Article

Research on Speeds at Roundabouts for the Needs of Sustainable Traffic Management

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Abstract: Knowledge of the characteristics of speed at roundabouts is very important in design procedures, simulation models, and determining the influence of these roundabouts on traffic conditions in a street network. Sustainable management in the street network means the influence of all its parts on traffic conditions and travel time. In order to reliably determine roundabouts parameters in the procedures of planning and the choice of sustainable method of traffic management, it is very important to know the values of the traffic flow parameters, particularly the speeds at the entry and exit leg, as well as in the circulatory zone. This article analyses the speed characteristics in traffic flow at urban roundabouts with different geometrical characteristics in the city of Banja Luka. The applied method for traffic data collecting in this research was the method of video recording processing, which excludes any influence on driver behavior. Furthermore, statistical analysis was conducted, which established the correlation between the achieved speeds and geometrical characteristics of the intersection. Due to roundabout characteristics, the research was focused on the access, that is, the entry leg, the segment of the circulatory zone and the exit leg. The research results showed there is a significant dependence between geometrical characteristics of certain elements of the roundabout on speeds. In the further course of the research, it was proved that the variation of speeds at the segments of roundabouts significantly affects the size of time losses and emission of pollutants, i.e., parameters based on which it is possible to objectively assess the possibility of sustainable implementation of the planned solution of roundabouts of similar geometry within the street network in cities similar to Banja Luka.

Keywords: urban roundabout; speed; sustainable management; geometrical characteristics

1. Introduction

The speed is a parameter of traffic flow which defines functionality and the quality of traffic conditions on the part of a road or street network. Since the first scientific and expert articles, for the parts of road and street network with the conditions of continuous traffic flows, functional connection between geometrical and constructive characteristics of the road and traffic flow speed has been determined. On all road types, through different dependence and correlations the influence of the width and the number of traffic lanes, lateral clearances, curvature characteristics and grade on the speed are expressed [1]. Due to the functional dependence of speed with other traffic flow parameters, primarily with flow and density, it is well known that traffic flow speed affects roads capacity; thus, the quality of traffic conditions, expressed through level of service.

The influence of geometrical characteristics and environment on speed and traffic conditions was also proved at signalized intersections, although they are ruled by the conditions of interrupted traffic flow. When saturated flow volume is being determined, the grade is considered, as well as the number and the width of traffic lanes, but also

the type of maneuver (straight, left or right) because in case of turning, trajectory radius directly affects speed. Apart from that, other features are also considered, such as parking, public transportation characteristics, disturbances by pedestrians and cyclists, etc. [2].

When traffic conditions are determined at all types of non-signalized intersections, usually Harders [3] or Siegloch [4] models are applied, based on the probability of accepting critical gap occurring in the priority flow by the drivers who perform minor maneuver. This method is also applied for the analysis of traffic conditions at roundabouts where the right of way is given to the traffic flow in the circulatory zone [1]. These models do not consider intersection geometrical characteristics, that is, their influence on traffic flow parameters, capacity and traffic conditions. Since the end of the previous century, traffic conditions at roundabouts where vehicles in the circulatory zones have priority, the aforementioned models have also been applied for their determination. In the street network, there are roundabouts with significantly different geometrical characteristics, which quite certainly can affect the way of movement and vehicle speed [5].

Since the beginning of this century, roundabouts have been applied with more frequency, even to the arterials of the primary street network. With the aim of having a sustainable traffic management in the street network, that is, the influence of certain segments on the time and emission of pollutants, it is necessary to know characteristic values of traffic flow parameters [6–8]. Roundabouts, due to their specific traffic mode, can significantly affect traffic conditions, not only on approaches to the roundabout, but also in the surrounding street network, particularly in the conditions of a saturated traffic flow when even small disturbances at any segment can cause congestions and the effects of shock waves. For this reason, when traffic is planned, as well as in the procedures of optimal management, it is particularly important to know the values of speeds at different segments of roundabouts, so as to approach near the results of analyses and simulations to real traffic conditions. Quality analysis of traffic conditions in the street network and the choice of optimal, that is, sustainable method of traffic management demands, requires the knowledge of the characteristics of the traffic flow and the geometry of roundabouts on traffic flow speed [9]. Accordingly, the main aim of this paper is to determine whether there are functional correlations between geometrical characteristics of roundabouts and speed in a traffic flow.

Methodological approach to the problem of the influence of the geometry of roundabouts on the traffic flow speed, as well as the regression model for the calculation of the speed of the flow in circulation, can be applied to all typical segments of roundabouts of different geometries, similar to those that have already been the subject of research and analyses. Thus, considering the average delays generated at roundabouts, and which are determined through standard models, it is possible to determine the influence of different types of roundabouts on the emission of pollutants in a more precise way.

In addition to the application of the results achieved in this paper in the field of Traffic Management and Transport Planning, the results can also be applied in the field of Traffic Safety. Namely, these results can be used to determine the impact of the roundabout on the level of service as well as the selection of an optimal method of traffic regulation and the segment of the street network, which is extremely important for traffic safety management. Furthermore, speed projections by roundabout segments can be used to assess risk and define concrete measures to increase the safety of road users [10].

This article consists of six sections. Introduction provides the basic observations and initial guidelines related to the topic the article deals with. The second section deals with the analysis of the previous research studies relevant to this subject matter. The third section gives the description of the analyzed locations, as well as the methodology of vehicle speed data collecting and processing. The fourth section represents a section with the display of descriptive parameters of the analyzed samples, as well as the results of the statistical processing with a discussion. The fifth section analyses the influence of the research results on traffic flow parameters and the emission of pollutants, which are used as a basis for the assessment of roundabout application on the parts of the street network

in the procedures of planning and operational analysis. The last section contains the main conclusions and guidelines for further research.

2. Previous Research Studies

The first concept of circular traffic flow at intersections appeared in the United States of America in the early 1930s. The new method of regulation meant signposts putting into the intersection center, alternatively called "Dummy Cop", around which there was circulatory traffic. At roundabouts, at the beginning of their application, there were no concrete rules for defining vehicle circulation. With the first applied principle, the rule of the right, it was defined that the vehicles which enter the intersection have priority over those already being in the intersection. This regulation method resulted in congestion of intersections with increased traffic volume [11]. The concept of contemporary roundabouts was developed in 1960 in Great Britain when smaller roundabouts were proposed, with a greater vehicle lane deflection. In 1966, a rule was adopted that circulatory vehicles in roundabouts have the priority; that is, the vehicles at the intersection access are obliged to give way to the vehicles in the circulatory zone [12].

Previous research studies imply that there is a significant influence of local traffic conditions on the value of traffic flow parameters, thus the value of capacity of all types of priority intersections, which include circular priority intersections. [13]. Research studies [14] conducted just before writing the manual HCM 2016 (Highway Capacity Manual 6) established the differences in capacities all over the USA. They imply that possible differences occur due to local cultural behavior of drivers or different geometrical characteristics of roundabouts. Geometrical characteristics of roundabouts mean the number of traffic lanes, the width of the entry leg, the values of the inscribed circle diameter etc. Therefore, there is a possibility of expanding and correcting a thorough analysis conducted in a certain country for analyzing it in other countries.

