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Model of vehicle path radius at roundabout centre

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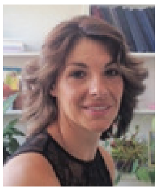

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Preliminary note

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Model of vehicle path radius at roundabout centre

Field investigations of real-life vehicle paths at single lane rural roundabouts, conducted on a sample of 22 straight directions through roundabouts of varying properties, are presented in this paper. Statistically significant correlations of some roundabout elements and vehicle path radii at roundabout centre were determined and used as a basis for developing a model of vehicle path radius at roundabout centre, for the case of vehicles moving straight through the roundabout.

Key words:
roundabout, vehicle path, geometric elements, model of vehicle path

Prethodno priopćenje

Sanja Šurdonja, Vesna Dragčević, Aleksandra Deluka - Tibljaš, Željko Korlaet

Model radijusa putanje vozila u sredini kružnog raskrižja

U ovome radu su prezentirana terenska istraživanja stvarnih putanja vozila na jednotračnim izvanurbanim kružnim raskrižjima, provedena na uzorku od 22 ravna smjera kroz kružna raskrižja različitih obilježja. Utvrđene su statistički značajne korelacije određenih elemenata kružnih raskrižja s radijusom putanje vozila u sredini kružnog raskrižja, na temelju kojih je razvijen model radijusa putanje vozila u sredini kružnog raskrižja, za slučaj kretanja vozila ravno kroz raskrižje.

Ključne riječi:
kružno raskrižje, putanja vozila, geometrijski elementi, model putanje vozila

Vorherige Mitteilung

Sanja Šurdonja, Vesna Dragčević, Aleksandra Deluka - Tibljaš, Željko Korlaet

Radiusmodell einer Fahrzeugspur in der Mitte eines Kreisverkehrs

In dieser Abhandlung werden Felduntersuchungen der tatsächlichen Fahrzeugspuren bei einspurigen Kreisverkehren außerhalb der Stadt präsentiert, durchgeführt an einer Stichprobe von 22 geraden Richtungen durch den Kreisverkehr mit unterschiedlichen Eigenschaften. Festgestellt wurden statistisch bedeutende Korrelationen bestimmter Elemente der Kreisverkehre mit einem Radius der Fahrzeugspur in der Mitte des Kreisverkehrs, aufgrund dessen ein Radiusmodell der Fahrzeugspur in der Mitte des Kreisverkehrs entwickelt wurde, für den Fall, dass das Fahrzeug gerade durch die Kreuzung fährt.

Schlüsselwörter:
Kreisverkehr, Fahrzeugspur, geometrische Elemente, Modell des Fahrzeugpfads

1. Introduction

To ensure proper functionality and traffic safety at intersections, it is important to establish a correlation between the speed and the various parameters affecting the speed [1]. Various research has shown that vehicle speed in roundabouts is greatly dependant on vehicle path in the roundabout [2, 3]. Montella et al. state that the most direct, straightest path that the vehicle can have when entering, passing through, and exiting the roundabout, in free flow traffic conditions, is also the fastest path the vehicle can use when passing through the roundabout [2].

Two models are commonly used in technical regulations for testing the speed of vehicles passing through roundabouts: Dutch model [4,5], which is also used in current Croatian [6] and some other European guidelines for roundabouts [7, 8], and American model [9, 10], which is also used in Australia [11]. Dutch model calculates the transit speed based on vehicle path radius, which is the result of geometric elements of the roundabout. The American model for transit speed calculation is based on vehicle path definition according to certain rules and application of the formula for vehicle speed in horizontal curve.

Considering a wide variety of design practices, diversity of design vehicles, and general traffic culture and tradition differences, the application of procedures developed under conditions different from local ones may result in significant deviations of calculated speeds, when compared to actual speed values.

The experimental speed tests carried out on roundabouts in Croatia show that measured speed values differ significantly from the speeds used to check consistency of geometric elements during design [12]. In addition, the recommended distances, based on which vehicle paths used in speed calculations are formed, differ significantly from the distances determined in field studies. This particularly applies to the central part of vehicle path in roundabouts [13]. The actual vehicle path through roundabouts should therefore be determined with greater accuracy, which would in turn enable a more accurate calculation of transit speeds.

