**) The Slovak regulations; (**black**) The Czech regulations.

3.1.2. Geometry Check

The check of the geometrical elements of the turbo roundabout is mainly in the inspection of the position of a turbo block. In this case, auxiliary lines are drawn by extending the outer boundaries (edges) of the entrance and exit roads in both horizontal and vertical directions. The distance between the auxiliary lines and the circles with a radius for determining the position of the 0.30 m wide physical separation on the circulatory roadway is measured. If the distances are approximately the same, the position of the translation axis is correct.

If the position of the translation axis of the turbo block is correct, the trajectories of the passage for all directions are smooth. The speed, transverse acceleration, and the radii of the trajectory are set correctly. If any of these trajectories appear to be diffracted, the translation axis must be rotated. Each time the position of the translation axis is changed, it is necessary to correct all radii of rounding at the entrance and exit to/from the turbo roundabouts [44].

There must also be a concord between the speed of the passage and the transverse acceleration for a correct design of the turbo roundabout. These aspects also have an influence on the capacity of the turbo roundabout. The achieved speed of the passage of vehicles through the turbo roundabouts should be less than 40 km/h [28]. The achieved speed of the vehicle obtained from the calculation (limit speed) should be lower than the design speed of the passage of 35 km/h and at the same time it should be higher than 20 km/h for the design vehicle (car). According to [32], the transverse acceleration of the design vehicle should not exceed 0.33 g at 20 km/h at any part of the turbo roundabout.

The achieved speed at the arc is calculated according to following formula [32]:

$$v_1 = 3.6 \times \sqrt{g \times R_L \times f_0'} = \sqrt{127 \times R_L \times f_0'} \ \ [\text{km/h}] \tag{1}$$

where:

- g gravitational acceleration (m/s^2);
- R_L radius of circular trajectory (m);
- f_0' coefficient of transverse friction (0.35 for speed up to 20 km/h and 0.40 for speed over 20 km/h).

Relative transverse acceleration is calculated according to the following formula [32]:

$$a = \frac{\left(\frac{v_1}{3.6}\right)^2}{R_{L \times g}} \tag{2}$$

where:

- v_1 achieved speed at the arc (km/h);
- R_L radius of circular trajectory (m);
- g gravitational acceleration (m/s^2);
- a values are given in multiples of g.

Speed limit at the arc is calculated according to the following formula [32]:

$$v_m = 3.6 \times \sqrt{g \times R \times (f + 0.01 \times p)} = \sqrt{127 \times R \times (f + 0.01 \times p)} \ \ (\text{km/h}) \tag{3}$$

where:

- g gravitational acceleration (m/s^2),
- R radius of circular trajectory (m),
- p road cross fall, if there is an opposite fall, negative value is used (%).

Relative transverse acceleration of speed limit is calculated according to the following formula [3]:

$$a = \frac{\left(\frac{v_m}{3.6}\right)^2}{R \times g} \tag{4}$$

where:

- v_m achieved speed at the arc (km/h),
- R radius of circular trajectory (m),
- g gravitational acceleration (m/s^2),
- a values are given in multiples of g.

The radii of individual circular trajectories of the passage of the vehicle are obtained by approximating the trajectory of the passage of the design vehicle by a set of simple circular arcs.

The designed turbo roundabout according to the Slovak and Czech regulations, were compared with the control of the speed of the passage of the vehicle, which is stated for the given type of turbo roundabout in the regulations. The geometry according to technical regulations TP 14/2015 [44] and TP 135 [31], and the design (Steps 1–6 see above) were compared within the evaluation of the effectiveness of turbo roundabouts. Swept paths were constructed on the basis of experience gained from our measurements and evaluation. Therefore, the passage was verified in the way vehicles use the spatial solution of the turbo roundabout. For these reasons, differences emerge in comparison with the regulation for designing.

The geometry according to TP 14/2015 [44] and a comparison with the design (Steps 1–6) within the evaluation of the effectiveness of turbo roundabouts are shown in Figure 17. For comparison, the measured values of individual arcs are given in Table 3. In this table, the speed control stated in TP 14/2015 [44] for this type of turbo roundabout is performed. In Table 4, a speed control is performed on the prepared design.