Analyzing the available literature [15–32], it was determined that many research studies emphasize speed as one of the most significant parameters in roundabouts geometrical shaping, as well as the key parameter in micro-simulating traffic models. In order to evaluate the influence of the roundabout geometry, certain simulation models enable the distributions of speed, that is, defining the deceleration zone when approaching the roundabout, circulatory speed and acceleration speed to the common values at the links [15]. In many research studies, it has been shown that there is a connection between geometrical characteristics of the roundabout, speed and capacity, traffic flow parameters and traffic conditions [16,17]. The combination of the influence of geometry, traffic flow parameters, and driver behavior make the traffic conditions at a roundabout very complex with significant variations of the speed and other parameters of traffic flow. According to the research study from 2011, it is necessary to use the parameter of roundabout diameter for the calculation of roundabouts capacity [18], whereby bigger roundabouts use the exponential coefficients of the model, which directly regresses.

Chen, Persaud and Lyon [19] established the relationship between some geometrical characteristics of roundabouts and average speed which was defined as the average value of entrance speed, the speed within the roundabout and the exit speed. Statistical analysis included 15 different geometrical parameters, and by means of linear regression they highlighted three main parameters for the definition of average speed: Diameter of the inscribed circle, entrance width and the width of lanes within the roundabout. For a well-controlled going through a roundabout, geometrical elements are applied for vehicles' speed reducing at the access to the intersection, it also limits the speed in the roundabout and enables reaching a normal speed after leaving the roundabout [20].

Prediction of speed at roundabouts is of essential importance in the design process due to different design elements defining and dimensioning. After the study carried out on roundabouts in Australia, Great Britain and the USA [21], it was concluded that entrance radius and minimal radius of the central circular island are two basic parameters that define frameworks for roundabouts design. The results of this study showed that the

higher value of entrance radius, the lower entrance speed into the roundabout, and the correlation between the increase of minimal value of the central circular island, which is dependent on the increase of design speed at the approach to the roundabout.

The research conducted on roundabouts in the Municipality of Cuneo, located in the Northwest of Italy, studied the influence of the main geometrical parameters of the roundabout on vehicles' speed. This research included the analysis of vehicle speed on the approach to the intersection, in the very roundabout flow and at the exit segment. The research results showed that geometrical elements of the roundabout mostly affect the vehicles' speed in the roundabout, as well as that this speed can be dependent on the inner diameter of the roundabout, roundabout roadway width and the width of inflow roadway lane [22]. Another method for determining the speed of vehicles going through the roundabout is based on defining the vehicles' path [23]. With this approach, vehicle speed at roundabouts is correlated to vehicle path radius, super elevation and side friction factor. In other articles, the influence of intersection geometry on speed was confirmed, and a significant difference in speed on the approach within the circulatory zone and the exit leg was proven [24].

Taking into consideration the models based on acceptable follow-up gaps, many research studies proved a correlation among geometrical characteristics of roundabouts, speed and capacity—thus, traffic conditions as well [25,26].

Speed is one of the basic parameters defined in simulation models to describe real traffic conditions at roundabouts [27]. In order to evaluate the influence of intersection geometry, certain simulation models enable speed distribution, that is, define the zone of speed reduction when approaching the roundabout, the circulatory speed and the acceleration to the common values at the links [15]. For this reason, it is very important to know speed distribution depending on the geometrical characteristics of intersections.

The research conducted at four roundabouts from the group of mini and small urban roundabouts on the territory of the City of Zagreb [28], was carried out with the aim of determining the connection of the design speed and vehicles trajectory, that is, comparison of the measured speeds in the field and the adopted design speeds for the corresponding trajectory. The results have shown certain deviations, which the authors explained with a specific position of the intersections in the street network, elements of the geometrical design of the intersections, the structure of traffic flow. Also, in the same town, for the needs of defining the model of trajectories of the vehicles within the roundabout, a research study was conducted [29] that determined the connection among the radius, deflection angle and the radius of central island.

In the town of Livorno [30], geometrical characteristics at roundabouts were analyzed and those intersections were built more than fifty years ago, with the outer diameter of more than 100 m, with the aim of the reconstruction from the aspect of the geometrical parameters correction. Thus, through simulation software packages, a significantly better level of service was achieved.

Certain research studies have shown that the probability of a traffic accident occurrence is proportional to the speed squaring [31]. Consequently, the research on flow speed is also justified, in this case at roundabouts. Other authors, using the data on traffic accidents and vehicle trajectories processed through software packages AIMSUN and VISSIM, conducted the comparative analysis and formed the model for predicting collisions, that is, the assessment of roundabouts safety in Slovenia [32].

Research on the impact of road geometry and traffic flow parameters on traffic safety has shown that there is a significant dependence [33]. However, in the Southeastern Europe (SEE) region, surveys about roundabouts are still rare and are mainly focused on determining the influence of drivers' behavior on traffic flow parameters [34]. This paper is a result of the first research conducted in Bosnia and Herzegovina (BiH) with the aim of considering the influence of geometry on the speed of traffic flow at different segments of roundabouts with the possibility of application in the field of Traffic Management and Transport Planning.

3. Methodology

3.1. Key Roundabout Dimensions

In order to describe a roundabout as an object on road and street network, it is necessary to previously define basic dimensions, that is, key geometrical characteristics. In the process of design and detail analyses of roundabouts, it is necessary to define numerous geometrical parameters, whereby the following elements are defined as the key ones [35]:

- Inscribed circle diameter (D1), basic parameter used to define the size of a roundabout. It is measured between the outer edges of the circulatory roadway.
- Central island circle diameter (D2), measured between the internal edges of the circulatory roadway.
- Circulatory roadway width (W_cr), defines the roadway width for vehicle circulation around the central island. It is measured as the width between the outer edge of this roadway and the central island. It does not include the width of any mountable apron, which is defined to be part of the central island. For speed and traffic conditions, the number of traffic lanes in circulatory zone (N_cr), also matters, as well as width of the lane on circulatory roadway (W_lnc). Accordingly, radius of center line of circulatory lane (R_lnc) is also a parameter that can influence movement speed in the circulatory zone.
- Approach width, the width of the roadway used by approaching traffic upstream of any changes in width associated with the roundabout. This parameter depends on the number of lanes on the approach (N_lne) and width of the lane on the approach (W_lne).
- Departure width, width of the roadway used by departing traffic downstream of any changes in width associated with the roundabout. This parameter depends on the number of lanes on the departure (N_lnx) and width of the lane on departure (W_lnx).
- Entry width (W_en), defines the width of the entry where it meets the inscribed circle. It is measured perpendicularly from the right edge of the entry to the intersection point of the left edge line and the inscribed circle.
- Exit width (W_ex), defines the width of the exit where it meets the inscribed circle. It is measured perpendicularly from the right edge of the exit to the intersection point of the left edge line and the inscribed circle.
- Entry radius (R_en) the minimum radius of curvature of the outside curb at the entry.
- Exit radius (R_ex) the minimum radius of curvature of the outside curb at the exit.

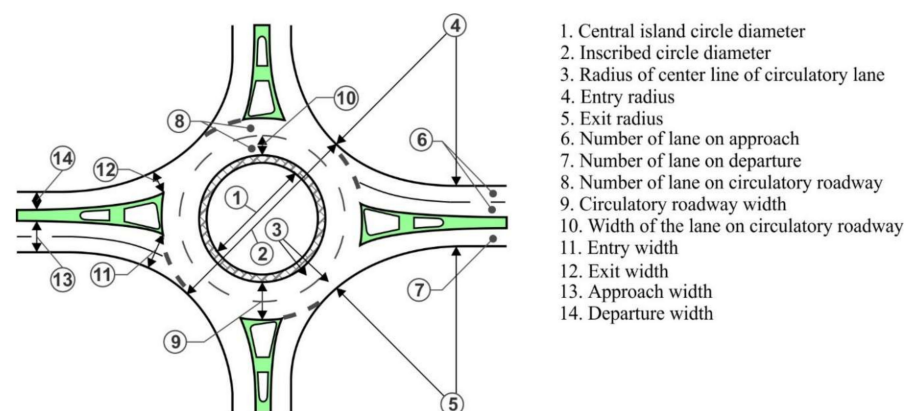In the following figure (Figure 1), there are labeled roundabout key elements.