In their paper, Pilko et al. emphasize the importance of determining the actual vehicle path and transit speeds, as possible parameters for validating the multicriteria model developed for the optimization of geometric elements, efficiency, and safety at single-lane roundabouts [14].

Sangyoup and Jaisung developed a model for predicting the number of accidents at roundabouts based on the study of transit speeds at various positions in the wider and narrower areas of the roundabout, using for that purpose a set of geometric elements such as the number of intersection legs, the number and width of traffic lanes at roundabout entrance, the number and width of lanes in circulatory roadway, and the effective widening of entry lane [15].

This paper presents a research that was conducted to determine correlation between the vehicle path through the roundabout and its geometrical elements, which is the basis for defining a more accurate vehicle path model. The model was developed using the regression analysis based on experimental data gathered from ten roundabouts, i.e. from a total of 20 straight directions of vehicle movement. The research results and the model of vehicle path radius in the middle of roundabout are presented so as to define a new vehicle transit speed model for roundabouts.

2. Vehicle path through roundabout

The path of vehicle movement through a roundabout must be established so as to enable application of procedures on which the transit speed check is based, as provided in applicable national guidelines for the design of roundabouts. For the purposes of this paper, national guidelines used in the United States [9, 10], Australia [11], the UK [16], the Netherlands [4, 5] Croatia [6], Slovenia [7], and Serbia [8] were analysed.

The basic assumption of all guidelines is that the vehicle path in a roundabout consists of multiple circular arches in case the vehicle passes straight through the intersection and turns left, or of one circular arc in case the vehicle makes the right turn. The guidelines define the way in which a vehicle path is formed, while taking into account safety distances between the vehicle and raised curbs, marked centre lines, or marked edge of the central island. The geometrical elements and safety distances from raised curbs at roundabout approaches and within the roundabout differ in the aforementioned guidelines, which ultimately results in different assumed path of the vehicle.

2.1. Defining vehicle path according to analysed guidelines

Design elements and methodology for checking intersection consistency in terms of vehicle swept path analyses, visibility, and speed, as defined in Croatian guidelines [6], are compatible with relevant provisions of Dutch [4, 5], Slovenian [7] and Serbian guidelines [8]. It is possible to define a vehicle path through a roundabout in the case of an intersection in which the axes of opposite intersection legs form an approximate angle of 180°. The vehicle path radius (Figure 1) depends on geometric elements of the roundabout and is calculated according to expression (1):

$$R = \frac{(0{,}25 \cdot L)^2 + \left(0{,}5 \cdot (U+2)\right)^2}{U+2} \quad (1)$$

where:

- R - radius of vehicle path through a roundabout [m]
- L - tangential distance between the beginning of the entrance radius and the end of the exit radius [m]
- U - the distance of the tangent between the beginning of the entrance radius and the end of the exit radius to the edge of the central island [m].

The shortcoming of these guidelines is that they do not offer the possibility of constructing a vehicle path in the case of turning left or right in a roundabout, and in the case of a roundabout where design intersection elements applied differ from recommendations given in Dutch guidelines (for example, an extension at the entrance or an angle between intersection legs other than 180°).

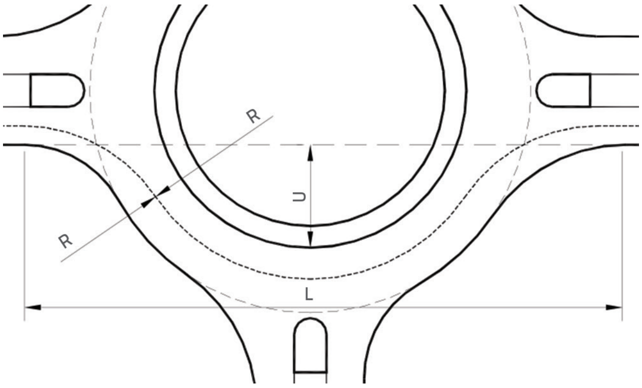

Figure 1. Definition of U and L parameters for the model [4, 5]

According to American guidelines [9, 10], it is mandatory to draw vehicle paths through a roundabout for all allowed directions of movement in a roundabout (Figure 2). The assumption is that in the case of left turn, the vehicle path radius is the smallest, and it is expected to develop a lower speed compared to other possible directions of travel. The largest path radii and vehicle speeds are expected in the case of straight movement through the roundabout or in the case of left turn.