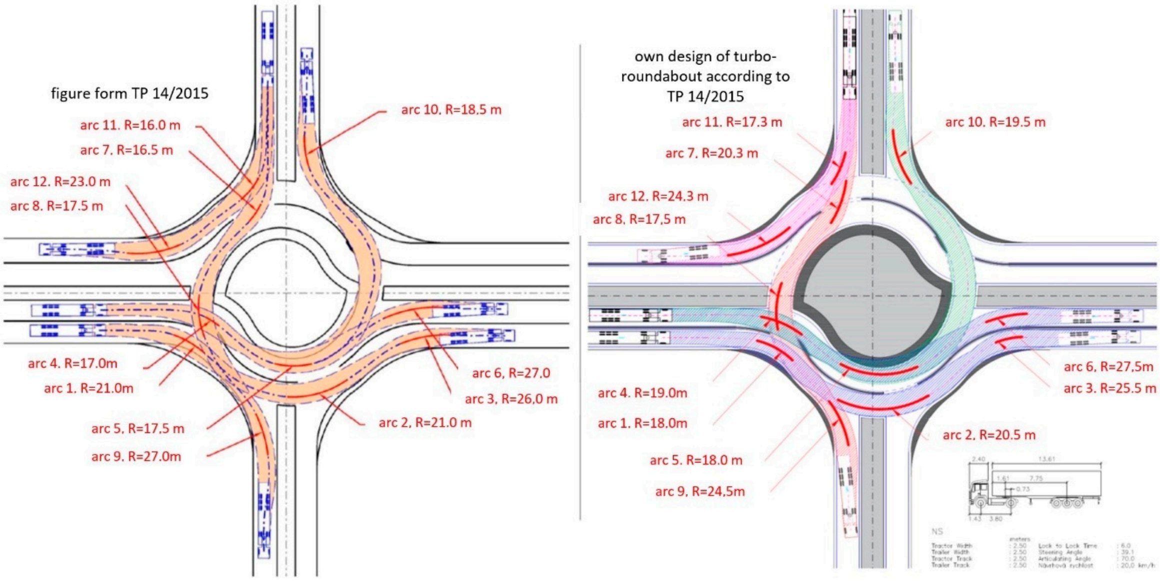

Figure 17. An approximation of the design vehicle by a set of simple circular arcs. (**left**) Turbo roundabout from TP 14/2015 [34]; (**right**) Own design of turbo roundabout according to Steps (1–6) described in Section 3.1.1, for verification of the evaluation of effectiveness of a turbo roundabout.

Table 3. Standard turbo roundabout, values according to TP 14/2015.

	Radius [m]	Speed Limit [km/h]	Speed Limit 20 km/h ≤ v ≤ 35 km/h [-]	Relative Transverse Acceleration for Speed Limit [g]	Speed Limit Lower than 20 km/h [-]	Transverse Acceleration for Speed of 20 km/h [g]	Transverse Acceleration Is Lower than 0.33 g According to ČSN 73 6102 [-]
Arc 1	21.0	26	COMPLY	0.25	NO	0.15	COMPLY
Arc 2	21.0	26	COMPLY	0.25	NO	0.15	COMPLY
Arc 3	26.0	29	COMPLY	0.25	NO	0.12	COMPLY
Arc 4	17.0	23	COMPLY	0.25	NO	0.19	COMPLY
Arc 5	17.5	24	COMPLY	0.25	NO	0.18	COMPLY
Arc 6	27.0	29	COMPLY	0.25	NO	0.12	COMPLY
Arc 7	16.5	23	COMPLY	0.25	NO	0.19	COMPLY
Arc 8	17.5	24	COMPLY	0.25	NO	0.18	COMPLY
Arc 9	27.0	29	COMPLY	0.25	NO	0.12	COMPLY
Arc 10	18.5	24	COMPLY	0.25	NO	0.17	COMPLY
Arc 11	16.0	23	COMPLY	0.25	NO	0.20	COMPLY
Arc 12	23.0	27	COMPLY	0.25	NO	0.14	COMPLY

Table 4. Standardturbo roundaboutthe verification for the evaluation of the effectiveness of a turbo roundabout (according to own design).

	Radius [m]	Speed Limit [km/h]	Speed Limit 20 km/h ≤ v ≤ 35 km/h [-]	Relative Transverse Acceleration for Speed Limit [g]	Speed Limit Lower than 20 km/h [-]	Transverse Acceleration for Speed of 20 km/h [g]	Transverse Acceleration Is Lower than 0.33 g According to ČSN 73 6102 [-]
Arc 1	18.0	24	COMPLY	0.25	NO	0.17	COMPLY
Arc 2	20.5	26	COMPLY	0.25	NO	0.15	COMPLY
Arc 3	25.5	28	COMPLY	0.25	NO	0.12	COMPLY
Arc 4	19.0	25	COMPLY	0.25	NO	0.17	COMPLY
Arc 5	18.0	24	COMPLY	0.25	NO	0.17	COMPLY
Arc 6	27.5	30	COMPLY	0.25	NO	0.11	COMPLY
Arc 7	20.3	25	COMPLY	0.25	NO	0.15	COMPLY
Arc 8	17.5	24	COMPLY	0.25	NO	0.18	COMPLY
Arc 9	24.5	28	COMPLY	0.25	NO	0.13	COMPLY
Arc 10	19.5	25	COMPLY	0.25	NO	0.16	COMPLY
Arc 11	17.3	23	COMPLY	0.25	NO	0.18	COMPLY
Arc 12	24.3	28	COMPLY	0.25	NO	0.13	COMPLY

The evaluation of the geometry according to TP 135 [31] and the comparison with the design (Steps 1–6) within the evaluation of the effectiveness of turbo roundabouts is shown in Figure 18. For comparison, the measured values of individual arcs are given in Table 5. In this table, the speed control given in TP 135 [31] for this type of turbo roundabout is performed. In Table 6, a speed control is performed on the made design.