1. Central island circle diameter
2. Inscribed circle diameter
3. Radius of center line of circulatory lane
4. Entry radius
5. Exit radius
6. Number of lane on approach
7. Number of lane on departure
8. Number of lane on circulatory roadway
9. Circulatory roadway width
10. Width of the lane on circulatory roadway
11. Entry width
12. Exit width
13. Approach width
14. Departure width

Figure 1. Drawing of key roundabout dimensions.

The research analyzed the influence of all aforementioned geometrical elements on the speed at the entry leg, circulatory zone and bottleneck exit leg.

3.2. Description of the Research Location

Data collecting was conducted by recording real traffic flows at four urban roundabouts. The recording was carried out by means of a drone "DJI Mavic 2 Pro", which was set at a certain height above the analyzed roundabouts and it recorded traffic. The analyzed intersection is in Banja Luka (Bosnia and Herzegovina), a town with around 180,000 inhabitants. The intersections used for data collecting are in the urban area of the town, and their type belongs to mid-sized roundabouts and large town roundabouts. In the City of Banja Luka, there are a total of 15 roundabouts, out of which 9 are urban roundabouts. A sample of 4 out of 9 urban roundabouts covered all types, taking into account the characteristic geometrical parameters to be analyzed. The researched intersections are at the edge of the central zone of Banja Luke, with AADT of around 20,000 veh/day. Traffic for trucks is prohibited on these roundabouts. In addition, during the observed period, no occurrence of buses was recorded at the intersections or the number of buses was negligible. Given such a structure of traffic flow, only the speeds of passenger cars were analyzed in the paper, in other words, the analysis was performed on the basis of a homogeneous traffic flow composed of passenger cars.

The recording was conducted in July and August 2019. During the recording, it was sunny with the temperature of 25–35 °C, without fog, rain, gales or any other unfavorable climate conditions, the roadway was dry and without any damages, and the traffic without the situations which would influence unhindered and safe traffic, that is, there were no factors which would cause negative effects on drivers' behavior and vehicles' movement. Figures 2 and 3 show the position of the analyzed intersections in the street network of the town of Banja Luka, as well as the observed roundabouts appearance. Table 1 gives the data on the exact position of the intersections, and Table 2 the basic geometrical characteristics of the observed intersections, that is, approaches.
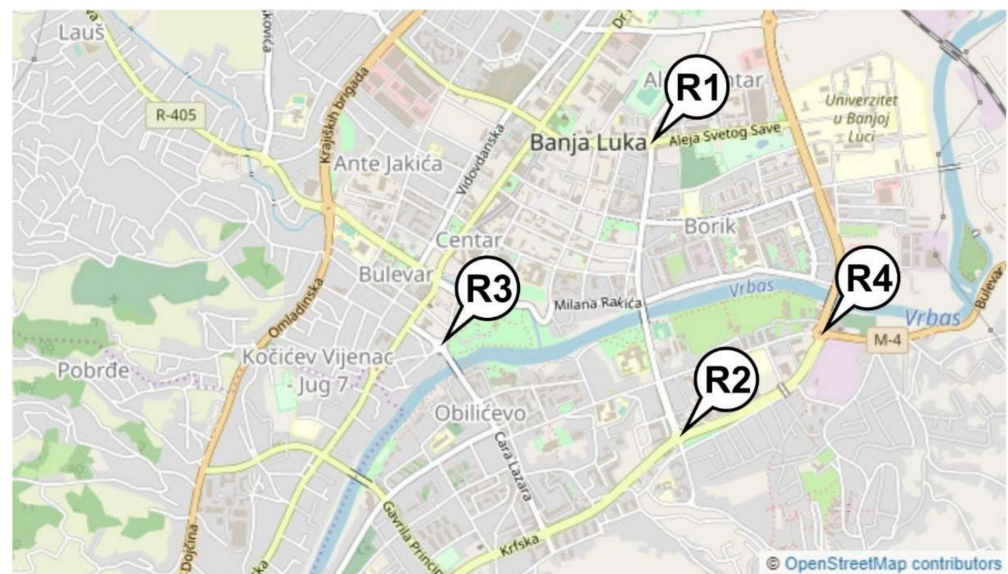

Figure 2. Positions of the analyzed intersections in the street network of the town of Banja Luka.
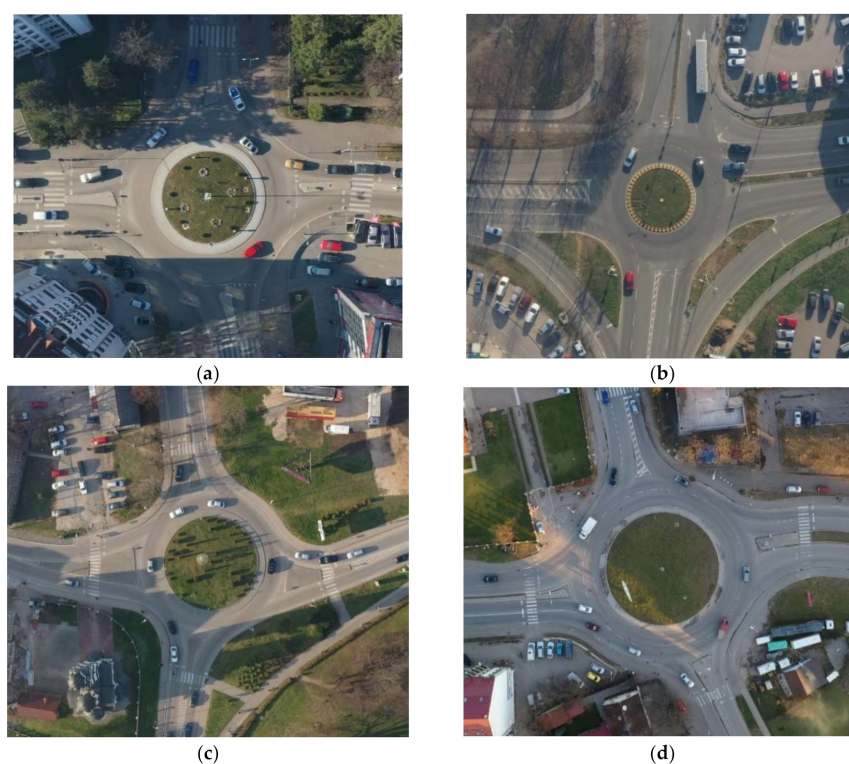
(a)　　　　　　　　　　　　　　　(b)

(c)　　　　　　　　　　　　　　　(d)

Figure 3. Ortho-photo image of the analyzed intersections: (**a**) R1: Gundulićeva–Aleja svetog Save; (**b**) R2: Majke Jugovića–Bul. Desanke Maksimović; (**c**) R3: Patre, Cara Lazara–Teodora Kolokotronisa, Isaije Mitrovića; (**d**) R4: Bul. Desanke Maksimović–Bul. Vojvode Stepe Stepanovića.

Table 1. Data on the position of the analyzed intersections.