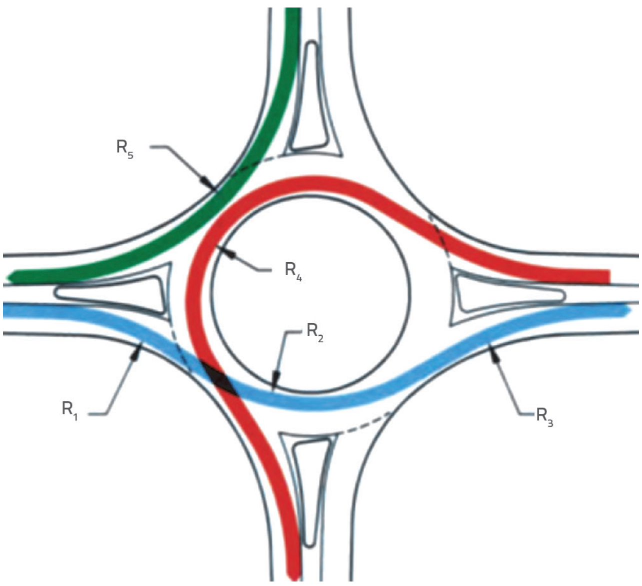

Figure 2. Vehicle path radii [9,10]

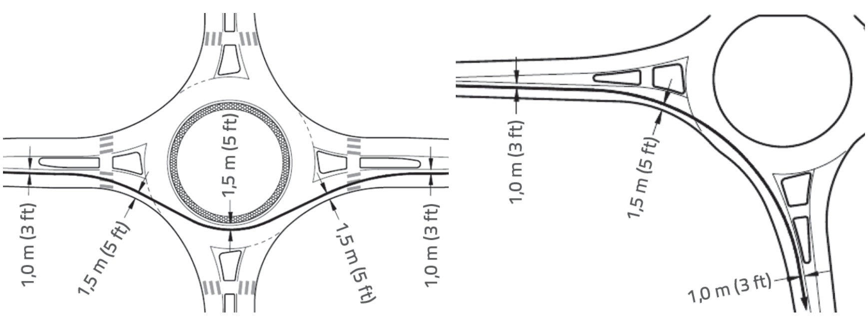

Figure 3. Construction of straight (left) and right turn path (right) for vehicle running through intersection [5]

These radii represent the axis of the vehicle and are not equal to the radii of intersection design elements (the radius of the entrance and exit from the roundabout, i.e. the radius of the central island). When constructing a vehicle path, a vehicle width of 2 m is assumed, and a minimum protective distance of 0.5 m of the vehicle edge from the marked lines or from the middle of the pavement and the raised curbs. Regarding the above, when designing a vehicle path, the recommended distance of the vehicle axis from the raised curbs and the central island is 1.5 m, and 1.0 m from the marked lines (Figure 3).

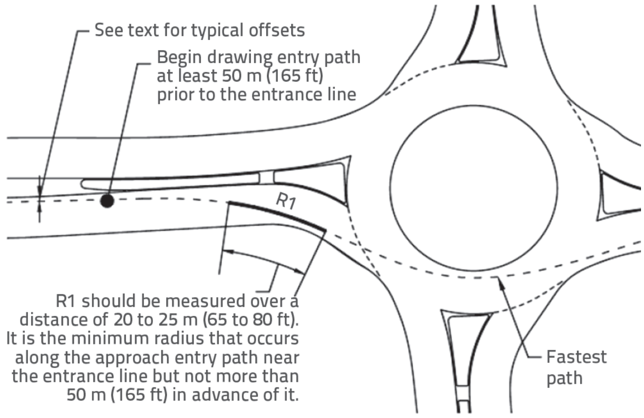

Figure 4. Determining path radius at entrance [5]

The assumption of American guidelines is that the entrance radius, when driving straight through the roundabout, is the result of deflection imposed on the vehicle by applying design elements at the entrance of the roundabout (the width of the entrance of the roundabout, the entrance radius, the angle of deflection, etc.). Figure 4 shows the way in which radius value at the entrance is defined. The construction of the path should start at least 50 m before the stop line using the aforementioned safety distances from raised curbs or marked lines. The radius value is measured near the stop line, and the length of the arc should not be smaller than 20 to 25 m (Figure 4).