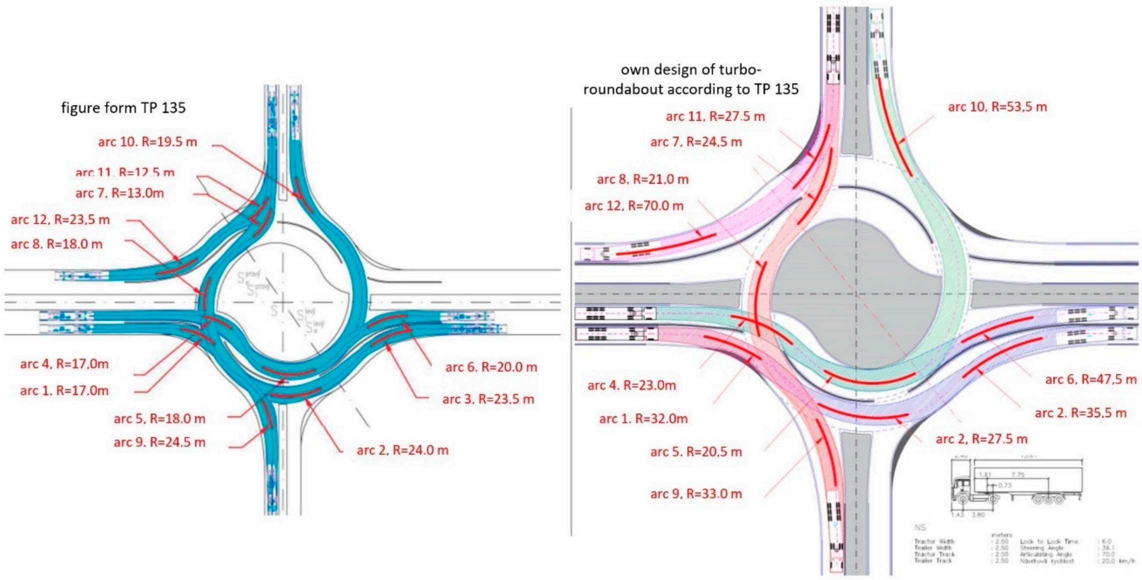

Figure 18. An approximation of trajectory of design vehicle by a set of simple circular arcs. (**left**) TP135 [31]; (**right**) Own design of turbo roundabout according to Steps 1–6, described in Section 3.1.1, for the verification of the effectiveness of a turbo roundabout.

Table 5. Small standard turbo roundabout, values according to TP 135.

	Radius [m]	Speed Limit [km/h]	Speed Limit 20 km/h ≤ v ≤ 35 km/h [-]	Relative Transverse Acceleration for Speed Limit [g]	Speed Limit Lower than 20 km/h [-]	Transverse Acceleration for Speed of 20 km/h [g]	Transverse Acceleration Is Lower than 0.33 g According to ČSN 73 6102 [-]
Arc 1	17.0	23	COMPLY	0.25	NO	0.19	COMPLY
Arc 2	21.0	26	COMPLY	0.25	NO	0.15	COMPLY
Arc 3	15.5	22	COMPLY	0.25	NO	0.20	COMPLY
Arc 4	16.5	23	COMPLY	0.25	NO	0.19	COMPLY
Arc 5	12.5	20	COMPLY	0.25	YES	0.25	COMPLY
Arc 6	24.5	28	COMPLY	0.25	NO	0.13	COMPLY
Arc 7	12.0	20	COMPLY	0.25	YES	0.26	COMPLY
Arc 8	15.0	22	COMPLY	0.25	NO	0.21	COMPLY
Arc 9	12.5	20	COMPLY	0.25	YES	0.25	COMPLY
Arc 10	19.0	25	COMPLY	0.25	NO	0.17	COMPLY
Arc 11	18.0	24	COMPLY	0.25	NO	0.17	COMPLY
Arc 12	24.0	28	COMPLY	0.25	NO	0.13	COMPLY

Table 6. Small standard turbo roundabout, a verification for the evaluation of the effectiveness of the turbo roundabout (according to own design).