Position of Intersection in WGS-84 Coordinate System	R1	R2	R3	R4
Latitude	44.773963	44.762172	44.765897	44.766366
Longitude	17.199593	17.201245	17.187834	17.209049

Table 2. Geometrical characteristics of the analyzed intersections.

Geometrical Characteristics	R1	R2	R3	R4
D1—Inscribed circle diameter (m)	33.60	32.00	43.00	57.20
D2—Central island circle diameter (m)	22.00	16.00	31.00	34.80
W_cr—Circulatory roadway width (m)	5.80	8.00	6.00	9.40
N_cr—Number of lane on circulatory roadway	1	2	1	2
W_lnc—Width of lane on the circulatory roadway (m)	5.80	4.00	6.00	4.70
W_en—Entry width (m)	5.00	7.50	5.10	7.50
N_lne—Number of lane on approach	1	2	1	2
W_lne—Width of lane on approach (m)	4.00	3.50	4.50	3.75
W_ex—Exit width (m)	5.20	8.40	5.00	9.00
N_lnx—Number of lane on departure	1	2	1	2
W_lnx—Width of lane on departure (m)	4.00	3.50	4.50	3.80
R_en—Entry radius (m)	15.00	12.00	13.00	23.00
R_ex—Exit radius (m)	15.00	16.00	40.00	26.00

3.3. Data Collection Method

For determining the vehicles' speed, the method of video recording processing and analysis was used. Video recording processing proved to be an extremely efficient method for traffic flow parameters measuring, because its use minimizes the influence of the research on the drivers. The applied method enabled the analysis in real traffic flow, in which the speed of traffic flow depends exclusively on the degree of interaction between vehicles and the geometric characteristics of the intersection. Data collected and processed in this way represent an efficient and practical basis in many research studies of traffic flow parameters [36,37]. The collected video material of the frequency 24 fps was processed with the software package Kinovea (Figure 4), which enables referential lines marking, the analysis of the objects movements in the recording, and the recording survey by sequences in the accuracy of approximately 0.042 s. The measured speed represents the mean spatial speed measured between two referential lines at the measuring area.
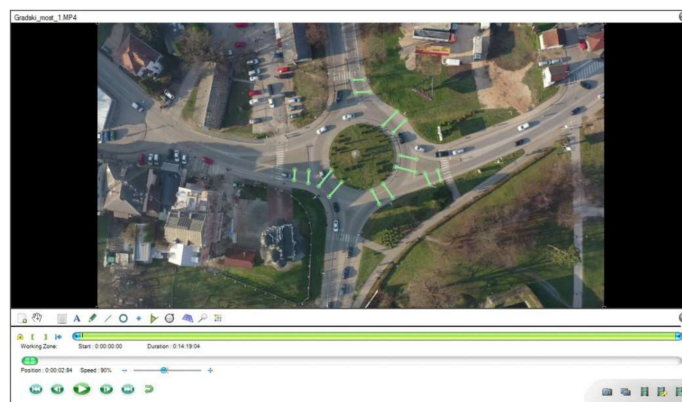

Figure 4. Display of video recording processing.

During the period of collecting data on vehicle speed, it was adopted that a vehicle goes through three typical segments: entry leg–A road part immediately before the circular traffic flow; circulating–A road part in the lane within the circular traffic flow; and the exit leg–A road part immediately after the circular traffic flow. Accordingly, the speed of vehicles' going through the roundabout was divided in the following way.

- Vehicles' speed at the inflow leg (approach)to the roundabout, entry speed (S_en),
- Vehicles' speed in the roundabout, circulatory speed (S_cr),
- Vehicles' speed at the outflow leg of the roundabout, exiting speed (S_el).

During samples forming, the recording was made only for the speeds of the vehicles whose movement was not influenced by the interaction with other participants in traffic flow.

Obstructions that could have appeared as the consequence of these interactions are:

- Vehicles stopping or deceleration, which occurs as a consequence of the change in the movement of the preceding vehicle;
- Vehicles stopping or deceleration on the entry leg to the intersection with the aim of giving way to a pedestrian or a vehicle which is within the roundabout;
- Circulating vehicles stopping or deceleration with the aim of speed adjustment to the speed of the vehicle that is leaving the roundabout flow or which is changing lanes within the roundabout with two traffic lanes;
- Vehicles stopping or deceleration at the exit leg of the intersection with the aim of giving way to a pedestrian;
- Vehicles stopping or deceleration, which occurs as the consequence of unforeseen actions in the intersection zone (improper pedestrians going across the road outside the pedestrian crossing, improper stopping and parking on the roadway, etc.)

If the vehicle was hindered in any of the aforementioned ways, its speed, in that case, is not taken as relevant. In this way, the only collected and considered speeds were the speeds of the vehicles whose movement was influenced only by geometrical characteristics of the intersection.

Methodology steps in the process of data collecting for the needs of the subject analysis have been shown by means of the algorithm (Figure 5). The given algorithm followed by the drawing showing the zones where speed measuring was conducted.
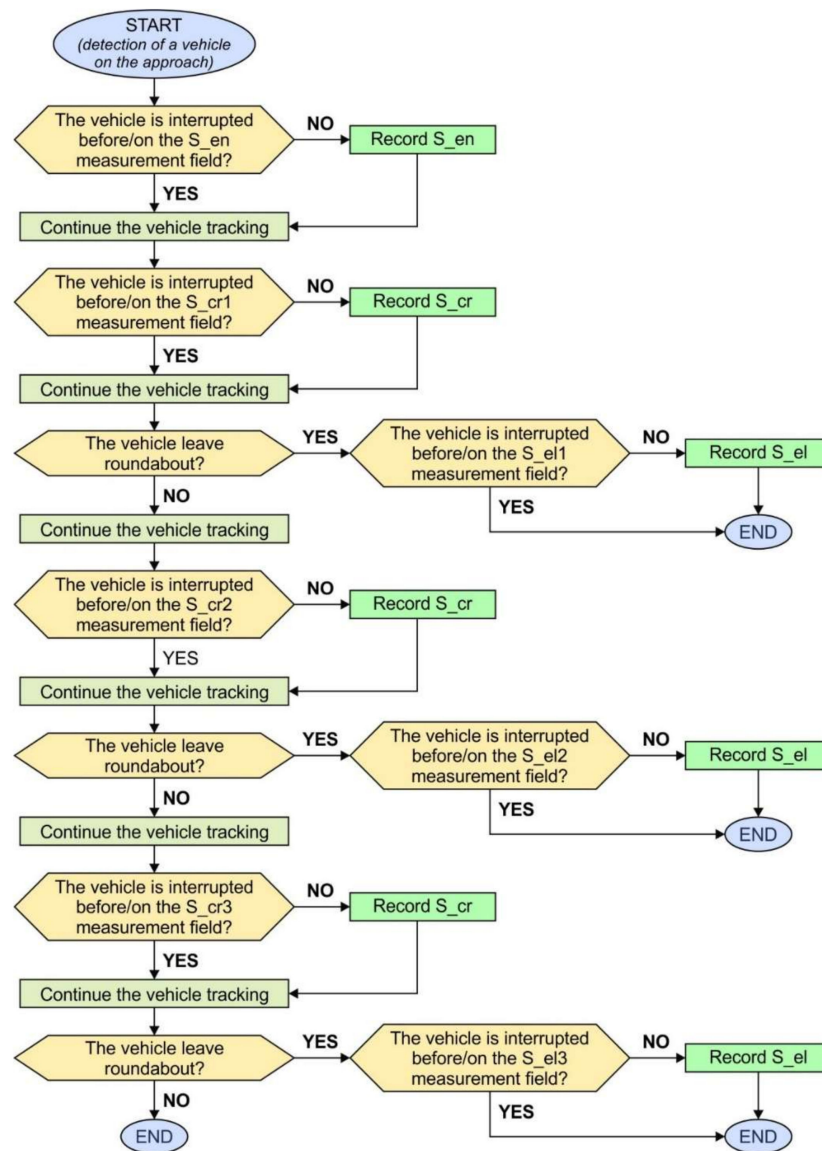
Figure 5. Algorithm of data collection.