According to Australian [11] and English guidelines [16] the vehicle path is defined in a way similar to the methodology used in American guidelines [5], but only in the case of straight movement through the roundabout. The method of designing the mentioned path through a single-lane roundabout according to Australian and English guidelines is shown in Figure 5. After determining the entrance radius value for vehicle path, it must be compared with the values recommended in guidelines [11].

According to English guidelines, the entrance radius of the vehicle (a) is measured in the area of the stop line marked on the pavement at the entrance to the roundabout. It must not be under 25 m and the vehicle path construction should begin at least 50 m before the stop line. After the path is constructed, the value of the entrance radius of the

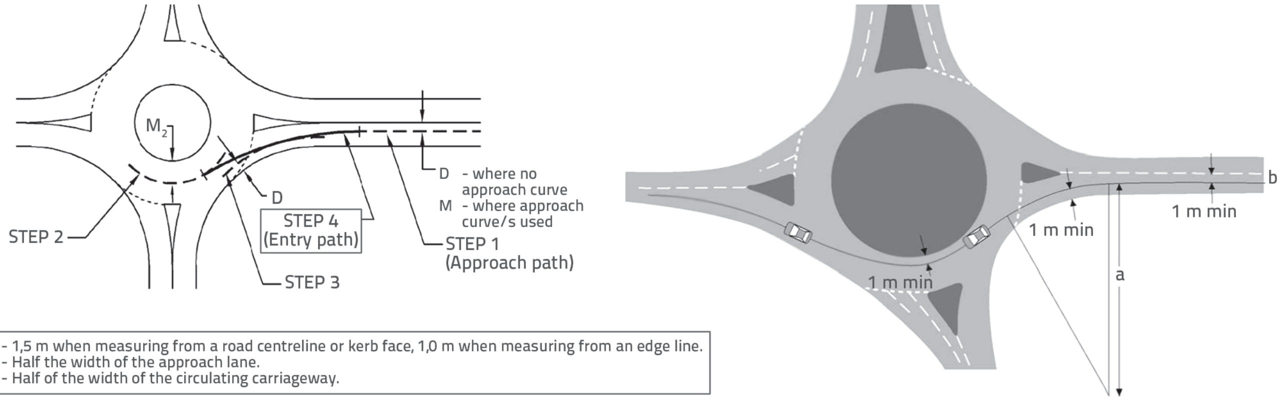

Figure 5. Theoretical vehicle path through roundabout according to Australian guidelines (left) [11] and English guidelines (right) [16]

path is determined and it should not be over 70 m in compact roundabouts (roundabouts at which there is no effective widening of entry lane at the entrance to the roundabout), while at other roundabouts the entrance radius value must not exceed 100 m [16].

2.2. Experimental testing of vehicle path

Experimental vehicle-path tests shown in [13] were conducted to determine applicability of the existing manners of defining the vehicle path in local conditions at roundabouts designed according to Croatian guidelines [6]. The paper presents results obtained at two roundabouts in Croatia (Figure 6). Two possible straight directions of movement were analysed at each roundabout.

In the first step, theoretical paths of the vehicles were drawn for both intersections on topographic survey maps (by adopting recommendations given in American guidelines), and path radii at the entrance, centre, and exit were read. In the next step, the vehicle theoretical path radius was obtained on the basis of design elements of the roundabouts, using the expression specified in Croatian, Dutch, Slovenian and Serbian guidelines.