	Radius [m]	Speed Limit [km/h]	Speed Limit 20 km/h ≤ v ≤ 35 km/h [-]	Relative Transverse Acceleration for Speed Limit [g]	Speed Limit Lower than 20 km/h [-]	Transverse Acceleration for Speed of 20 km/h [g]	Transverse Acceleration Is Lower than 0.33 g According to ČSN 73 6102 [-]
Arc 1	32.0	32	COMPLY	0.25	NE	0.10	COMPLY
Arc 2	27.5	30	COMPLY	0.25	NE	0.11	COMPLY
Arc 3	35.5	34	COMPLY	0.25	NE	0.09	COMPLY
Arc 4	23.0	27	COMPLY	0.25	NE	0.14	COMPLY
Arc 5	20.5	26	COMPLY	0.25	NE	0.15	COMPLY
Arc 6	47.5	39	NOT COMPLY	0.25	NE	0.07	COMPLY
Arc 7	24.5	28	COMPLY	0.25	NE	0.13	COMPLY
Arc 8	21.0	26	COMPLY	0.25	NE	0.15	COMPLY
Arc 9	33.0	32	COMPLY	0.25	NE	0.10	COMPLY
Arc 10	53.5	41	NOT COMPLY	0.25	NE	0.06	COMPLY
Arc 11	27.5	30	COMPLY	0.25	NE	0.11	COMPLY
Arc 12	70.0	47	NOT COMPLY	0.25	NE	0.04	COMPLY

A comparison of the values of radii according to TP 14/2015 and TP 135 regarding the size of radii and the speed limit of vehicles is shown in Figure 19.

The tables above show an increase in the radius of the arcs in some passages. The larger size of the approximate radii of the arcs is especially found in turbo roundabouts designed according to TP 135. This regulation lists the possible trajectory of the passage of the vehicle, which does not fully correspond to the trajectory according to the conducted research on the evaluation of the effectiveness of a turbo roundabout. During the verification of the turbo roundabout, the design vehicles approach the turbo roundabout at a higher speed, and this speed gradually increases, with the highest speed when they exit the turbo roundabout.

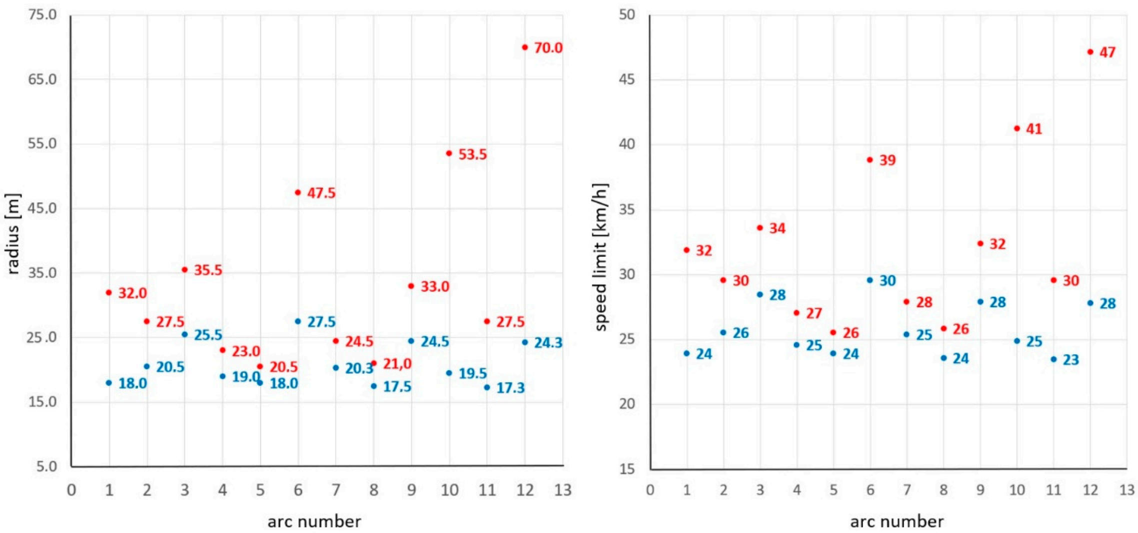

Figure 19. A comparison of values of radii and speed limit according to TP 14/2015 and TP 135. (**red**) TP 135; (**blue**) TP 14/2015).

During the verification of the swept paths, the vehicles at turbo roundabouts according to TP 135 had many times more space on the circulatory roadway than that with TP 14/2015. For these reasons, there may also be safety risks in the event of passage of a car. Despite the current trend of narrowing lanes and increasing traffic safety, vehicles have sufficient space for maneuvering and a fast trajectory of the passage through the turbo roundabout, which was verified as part of the evaluation of the effectiveness of the turbo roundabout according to TP 135.

A spike was an important element in the verification of swept paths of vehicles on turbo roundabouts according to TP 14/2015. Although it is allowed to drive over this element in the regulations (especially the rear axle of the design set), the vehicles were directed to the lane on the circulatory roadway (possibly for the usage of the truck apron). The swept path when the vehicle kept in the lane (i.e., the vehicle does not use the truck apron for the passage) showed the desired speed reduction (i.e., more than 20 km/h and less than 35 km/h) for the design vehicle.