As it can be seen in Figure 6, the average measuring points were positioned at all inflow and outflow bottlenecks, and in the circulatory zone at all segments between neighboring approaches. In accordance with the cross-sectional layout where the measuring was conducted for the unhindered vehicles at the inflow and outflow bottleneck, one-speed measuring was conducted at the cross-section. However, in the circulatory zone, speed measuring was conducted at all cross-sections, for the vehicles which turn right at one cross-section (e.g., S_cr1), for the vehicles that go straight through the intersection at two cross-sections (e.g., S_cr1 and S_cr2) and for the vehicles that turn left at three cross-sections (e.g., S_cr1, S_cr2 and S_cr3).
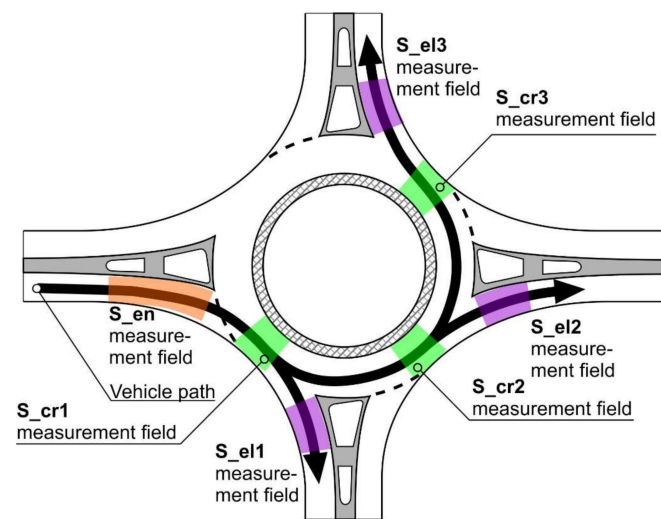
Figure 6. Zones of typical vehicles' speeds measuring at the roundabout.

4. Research Results and Discussion

This section shows the research results which means descriptive statistical parameters of the collected samples and the results of statistical analyses of the interconnection of the speed and geometrical characteristics of the intersections. In order to describe the characteristics of the observed sample, the collected data are presented through the following descriptive:

- **N**—Total number of observations;
- **Mean**—The sum of all the observations divided by the number of observations (arithmetic average);
- **SEMean**—Standard error of the mean;
- **StDev**—Standard deviation of data;
- **Min**—Lowest value in observed data set;
- **Q1**—First quartile of observed data set, 25% of the data are less than or equal to this value;
- **Median**—The middle of the range of data, 50% of the data are less than or equal to this value;
- **Q3**—Third quartile of observed data set, 75% of the data are less than or equal to this value;
- **Max**—Highest value in observation data set.

All statistical analyses have been conducted by means of Minitab® statistical software.

4.1. Vehicles Speed at the Entry Leg

For the needs of analysis which was conducted within this paper, the surveyed speeds at the entry legs were only for the vehicles which, arriving at the intersection, were not hindered by other circulating vehicles. The analysis was carried out with the sample of 537 vehicles with the entrance speeds of the following characteristics (Table 3):

Table 3. Results of the measured vehicles' speeds on leg.

Variable [1]/Roundabout	Descriptive Statistic Parameters								
	N	Mean	SEMean	StDev	Min	Q1	Median	Q3	Max
S_en/R1	104	23.03	0.35	3.59	15.31	20.96	22.94	24.92	32.05
S_en/R2	171	28.67	0.39	5.16	16.02	24.99	28.79	32.14	46.09
S_en/R3	103	25.29	0.38	3.89	18.06	22.50	24.77	26.87	39.13
S_en/R4	159	29.26	0.44	5.61	12.49	25.20	28.80	32.63	52.17

[1] Variable abbreviations: S_en—vehicle speed on entry leg (km/h); R1, R2, R3 and R4—identification mark of analyzed roundabout.

What was further surveyed was how the entrance speed (S_en) depends on the following geometrical parameters of the roundabout: inscribed circle diameter (D1), central island circle diameter (D2), entry radius (R_en), entry width (W_en), number of lane on leg (N_lne) and width of lane on leg (W_lne). The correlation of the achieved S_en depending on the aforementioned intersection geometrical characteristics was determined by means of the Pearson correlation coefficient (Table 4).

Table 4. Pearson correlations of S_en and factors D1, D2, R_en, W_en, N_lne, W_lne.

Factor	D1	D2	R_en	W_en	N_lne	W_lne
Pearson correlation	0.191	0.048	0.172	0.437	0.434	−0.303
p-Value	0.000	0.269	0.000	0.000	0.000	0.000

On the basis of the conducted analysis, it can be stated that, taking into consideration all the aforementioned parameters of geometrical characteristics of roundabout, speed S_en is mostly influenced by entry width (W_en) and the number of lanes (N_lne) (Figure 7). According to the determined coefficients, it can be said that between speed S_en and these factors there is a real and significant linear correlation [38]. The increase of these two factors directly influences the increase of average entrance speed of vehicles.
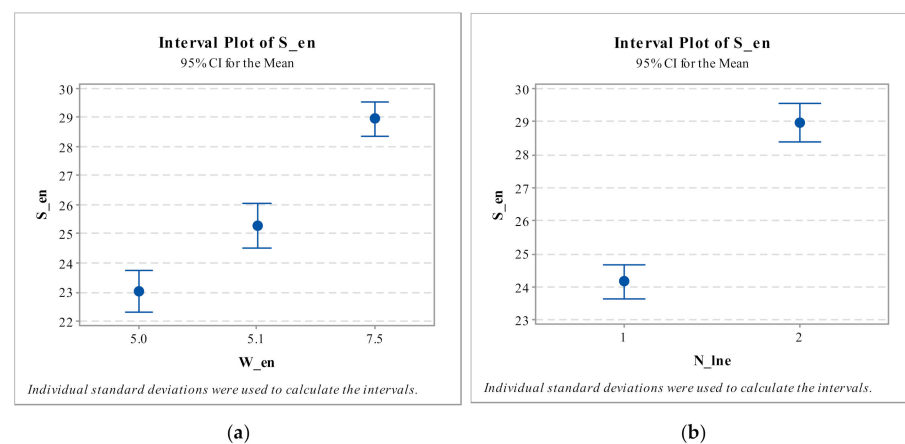

(**a**) (**b**)

Figure 7. Interval plot of S_en: (**a**) depending on the factor W_en; (**b**) depending on the factor N_lne.

4.2. Vehicles Speed in the Roundabout

The speed of vehicles in the roundabout (S_cr) represents the average speed in the measurement zone in the lane designated for vehicles circulating. The analysis was conducted on the sample of the speed of 1095 vehicles that moved unhindered in circulatory lanes (Table 5).

Table 5. Results of the measured vehicles' velocities on circulatory roadway.