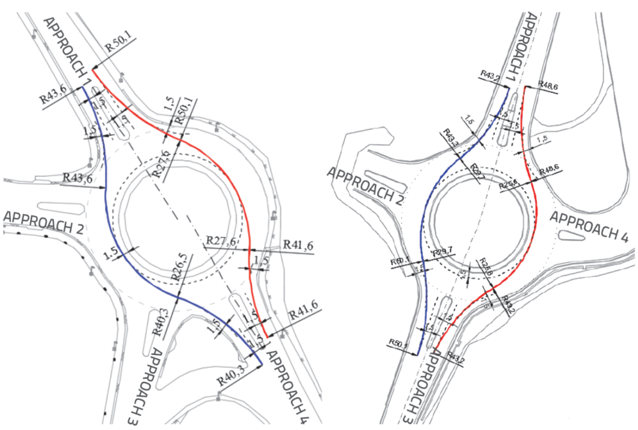

Figure 6. Theoretical vehicle paths developed according to US guidelines: a) Omišalj roundabout b) Adria roundabout

Finally, an experimental path test was conducted using the accurate Hiper V Dual Frequency Global Navigation Satellite System (GNSS) device. This device can record vehicle position with the following accuracy: horizontal 10 mm + 1 ppm, vertical 15 mm + 1 ppm, or 5 georeferenced points in 1 second. The device was installed on the roof of an Alfa Romeo 159 sportwagon personal vehicle, measuring 4469 mm in length, 1828mm in width, and 1417 mm in height. These values fall within the statistically determined values for a standard mid-size personal vehicle used in the Republic of Croatia [17]. Experimental measurements were carried out by 3 drivers with similar driving experience, each of which performed N number of passes (N = min 50) on each of two straight directions through the roundabout. The driving was carried out in stable weather conditions, and in free traffic flow.

The radii of the path at the entrance, in the middle of the roundabout, and at the exit of the roundabout, were approximated for each recorded vehicle path transmitted to a topographic survey map of the actual roundabout using AutoCAD software. The radii were approximated in such a way that they do not deviate from the actually recorded (dotted) path of the vehicle by more than 10 cm. Their lengths were measured, as well as the distance from the raised curb at the entrance, from the central island and at the exit, and average values were determined.

The above values were then compared to the recommendations given in American [9, 10], Dutch [4, 5], Australian [11] and English uidelines [16].

it can be concluded from Table 1 that the theoretical radius value, determined according to Dutch, Slovenian, Croatian and Serbian guidelines, is nearest to the experimental path radius of the vehicle in the middle of the roundabout. According to the mentioned guidelines, the assumption is that the vehicle path is at least 1.0 m away from raised curbs or marked lines, which has not been achieved in the case of experimental paths. The experimental paths are on an average 1.5 m and 1.7 m away from raised curbs at the entrance and exit, respectively while, in the middle of the roundabout, they are on an average 0.7 m away from the raised curb of central island.

Radii at the entrance, read for theoretical paths developed according to the US guidelines, are significantly closer to the radii values at the entrance for experimental paths, although the recommendations for the radius length of the entrance path were not met in 3 out of the 4 mentioned guidelines. The