4. Discussion and Conclusions

In this paper, we analyze the geometric designs of turbo roundabouts and in order to verify their effectiveness one needs to know (understand) all the issues of traffic in turbo roundabouts. Therefore, we investigated, from 2014 to 2019, 105 turbo roundabouts in Europe (the Czech Republic, Luxembourg, Hungary, Germany, the Netherlands, Poland, Austria, Slovenia, and the UK). The aims of the study were to analyze the regulations for designing turbo roundabouts, as well as the geometric design elements and traffic signs, and to determine the behavior of drivers on particular types of turbo roundabouts, identify conflict situations, and analyze their causes. The main focus of the study was to optimize the design of a turbo roundabout.

A variety of technical equipment was used to conduct the analyses such as special recording devices (cameras, cameras with "super slow motion" shooting mode, cameras mounted on the vehicle, 360° cameras, etc.) [5,40]. These devices were installed at individual turbo roundabouts (a total of 105 turbo roundabouts). Data were recorded for a minimum of four hours up to a few days. For further evaluation of the analysis of vehicle movement on the turbo roundabout, it was necessary to have records from above (bird's eye perspective). UAV "drones" were used for this purpose [9,20]. On the selected turbo roundabout, shots from the drone and recording devices were supplemented by counting devices. There were several types (counting cards NU-METRICS NC-200, VIACOUNT II, and ICOMS TMS-SA) [20]. For verification, the obtained data were supplemented with values from measurements by handheld radar. Special data processing programs GOOD-VISION [49] and DATA FROM SKY [50] were used for data processing, especially data from cameras (recording devices and drones).

The analysis and evaluation of the given hypotheses of the research also involved computational procedures from Czech standards and regulations [33,51,52] and foreign standards and regulations [37,38,44,53–55], technical conditions [2], methodologies [30] for designing of turbo roundabouts, and calculations for turbo roundabout capacity [56–61]. For the evaluation, our own procedures were designed, where simulations of the passage of a vehicle through a turbo roundabout, the probability of analysis in terms of the use of lanes, the passage of the vehicle through physical separation elements, etc. were performed, including verification with data from real traffic (data obtained and evaluated from measurements). On the basis of the processed data and the evaluated results, we reliably verified the geometry of an intersection with the help of a design vehicle, and we determined the accuracy of the design, whether modifications were needed or not, as well as if the regulations for the design needed modifications.

The comparison of two sets of regulations (Czech and Slovak) for the design of a turbo roundabout, shows that there are different movements (behaviors) of traffic at each turbo roundabout. This fundamental difference in the design and geometry of a turbo roundabout may subsequently affect the safety of the traffic, the capacity of the turbo roundabout or its section (delay time, congestion), or the behavior of the traffic participants themselves. The driver of the vehicle may choose an unsuitable lane when passing through the turbo roundabout, may be confused when entering the roundabout, may be influenced by other road users, and may be misled due to traffic signs or the geometry of the turbo roundabout. These aspects can be evaluated independently using the method of conflict situations [3,5,20]. Incorrectly designed geometry can also have a major influence on the life cycle assessment (LCA) of a turbo roundabout [27] and on the increased emission share [28,29].

In this study, on the basis of the evaluated data we analyzed the issue of designing turbo roundabouts, including an approach for verification. Therefore, the aim was to draw attention to the fundamental differences and non-negligible influence of the geometric design. This hypothesis was confirmed on the abovementioned example of the Czech regulations. Large differences in the radii of individual circles in a turbo block, based on the Czech regulations, resulted in an undesirable increase in the width of the lanes, which resulted in an unsatisfactory width arrangement. Vehicles, especially on the circulatory roadway, could significantly increase speed. This subsequently affected the entry of other vehicles into the turbo roundabout and had a negative impact on capacity and safety. Furthermore, based on the geometric design, we found that the rotation of the translation axis by a predetermined value paradoxically enhanced the entry speed of vehicles into the turbo roundabout. This fact was also confirmed by a diversion (towards the axis of the approach) of 5° at the central island. This 5° diversion is difficult for a designer to implement, therefore, during the design process, they can evaluate the distance at which the diversion is to be made and how this element will subsequently influence the geometry. The Czech regulations use compound arches at the corners as compared with other regulations. Although the corner in a given type of turbo roundabouts is a negative element in its construction, it can be suitable for differently arranged turbo roundabout, which are mainly turbo roundabouts where the axes of the individual lanes are not perpendicular to each other, or different sizes of turbo roundabouts (turbo block). Then, this element of the compound corner suitably guides the vehicles at the exit. Therefore, this is a very important geometric element that could be incorporated into foreign regulations.