Variable [1]/Roundabout	Descriptive Statistic Parameters								
	N	Mean	SEMean	StDev	Min	Q1	Median	Q3	Max
S_cr/R1	235	20.49	0.19	2.95	9.35	18.65	20.22	22.25	29.33
S_cr/R2/inter. lane	142	19.28	0.31	3.67	9.82	16.86	18.91	21.45	34.87
S_cr/R2/exter. lane	180	21.36	0.27	3.68	7.85	18.98	21.29	23.68	30.90
S_cr/R3	249	22.40	0.20	3.15	15.15	20.22	22.09	24.05	33.86
S_cr/R4/inter. lane	163	25.15	0.28	3.55	16.33	22.50	25.23	27.38	37.44
S_cr/R4/exter. lane	126	26.15	0.38	4.23	5.64	23.14	26.26	28.92	35.01

[1] Variable abbreviations: S_cr—vehicle speed on circulatory roadway (km/h); R1, R2, R3 and R4—identification mark of analyzed roundabout.

The speed of the vehicles in the circulatory lane was analyzed depending on the following geometrical characteristics of the intersection: inscribed circle diameter (D1), central island circle diameter (D2), width of the circulatory roadway (W_cr), number of lanes on circulatory roadway (N_lnc) and width of the lane on circulatory roadway (W_lnc). Apart from the aforementioned geometrical parameters, what was also surveyed was speed dependence in relation to the radius of center line of circulatory lane (R_lnc), which practically represents the radius of the path of the circulating vehicle. Table 6 shows the values of Pearson correlation coefficient between the speed S_cr and the aforementioned geometrical characteristics of the intersection.

Table 6. Pearson correlations of S_cr and factors D1, D2, R_lnc, W_cr, N_lnc, w_lnc.

Factor	D1	D2	R_lnc	W_cr	N_lnc	W_lnc
Pearson correlation	0.518	0.467	0.527	0.331	0.169	0.000
p-Value	0.000	0.000	0.000	0.000	0.000	0.996

According to the established correlation coefficients, it can be said that between speed S_cr and the factor D1, D2 and R_lnc, there is a real and significant linear connection, while with the other factors that connection is smaller. For the needs of further analysis factor R_lnc and D1 are distinguished as the two with the highest correlation coefficient. The relationship of these two parameters and the value of the average speed in circulating for concrete values of the chosen factors have been shown in Figure 8.
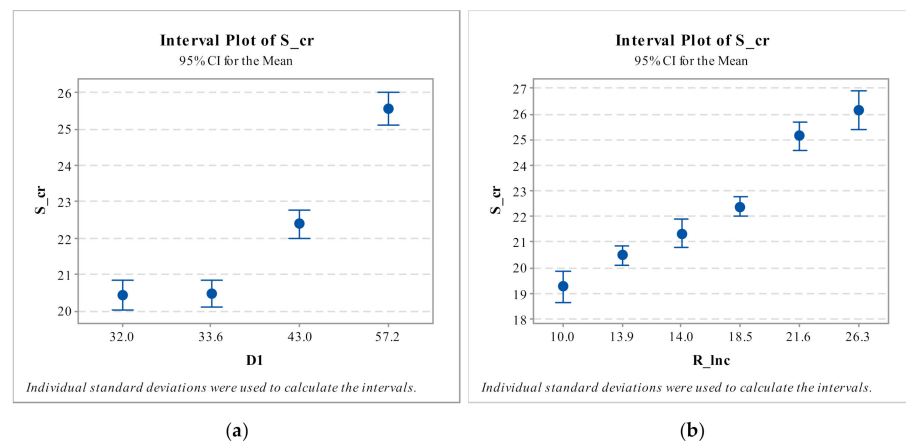

Figure 8. Interval plot of S_cr: (**a**) depending on the factor D1; (**b**) depending on the factor R_lnc.

Taking the average speed of circulating vehicles as a dependent variable and the radius of center line of circulatory lane as an independent variable, linear dependence was determined and it can be expressed with the following relation:

$$S\_cr = 2.169\ R\_lnc - 31.36$$

where: S_cr—Mean speed value of the circulating vehicle (km/h), R_lnc—Radius of center line of circulatory lane (m).

This relation has been determined by means of simple regression on the basis of the analysis conducted in statistical software Minitab®. Figure 9 shows the line which describes the dependence of the aforementioned variables, with 96.1% confidence interval (CI) and prediction interval (PI). Coefficient of determination R^2 which in this case is equal to 96.1% indicates that the model from the equation (1) has a good fit with observed speed values. A visual inspection of the plot (Figure 8) reveals that the data are randomly spread about the regression line, implying no systematic lack-of-fit. The R2-adjusted for this regression is 95.2%.
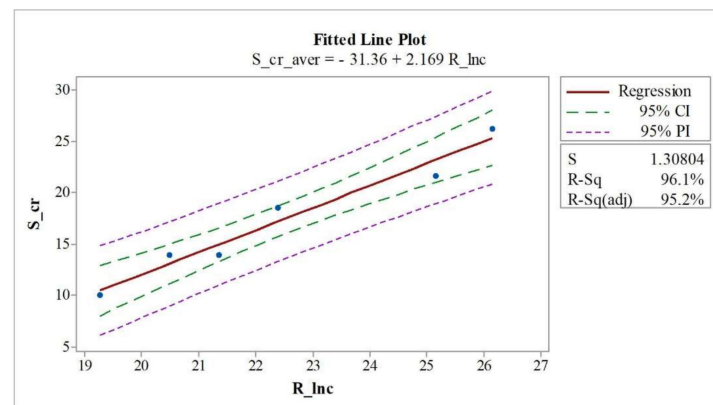
Figure 9. Fitted line plot of average S_cr depending on the factors R_lnc.

After the analysis of the interconnection of the average circulatory speed and the factor with which it achieves the highest correlation, the multiple regression analysis was conducted, which includes other factors given in Table 6. Further analysis defined the multiple regression subset models that produce the highest R2 values from full set of the specified predictor variables from Table 6. Table 7 shows five top-rated models. Generally observing, the introduction of more factors, in this case, does not give significant improvement of the very regressive model considering the fact that the increase of R2 is extremely small, and the value of R2-adjusted is decreasing.

Table 7. Best subset multiple regression models.

Number of Predictors	Multiple Regression Equation	S	R^2	R^2-Adjusted
2	S_cr_aver = −32.41 + 2.378 R_lnc − 0.468 W_cr	1.377	96.8	94.6
2	S_cr_aver = −33.8 + 2.366 R_lnc − 0.046 D1	1.493	96.2	93.7
3	S_cr_aver = −40.6 + 2.94 R_lnc − 0.354 D1 + 0.270 D2	1.515	97.4	93.5
3	S_cr_aver = −40.0 + 3.05 R_lnc − 0.133 D1 − 0.694 W_cr	1.532	97.3	93.4
4	S_cr_aver = −41.2 + 2.72 R_lnc − 0.73 D1 + 0.74 D2 + 1.2 W_cr	1.127	97.4	87.2

4.3. Vehicles Speed at Exit Leg

The speed of vehicles on the exit leg (S_el) represents the average speed in the measurement zone immediately after the traffic lane designated for circulating. The analysis was conducted on the sample of 773 velocities of vehicles that left the circulatory lane unhindered. The observed sample has the following general characteristics (Table 8):

Table 8. Results of the measured vehicles' speeds on departure.

Variable [1]/Roundabout	Descriptive Statistic Parameters								
	N	Mean	SEMean	StDev	Min	Q1	Median	Q3	Max
S_el/R1	180	27.66	0.47	6.31	4.33	24.12	27.45	30.77	65.16
S_el/R2	193	29.62	0.43	6.02	15.55	25.47	29.75	33.72	44.55
S_el/R3	224	27.15	0.38	5.72	3.09	23.58	26.18	29.92	49.09
S_el/R4	176	30.24	0.34	4.55	14.75	27.34	30.25	32.80	42.60

[1] Variable abbreviations: S_cr—vehicle speed on exiting leg (km/h); R1, R2, R3 and R4—identification mark of analyzed roundabout.