Table 1. Comparison of experimental and theoretical paths

Roundabout	Direction of movement	Vehicle path		Vehicle path radius at the entrance R_1 [m]	Length of the entry path radius L_1 [m]	Safety distance from the path to the raised curb at the entrance X_1 [m]	Vehicle path radius in the middle R_2 [m]	Length of middle path radius L_2 [m]	Safety distance from the path to the central island X_2 [m]	Vehicle path radius at the exit R_3 [m]	Length of exit path radius L_3 [m]	Safety distance from the path to the raised curb at the exit X_3 [[m]
Omišalj	Direction 1 - 4	Experimental tests		**42.9**	**18.5**	**1.5**	**23.3**	**20.9**	**0.5**	**49.9**	**20.2**	**1.8**
		Theoretical path	SAD	43.6	20 - 25	1.5	26.5	-	1.5	40.3	-	1.5
			DUTCH	24.6	-	min 1.0	24.6	-	min 1.0	24.6	-	min 1.0
			AUS	55.0	-	1.5	-	-	4.0	-	-	-
			UK	<100	25.0	1.0	-	-	1.0	-	-	1.0
	Direction 4 - 1	Experimental tests		**55.0**	**19.0**	**1.2**	**23.5**	**20.2**	**0.4**	**56.6**	**20.8**	**2.0**
		Theoretical path	SAD	41.6	20 - 25	1.5	27.6	-	1.5	50.1	-	1.5
			DUTCH	20.2	-	min 1.0	20.2	-	min 1.0	20.2	-	min 1.0
			AUS	55.0	-	1.5	-	-	4.0	-	-	-
			UK	<100	25.0	1.0	-	-	1.0	-	-	1.0
Adria	Direction 1 - 3	Experimental tests		**46.0**	**19.2**	**1.7**	**25.0**	**21.8**	**0.9**	**55.8**	**19.7**	**1.6**
		Theoretical path	SAD	43.2	20 - 25	1.5	29.7	-	1.5	50.1	-	1.5
			DUTCH	26.7	-	min 1.0	26.7	-	min 1.0	26.7	-	min 1.0
			AUS	55.0	-	1.5	-	-	4.0	-	-	-
			UK	<100	25.0	1.0	-	-	1.0	-	-	1.0
	Direction 3 - 1	Experimental tests		**47.7**	**21.6**	**1.4**	**21.8**	**23.0**	**1.0**	**52.2**	**20.1**	**1.3**
		Theoretical path	SAD	43.2	20 - 25	1.5	25.6	-	1.5	48.6	-	1.5
			DUTCH	24.4	-	min 1.0	24.4	-	min 1.0	24.4	-	min 1.0
			AUS	55.0	-	1.5	-	-	4.0	-	-	-
			UK	<100	25.0	1.0	-	-	1.0	-	-	1.0

recommended vehicle path safety distances from raised curbs (1.5 m) were not achieved, and the largest deviations were in the middle of the roundabout.

Australian [11] and English guidelines [16] provide only recommendations on path radius at the entrance, and path distance from raised curbs or marked lines, while English guidelines also provide recommendations for the length of path radius at the entrance.

3. Model of vehicle path through roundabout

Experimental paths, i.e. their elements, recorded by field tests differ significantly from the recommendations given in the analysed guidelines, which was an incentive for further research as shown.

Detailed experimental tests were conducted on a total of 11 single-lane suburban roundabouts [18] in order to define model for vehicle path in the middle of the roundabout.

When choosing roundabouts for experimental tests, the following criteria were adopted regarding location and design elements of the intersection:

- the axes of opposite legs of the roundabout form an angle of approximately 180°;
- the axes of opposite legs are straight or rounded for a radius greater than 250 m, minimally in the zone 50 m before the entrance of the roundabout, and 50 m after the exit from the roundabout;
- the values of roundabout design elements used are differ from one another;
- longitudinal slopes of intersection legs are approximately horizontal.

Eleven roundabouts were selected based on criteria adopted in this study. Four of them are located in Primorje – Gorski kotar County (location: Krk Island) and seven are situated in Istrian County (locations: Pula, Poreč, Žminj, and Bale). The selected

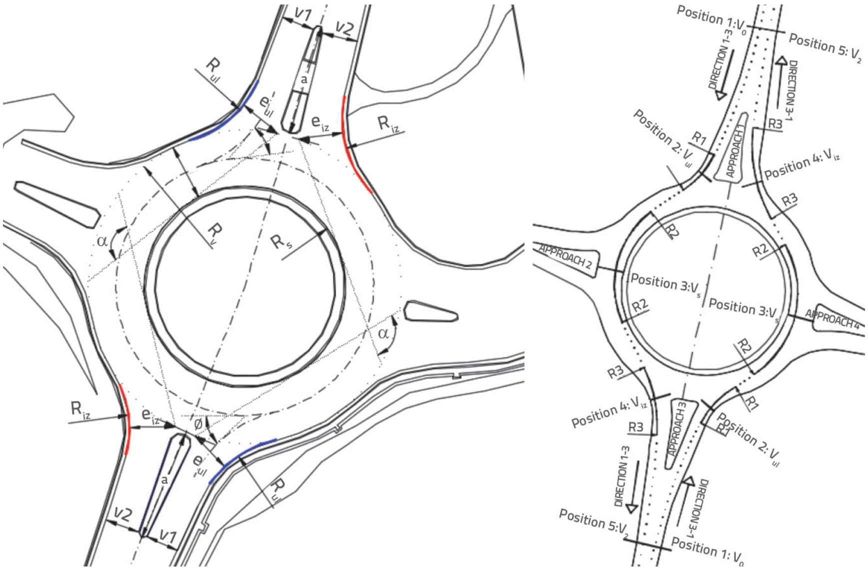

Figure 7. Data collected through experimental testing [18]: a) data on geometric design elements b) data on vehicle path elements

Figure 8 shows distribution of average vehicle-path radii in the middle of the roundabout for twenty straight roundabout directions used for model development.