An essential element for correct geometric design and verification of the design is the physical separation of the lanes. This element should be increased in the design, with regard to the trajectory of the vehicle passing through the turbo roundabout, the safety of traffic, and the sustainability of this type of traffic constructions in terms of structural elements of individual parts of the turbo roundabout. If the physical separation of the lanes is not realized, it is not possible to force the vehicles to pass through the turbo roundabout in the intended geometric trajectory, and this turbo roundabout can be a dangerous element in the road network. Furthermore, on the basis of the verification of the geometry, the usage of the so-called "spike" element is essential in the design. This element significantly influences the geometry at the point of entry into the turbo roundabout. The spike has a fundamental influence on the direction of vehicles, their speed and, especially in cooperation with the physical separation of lanes, the use of the effective width of the lane on the circulatory roadway. The functionality of the truck apron for the usage of entry/exit of larger vehicles to/from the turbo roundabout was confirmed. This is a standard feature that is used in multiple types of intersections. In conclusion, it should be noted that the Czech regulations, as currently proposed, contain shortcomings in the design of the geometry of turbo roundabouts. In some areas, it can be difficult for designers to understand and ambiguous for the design of the overall geometry.

Although the chosen Slovak regulations are one of the most recent regulations for the design of turbo roundabouts, the results show that the geometry of the turbo roundabouts must still be developed with regard to the passage of vehicles and the behavior of drivers in the turbo roundabout. One of the points of possible adjustment of the regulations is a slight increase in the radii of the turbo block, as vehicles move in close proximity to the curbs at some points in the turbo roundabout (a greater distance of the vehicle from the curb could be maintained here). Furthermore, it would be appropriate to allow the use of a compound corner in some types of turbo roundabouts, which would give the designer more options at the wrong crossing angle. Alternatively, it should be possible to increase the width of the truck apron in turbo roundabouts with smaller radii, i.e., it is necessary that this width is specified in the regulations. We can also apply this conclusion to other regulations that were mentioned in Section 2. The correct design and its verification in terms of geometry and swept paths is the first step in terms of safety and durability of a turbo roundabout, followed by verification of capacities, microsimulation models, etc.

In summary, overall, this study and especially the in-depth analysis of the design of turbo roundabouts, including the geometric design, helps us to identify possible problems. These are differences in the design and approach to designing turbo roundabouts and their subsequent impact on traffic infrastructure. Transport infrastructure is a system in which one negative element (e.g., an unsuitably designed roundabout) can fundamentally influence the behavior of transportation and its subsequent sustainability. In particular, it has an impact on transport safety, public health, and the environment.

Author Contributions: Conceptualization, J.P. and V.K.; methodology, J.P.; analysis of geometry of turbo roundabouts, J.P. and V.K.; writing—original draft preparation, J.P.; writing—review and editing, V.K.; project administration, J.P. and V.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by VŠB-TUO by the Ministry of Education, Youth, and Sports of the Czech Republic.

Acknowledgments: The work was supported by the conceptual development of science, research, and innovation assigned to VŠB-TUO by the Ministry of Education, Youth and Sports of the Czech Republic.

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

References

1. Zheng, L.; Ismail, K.; Meng, X. Traffic Conflict Techniques for Road Safety Analysis: Open Questions and Some Insights. *Can. J. Civ. Eng.* **2014**, *41*, 633–641. [CrossRef]
2. Kocourek, J.; Padelek, T. Application of the traffic conflict technique in the Czech Republic. In Proceedings of the 2016 Smart Cities Symposium Prague (SCSP), Prague, Czech Republic, 26–27 May 2016.
3. Krivda, V. Analysis of Conflict Situations in Road Traffic on Roundabouts. *Promet Traffic Transp.* **2013**, *25*, 295–303. [CrossRef]
4. Ismail, K.; Sayed, T.; Saunier, N. Methodologies for Aggregating Traffic Conflict Indicators. *Transp. Res. Rec. J. Transp. Res. Board* **2011**, *2*, 10–19. [CrossRef]