The speed of vehicles at the exit was analyzed depending on the following geometric characteristics of the intersection: inscribed circle diameter (D1), central island circle diameter (D2), exit radius (R_ex), exit width (W_ex), number of lane on exit leg (N_lnx) and

width of lane on exit leg (W_lnx). Pearson correlation coefficient between the speed S_el and the aforementioned geometrical characteristics of the intersection has the following values (Table 9).

Table 9. Pearson correlations of S_el and factors D1, D2, N_lnx, w_lnx.

Factor	D1	D2	R_ex	W_ex	N_lnx	W_lnx
Pearson correlation	0.080	−0.011	−0.099	0.221	0.217	−0.192
p-Value	0.026	0.753	0.006	0.000	0.000	0.000

On the basis of the determined *p*-values and correlation coefficient it can be said that the correlation between the speed S_el and factor D1 and D2 does not exist while the biggest, but a slight correlation is with factors W_ex and N_lnx (Figure 10). On the basis of the stated facts, it can be concluded that the speed of the exit vehicles is not correlated to a large degree with the surveyed geometrical characteristics of the intersection.
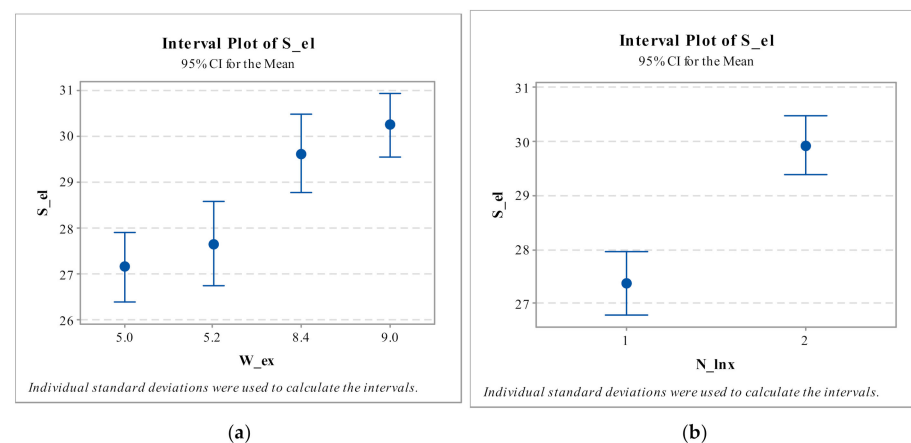

Figure 10. Interval plot of S_el: (**a**) depending on the factor W_ex; (**b**) depending on the factor N_lnx.

The analysis of the research results showed that certain factors have different effects on the speeds in the roundabout zone. Also, in order to examine the impact of as many geometric parameters as possible on the flow velocity, the subject research included intersections with significantly different geometric characteristics. If we consider the individual impact of factors, say D1 (Inscribed circle diameter) and D2 (Central island circle diameter), we could conclude that:

- If there are two intersections that are identical in all characteristics, except for parameter D1, there may be a difference in speeds S_en and S_cr, (*p*-value = 0.000), whilst this parameter will not have a significant impact on S_el (*p*-value = 0.026).
- If there are two intersections that are identical in all characteristics, except for parameter D2, there may be a difference in speed S_cr, (*p*-value = 0.000), whilst in the case of S_en and S_el it would have no effect (*p*-value = 0.269 and 0.753 respectively).

If a certain parameter affects the flow velocity in only one segment of the roundabout, it is clear that it will also affect the average speed observed at the level of the entire intersection. The significance of the influence of a certain element on the average speed observed at the level of the whole intersection would depend on the influence on a specific speed in the specific area of the intersection (S_en, S_cr or S_el). In addition, it must be taken into account that the data set formed in this way implies the possibility of a combined influence of different parameters, so the individual influence of a certain geometric factor must be considered separately. A specific and detailed examination of the influence of an individual factor in real conditions would involve analysis of at least 2 roundabouts, which differ only in 1 parameter. This type of analysis could be the subject of further research.

5. Application of the Research Results in the Procedure of Analysis of the Parameters of the Sustainable Functioning of Roundabouts

For the evaluation of sustainability of the proposed solutions of roundabouts in the procedures of planning analysis, and for operational analysis of traffic conditions at roundabouts, parameters which should be considered are total delays generated at the roundabout, fuel consumption, as well as pollutants emission. All models and applicative software packages for the analysis of traffic conditions (SINCRO, SIDRA, VISSIM, etc.) allow the possibility of defining basic access speeds and the speeds in the circulatory zone for unhindered vehicles. These speeds depend, among other things, on geometrical characteristics of the roundabout [12,13,15,18,19,39]. In the situations when the value of flow demand reaches the value of the access capacity, that is, when saturated flows and high-density flows are formed on approaches, the interaction degree between vehicles most affects the speed. For this reason, in the procedures of sustainability evaluation, through Traffic Impact Assessment Analysis (TIA) and Traffic Environmental Impact Analysis (TEA), the influence of basic vehicular speeds is neglected. Namely, operators most usually adopt the values of access speeds and the speeds in the circulatory zone, given as default. In order to consider the influence of the established values of basic speeds on the approaches to roundabouts and in the circulatory zone on the sustainable functioning of roundabouts, the analysis within the program "Trafficware Synchro" was conducted, by two scenarios:

- **Scenario SC1**- Analysis of traffic conditions by default values of access speeds on approaches to roundabouts and in the circulatory zone.
- **Scenario SC2**- Analysis of traffic conditions by the values of access speeds on approaches to roundabouts and in the circulatory zone, which have been established in the research (Figure 11).

Figure 11. The sequence of SC2 "Trafficware Synchro" analysis of R1 in 3D view.

Emission factors, as well as the parameters which depend on driver behavior (e.g., critical gap and follow-up time), adopted by basic values, they were defined in the program, since they were not the subject of the analyses. The results of the conducted analyses, by defined scenarios for all four intersections, are shown in Table 10.

The displayed data in the previous table refer to one analyzed approach at each roundabout. Analysis of geometrical characteristics of other accesses at the observed roundabouts does not imply significant differences. Therefore, it can be expected that there is a similar influence of the change of average speed of the flow on the parameters of traffic conditions on the approaches with similar characteristics as the analyzed ones.

The analyses results imply that there are significant differences between delays and the established emission of pollutants by two considered scenarios in the situation when traffic conditions on accesses to the roundabout are nearly like traffic conditions in the saturated flow R1 and R3. In SC2, that is, at lower speeds on the accesses and in the circulatory zone, all parameters used as a basis for the evaluation of the sustainability of

traffic conditions at roundabouts are significantly more unfavorable. At lower traffic load, that is, in traffic conditions close to free flow, favorable traffic conditions are obtained by SC2. This result is the consequence of a fact that at lower speeds there is a lower emission of pollutants for the vehicles which go through the roundabout without delays, and the influence of the emission which is the result of vehicles stopping on accesses is significantly lower compared to traffic conditions of higher density flow.

Table 10. Level of service parameters and pollutant emission at intersections.