The first step in the development of the multiple linear regression model was to determine the linear correlation (Pearson coefficient) between the path radius and geometric elements. The condition of normal data distribution had to be fulfilled to enable correlation of these elements. The normality of data distribution for each geometric element and path radius was verified by the Kolmogorov-Smirnov test (K-S test). The normality of data distribution was confirmed for the path radii and for all geometric design elements except for the width of circulatory roadway (u), length of splitter island at the entrance to the roundabout (a_1), length of splitter island at the exit from the roundabout (a_2), and the exit radius (R_{ex}), as shown in Table 2. The Box-Cox transformation was used for the variables (geometric elements) for which the distribution normality was not confirmed (u, R_{ex}, a_1, a_2). After that, the repeated KS test confirmed the normality of data distribution for the transformed variables.

intersections represent suburban type of roundabouts as they include no pedestrian and bicycle crossings. In fact, two of these intersections do have pedestrian crossings but the intensity of their use, and their impact on motor traffic flow, are negligible. For all selected roundabouts, the authors obtained topographic survey maps, showing current layout of these intersections.

The data collected at ten roundabouts (twenty straight directions) were used to determine the correlation between their geometric design elements and path radii, and to develop a numerical model, while the data from remaining one roundabout (two straight directions) were used for validation of the model. The methodology used in experimental testing implied collection of two types of data:

1. data on geometric design elements of roundabouts,
2. data on vehicle path radii in roundabouts.

The data on geometric design elements (Figure 7) were obtained and determined from topographic survey maps, showing current layout of these intersections. The data were additionally verified by direct field measurements at roundabout sites. Transit speed data and vehicle path radii were determined on the basis of data recorded for each vehicle pass with GNSS device, when driving straight through the roundabout. The driving was performed during stable weather conditions, in free traffic flow. The path of the vehicle was precisely recorded with 5 georeferenced points in 1 second. The transits in which the GNSS device did not continuously record the vehicle path were eliminated from further analysis and, in the end, 719 passes were adopted for analysis. Based on the data recorded by the GNSS device, the path of each vehicle pass through the roundabout was approximated using the AutoCAD software. The following data were thus recorded:

- path radius at the entrance - R_1,
- path radius in the middle - R_2 (Figure 8),
- path radius at the exit - R_3.

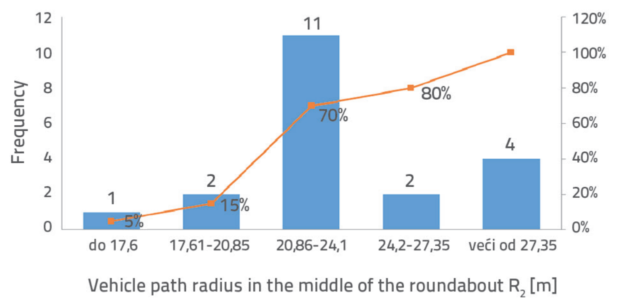

Figure 8. Distribution of experimentally collected data along radius of vehicle path at the middle of the intersection

Pearson's coefficients of linear correlation between geometric elements and path radius were determined once conditions relating to normality of data distribution are met (Table 3). The t-test was used for all values shown in Table 3 to determine the p-values that confirm statistical significance of a certain correlation. All correlation values for which p-values <0.05 were determined indicate that it is necessary to reject the null hypothesis, which states that the coefficient of correlation between certain data is equal to zero, i.e. that there is no statistically significant correlation. All coefficients that were found to be statistically significant are shown in Table 3.