5. Krivda, V.; Petru, J.; Macha, D.; Plocova, K.; Fibich, D. An Analysis of Traffic Conflicts as a Tool for Sustainable Road Transport. *Sustainability* **2020**, *12*, 7198. [CrossRef]
6. Terum, J.A.; Svartdal, F. Lessons Learned from Accident and Near-Accident Experiences in Traffic. *Saf. Sci.* **2019**, *120*, 672–678. [CrossRef]
7. Kacovsky, J.; Kocourek, J.; Padelek, T. Examination of logical trends in traffic and traffic accidents in the context of road safety at roundabouts. In Proceedings of the 2019 Smart Cities Symposium Prague (SCSP), Prague, Czech Republic, 23–24 May 2019.
8. Petru, J.; Krivda, V. The Process of Setting the Parameters for Ensuring Passage of Oversized Cargos. *Balt. J. Road Bridge Eng.* **2019**, *14*, 425–442. [CrossRef]
9. Petru, J.; Krivda, V. Height and Width Parameters for Ensuring Passage of Excessive Loads on Roads. *Acta Polytech.* **2017**, *57*, 209–217. [CrossRef]
10. Tollazzi, T.; Sraml, M.; Lerher, T. Roundabout Arm Capacity Determined by Microsimulation and Discrete Functions Technique. *Promet Traffic Transp.* **2008**, *20*, 291–300.
11. Krivda, V.; Petru, J. Proposal of capacity calculation of roundabout departure, with cycle traffic in conditions of the Czech Republic. In Proceedings of the 17th International Multidisciplinary Scientific GeoConference SGEM 2017, Albena, Bulgaria, 29 June–5 July 2017. [CrossRef]
12. Istoka Otkovic, I.; Tollazzi, T.; Sraml, M. Calibration of Microsimulation Traffic Model Using Neural Network Approach. *Expert Syst. Appl.* **2013**, *40*, 5965–5974. [CrossRef]
13. Tollazzi, T.; Mauro, R.; Guerrieri, M.; Rejcelj, M. Comparative Analysis of Four New Alternative Types of Roundabouts: "Turbo", "Flower", "Target" and "Four-Flyover" Roundabout. *Period. Polytech. Civ. Eng.* **2016**, *6*, 51–60. [CrossRef]
14. Guerrieri, M.; Mauro, R.; Tollazzi, T. Turbo-Roundabout: Case Study of Driver Behaviour and Kinematic Parameters of Light and Heavy Vehicles. *J. Transp. Eng. Part A Syst.* **2019**, *145*. [CrossRef]
15. Tollazzi, T.; Mauro, R.; Zilioniene, D.; Otkovic, I.I. Modern Roundabouts: A Challenge of the Future. *J. Adv. Transp.* **2019**. [CrossRef]
16. Martins, V.; Anholon, R.; Quelhas, O. Sustainability transportation methods. In *Encyclopedia of Sustainability in Hugher Education*; Filho, W.L., Ed.; Springer Nature Switzerland AG: Cham, Switzerland, 2019; pp. 1–7. [CrossRef]
17. Jha, M.K.; Ogallo, H.G.; Owolabi, O. A Quantitative Analysis of Sustainability and Green Transportation Initiatives in Highway Design and Maintenance. *Procedia Soc. Behav. Sci.* **2014**, *111*, 1185–1194. [CrossRef]
18. James, P.; Magee, L.; Scerri, A.; Steger, M.B. *Urban Sustainability in Theory and Practice*; Routledge, Taylor & Francis Group: London, UK; New York, NY, USA, 2015.
19. Magee, L.; Scerri, A.; James, P.; Thom, J.A.; Padgham, L.; Hickmott, S.; Deng, H.; Cahill, F. Reframing Social Sustainability Reporting: Toward an Engaged. *Environ. Dev. Sustain.* **2013**, *15*, 225–243. [CrossRef]
20. Kahle, L.R.; Gurel-Atay, E. *Communicating Sustainability for the Green Economy*; Routledge, Taylor & Francis Group: London, UK; New York, NY, USA, 2013.
21. Kiec, M.; Ambros, J.; Bak, R.; Gogolin, O. Evaluation of safety effect of turbo-roundabout lane dividers using floating car data and video observation. *Accid. Anal. Prev.* **2019**, *8*, 302–310. [CrossRef] [PubMed]
22. Petru, J. Evaluation of the Efficiency of Turbo Roundabouts. Habilitation Thesis (Title Associate Professor), VSB-Technical University of Ostrava, Ostrava, Czech Republic, 2020. (In Czech)
23. Kocianova, A. The contribution of the physical separation of lanes in terms of safety and capacity of turbo-junctions. *Svet Dopravy* **2016**, *1*, 1–6.
24. Kocianova, A. Capaciity liimiits of basiic turbo-roundabouts. *Communications* **2018**, *8*, 90–98.
25. Silva, A.B.; Mariano, P.; Silva, J.P. Performance assessment of turbo-roundabouts in corridors. In Proceedings of the 18th Euro Working Group on Transportation, EWGT 2015, Delft, The Netherlands, 14–16 July 2015.
26. Balado, J.; Diay-Vilarino, L.; Arias, P.; Novo, A. A safety analysis of roundabouts and turbo roundabouts based on Petri Nets. *Traffic Inj. Prev.* **2019**, *20*, 400–405. [CrossRef]
27. Raffaele, M.; Guerrieri, M. Comparative life-cycle assessment of conventional (double lane) and non-conventional (turbo and flower) roundabout intersections. *Transp. Res. Part D Transp. Environ.* **2016**, *48*, 96–111. [CrossRef]
28. Guerrieri, M.; Corriere, F.; Casto, B.L.; Rizzo, G. A model for evaluating the environmental and functional benefits of "innovative" roundabouts. *Transp. Res. Part D Transp. Environ.* **2015**, *39*, 1–16. [CrossRef]
29. Corriere, F.; Rizzo, G.; Guerrieri, M. Estimation of Air Pollutant Emissions in "Turbo" and in Conventional Roundabouts. *Appl. Mech. Mater.* **2013**, *394*, 597–604. [CrossRef]
30. Fortuijn, L.G.H. Turbo Roundabouts: Design Principles and Safety Performance. *J. Transp. Res. Board* **2009**, 16–24. [CrossRef]
31. *TP 135 Design of Roundabouts on Roads and Local Roads. Technical Conditions*; Ministry of Transport of the Czech Republic: Prague, Czech Republic, 2017.
32. Tollazzi, T. *Alternative Types of Roundabouts*; Springer International Publishing Switzerland: Cham, Switzerland, 2015.
33. *CSN 73 6102 Design of Intersections on Roads*, 2nd ed.; Czech Standards Institute: Prague, Czech Republic, 2012.
34. Maps. Available online: https://www.mapy.cz (accessed on 20 September 2020).
35. Google Maps. Available online: https://www.google.cz/maps (accessed on 20 September 2020).
36. Nitralive. Available online: https://www.nitralive.sk/vystavba/infrastruktura/65589-krizovatku-nitra-sever-po-dvoch-mesiacoch-otvoria-vodici-si-vydychnu (accessed on 20 September 2020). (In Slovak)