Measured Factors	R1		R2		R3		R4	
on Analyzed Approach	SC1	SC2	SC1	SC2	SC1	SC2	SC1	SC2
Volume (pc/h)	611		371		718		306	
V/C Ratio	0.98		0.21		1.27		0.39	
Denied Delay (hr)	40.9	71.6	0	0	83.7	111	0	0
Denied Del/Veh (s)	225.6	393.4	0.2	0.3	418.8	552.8	0.2	0.2
Total Delay (hr)	3.8	3.5	0.5	0.8	3.1	3.0	0.2	0.2
Total Del/Veh (s)	22.3	22.6	4.2	6.8	18.9	19.8	2.6	2.3
Stop Delay (hr)	4.2	4.3	0.3	0.8	3.4	3.5	0.1	0.1
Stop Del/Veh (s)	24.6	27.1	2.1	6.3	21	23.3	1.2	1.6
Travel Time (hr)	45.1	75.9	0.9	1.4	87.1	114.5	0.4	0.4
Avg Speed (kph)	4	4	16	10	4	4	16	15
Fuel Used (l)	40	66.7	1.7	1.8	76.4	100.1	1	0.8
Fuel Eff. (kpl)	0.4	0.2	7.9	7.8	0.2	0.1	6.1	7.1
CO Emissions (g)	556	884	87	44	997	1290	55	34
NOx Emissions (g)	9	9	13	6	8	7	9	6

The following graphs (Figure 12) show the differences in parameters values for the evaluation of traffic condition for the defined scenarios.
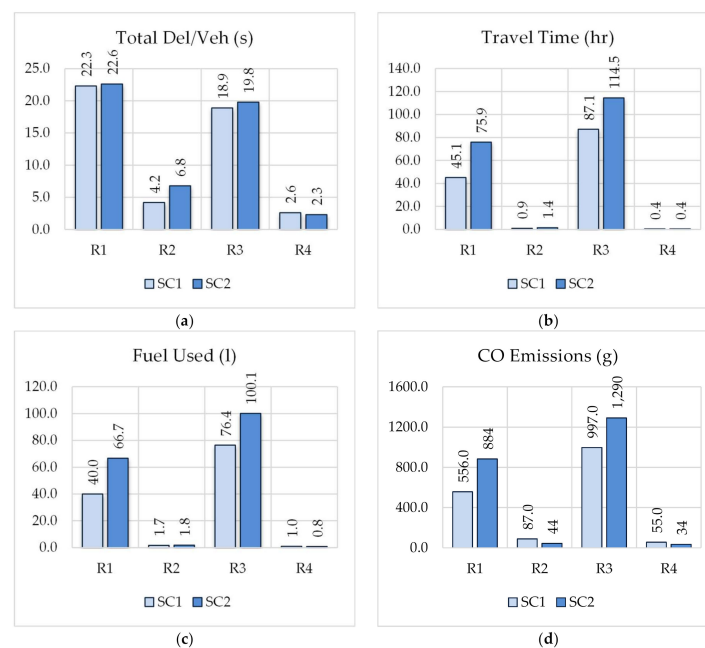

Figure 12. Basic differences of service parameters and pollutant emission: (**a**) Total Del/Veh (s); (**b**) Travel Time (hr); (**c**) Fuel Used (L); (**d**) R4: CO Emissions (g).

6. Conclusions

The research was conducted in a real traffic flow, at four roundabouts with significantly different geometrical characteristics, by means of the method of video recording processing, which excludes the possibility of the influence of the conducted research on driver behavior. The applied research methodology was oriented to determination of speeds characteristics at typical segments of roundabouts, and not to speed variations of particular vehicles when going through the roundabout. During sample forming the chosen speeds were only those of the vehicles whose movement on the approach, in circulatory flow and the exit leg from the intersection was not influenced by the movement of other vehicles in the flow, pedestrian movement in the intersection zone. This approach enabled the determination of the basic speed of traffic flow at typical segments of the roundabout. In this way, the impact of geometry on the traffic flow speed at roundabout segments was determined.

Research results analysis proved that between the speed at the exit leg and entry width (W_en) and the number of lanes (N_lne), there is a real and significant correlation. The increase of these two factors directly affects the increase of the average vehicle speed at the entry leg.

Therewith, the results analysis showed that in the circulatory zone there is a real and significant correlation between the speed and inscribed circle diameter (D1), central island circle diameter (D2), and radius of center line of circulatory lane (R_lnc), while with other analyzed factors the correlation is significantly smaller or there is no correlation. Taking into consideration the high degree of the correlation between the radius of center line of circulatory lane (R_lnc) and the speed of circulatory vehicles, a regression equation was formed which with a high degree of determination describes the connection between these two parameters.

The analysis of the speeds was limited to defining the dependence of speeds at the defined segments and geometrical characteristics of the intersection. However, this research did not determine the significant connection between geometrical characteristics of the intersection and the speed at the exit leg, which should be analyzed in further research. In addition, in further research studies there should be analyses on evaluation of the correlation between speeds in different sections, with the radius inserted in the "less effort trajectory".

In a special section, there is the analysis of the influence of the research results on traffic flow parameters and pollutants emission at roundabouts, used as a basis for sustainability evaluation within operative or planning Traffic Impact Assessment Analysis and Traffic Environmental Impact Analysis. The analysis was conducted in the program "Trafficware Synchro" by two scenarios depending of the traffic flow speed on the roundabouts. The results of the analyses showed that there is a significant influence of the speed values on the traffic flow parameters used for defining the level of service, and the significant influence of pollutants emission.

With these research results, which imply certain dependence of speeds and geometrical parameters of the roundabout, it is possible to expect that traffic flow speed will change in similar patterns at other roundabouts with similar geometrical characteristics. Within this paper, a regression model was defined, which describes, with an acceptable degree of determination, the dependence of the circulatory flow speed and certain geometrical roundabout parameters. Thus, the developed model can be used for a more precise determination of the influence of this segment of roundabouts with the geometry of similar roundabouts which were the subject of research, on the emission of all types of pollutants along street arterials. However, the characteristics of flow speeds at the exit and entry segment of the roundabout were adopted as empirically determined, and the further research will be directed to defining a model for determining the characteristics of traffic flow speed at these segments.

The research results shown in this paper can be used in the procedure of the analysis of the influence of roundabouts on the level of service of street network segments, that is, determination of the sustainability of the application of roundabouts at the observed

segment of the street network in the procedures of planning or operational analysis. Unlike other parts of street network, the influence of roundabouts on the level of service of segments of street network in the existing methodologies has not been completely defined. The result of the analyses conducted within this paper showed that, apart from delays, for defining the influence of roundabouts on the level of service of segments of street network, it is necessary to know the characteristics of speeds on the access, circulatory zone and the exit leg. The application of the real values of speeds on the segments of the roundabout enables a better quality assessment of traffic conditions at the roundabout in the context of sustainability.

Further research, as a continuation of this paper, should be focused on the research of the speed impact and its dependence on the geometric parameters of roundabouts, on traffic safety, taking into account traffic safety factors, vehicle and road. Such research would enable an objective consideration of the impact of roundabouts on traffic conditions and traffic safety in cities that are similar in size to Banja Luka. In addition, it is necessary to determine in further research the impact of the structure of traffic flow on the speed of traffic flow at certain segments of roundabouts. Namely, in accordance with the proven impact of the traffic flow structure on the value of traffic flow parameters on other parts of the road and street network, one can objectively expect a significant mathematical dependence of geometric elements of roundabouts and individual vehicle categories, i.e., traffic flow structure. Also, One of the further research directions is to develop of a hybrid fuzzy methodology which would eliminate shortcomings of the crisp approach [40–42].

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