37. *Turborotondes (Turbo Roundabouts)*; CROW Publication: Delft, The Netherlands, 2012.
38. *Roundabouts with a Spiral Course of the Circulatory Roadway*; Ministry of Transport Republic of Slovenia: Ljubljana, Slovenia, 2011.
39. *Arbeitspapier Turbokreisverkehre (Working Document on Turbo Roundabouts)*; FGSV: Hanover, Germany, 2015.
40. *Manual for Road Design in Republic of Serbia, Part 5.3 Roundabouts*; Serbian Authority for Roads: Beograd, Serbia, 2012.
41. *Guidelines for Design of Roundabouts with Spiral Circulatory Roadway on State Roads*; Croatian Authority for Roads: Zagreb, Croatia, 2014.
42. *TP 171 Swept Path for Verifying the Passability of Road Directional Elements*; Ministry of Transport of the Czech Republic: Prague, Czech Republic, 2005.
43. Chan, S.; Livingston, R. *Design Vehicle's Influence to the Geometric Design of Turbo Roundabouts*; Teach America: New York, NY, USA, 2014. Available online: http://teachamerica.com/RAB14/RAB14papers/RAB14ppr147_Chan.pdf (accessed on 10 April 2014).
44. *TP 14/2015 Design of Turbo-Roundabouts. Technical Conditions*; Ministry of Transport, Construction and Regional Development of the Slovak Republic Section of Road Transport and Roads: Bratislava, Slovakia, 2015.
45. *Eenheid in Rotondes (Uniformity in Roundabouts)*; CROW Publication: Ede, The Netherlands, 1998.
46. Bastos, S.; Santos, A.; Gaspar, M. *Turbo-Roundabout Use and Design*; Universidade de Coimbra: Coimbra, Portugal, 2013.
47. Tollazzi, T.; Rancelj, M. Modern and alternative types of roundabouts–state of the art. Sustainable urban development. In Proceedings of the 9th International Conference on Environmental Engineering, Vilnius, Lithuania, 22–23 May 2014.
48. Brilon, W. *Roundabouts: A State of the Art in Germany*; Teach America: New York, NY, USA, 2015.
49. GoodVision. Available online: https://goodvisionlive.com (accessed on 20 September 2020).
50. Data from Sky. Available online: https://datafromsky.com (accessed on 20 September 2020).
51. CSN 73 6101. *Design of Roads and Highways*; Czech Standards Institute: Prague, Czech Republic, 2018.
52. CSN 73 6110. *Design of Local Roads*; Czech Standards Institute: Prague, Czech Republic, 2018.
53. *Transportation Research Board 2010 Highway Capacity Manual—HCM2010*; Transportation Research Board: Washington, DC, USA, 2010.
54. *Transport Research Board 2010 Roundabouts: An Informational Guide—NCHRP Report 672*; Transportation Research Board: Washington, DC, USA, 2010.
55. FGSV Verlag. *2005 Handbuch für die Bemessung von Straßenverkehrsanlagen–HBS*; FGSV Verlag: Köln, Germany, 2015.
56. *Methodology for Designing Turbo-Roundabouts*; Brno University of Technology: Brno, Czech Republic, 2015.
57. *TP 188 Assessment of the Capacity of Uncontrolled Level Crossings. Technical Conditions*; EDIP; Ministry of Transport of the Czech Republic: Prague, Czech Republic, 2007.
58. *TP 234 Assessment of the Capacity of Roundabouts. Technical Conditions*; EDIP; Ministry of Transport of the Czech Republic: Prague, Czech Republic, 2011.
59. *TP 235 Assessment of the Capacity of Light-Controlled Intersections. Technical Conditions*; EDIP; Ministry of Transport of the Czech Republic: Prague, Czech Republic, 2011.
60. *TP 236 Assessment of the Capacity of Level Crossings. Technical Conditions*; EDIP; Ministry of Transport of the Czech Republic: Prague, Czech Republic, 2011.
61. *TP 16/2015 Calculation of Road Capacities. Technical Conditions*; Ministry of Transport, Construction and Regional Development of the Slovak Republic, Section of Road Transport and Roads: Bratislava, Slovakia, 2015.