The statistically significant linear correlation was confirmed between path radius in the middle of the roundabout R_2 and the following geometric elements:

- outer radius of the roundabout R_o (k = 0.9),

Table 2. Input variables of the model [18]

Roundabout	Direction	Geometric design elements													Experimental data		
		Entry width	Entry radius	Outer radius	Deflection angle	Entry angle	Width of splitter island	Width of traffic lane at the beginning of splitter island	Width of traffic lane at the end of splitter island	Radius of central island (including width of apron)	Exit width	Riz (Box - Cox trans. ^ = - 2)	a_1 (Box - Cox trans. ^ = - 1)	a_2 (Box - Cox trans. ^ = - 1)	Entry path radius	Middle path radius	Exit path radius
		e_{ul}	R_{ul}	R_v	α	ϕ	b	v_1	v_2	R_s	e_{iz}	$R_{iz\,(trans)}$	$a_{1\,(trans)}$	$a_{2\,(trans)}$	R_1	R_2	R_3
A	1 - 4	6.2	13.2	22.5	104.0	45.0	3.0	4.4	5.2	14.5	7.6	0.499	0.935	0.935	42.9	23.3	49.9
	4 - 1	5.8	8.6	22.5	110.0	41.0	3.0	4.0	4.5	14.5	6.6	0.499	0.935	0.935	55.0	23.5	56.6
B	1 - 3	6.4	18.0	24.5	108.0	36.0	5.7	5.0	4.2	16.5	6.9	0.499	0.988	0.942	41.1	22.1	81.2
	3 - 1	6.5	27.2	24.5	111.0	32.0	6.1	5.0	5.8	16.5	7.2	0.498	0.942	0.988	47.6	21.8	54.5
C	1 - 3	6.3	15.0	22.5	114.0	42.0	3.1	4.7	4.9	14.5	6.6	0.498	0.938	0.938	46.0	25.0	55.8
	3 - 1	6.1	15.8	22.5	101.0	43.0	3.2	4.7	5.1	14.5	6.6	0.498	0.938	0.938	47.7	21.8	52.2
D	1 - 3	5.3	15.0	35.0	96.0	35.0	10.0	4.7	5.7	27.0	6.6	0.499	0.956	0.956	38.5	29.9	45.7
	3 - 1	5.3	15.1	35.0	95.0	35.0	10.2	4.8	5.6	27.0	6.8	0.499	0.956	0.956	39.8	30.6	46.7
E	1 - 3	6.3	13.3	25.0	99.0	46.0	2.6	4.4	4.5	17.5	7.1	0.498	0.937	0.938	28.3	23.4	39.4
	3 - 1	6.4	13.4	25.0	96.0	42.0	2.6	4.5	4.3	17.5	6.7	0.498	0.938	0.937	33.8	23.2	42.6
F	1 - 3	6.8	31.5	25.5	108.0	29.0	7.8	5.1	5.8	17.5	7.0	0.500	0.952	0.952	42.7	23.1	70.3
	3 - 1	6.3	18.2	25.5	112.0	34.0	7.8	5.4	5.8	17.5	7.7	0.499	0.952	0.952	53.5	24.3	84.6
G	1 - 3	6.6	26.4	25.5	107.0	36.0	5.8	4.9	6.0	17.5	7.5	0.499	0.943	0.942	36.5	22.7	65.5
	3 - 1	6.8	27.0	25.5	106.0	34.0	6.0	5.0	6.0	17.5	7.3	0.500	0.942	0.943	43.7	23.8	59.3
H	1 - 3	5.3	15.3	35.0	97.0	35.0	10.1	4.6	5.5	27.0	6.3	0.499	0.956	0.958	41.2	29.7	47.6
	3 - 1	5.1	15.0	35.0	96.0	34.0	11.0	4.6	5.8	27.0	6.6	0.499	0.958	0.956	41.1	29.7	47.0
I	1 - 3	5.0	11.0	17.0	126.0	39.0	4.0	4.1	4.3	9.5	5.1	0.499	0.932	0.921	39.0	20.3	47.0
	3 - 1	4.7	10.2	17.0	122.0	38.0	4.1	3.9	4.1	9.5	5.4	0.499	0.921	0.932	37.6	19.8	59.4
J	1 - 3	4.8	10.8	16.0	124.0	42.0	3.9	4.1	5.0	10.0	5.6	0.498	0.943	0.888	33.8	24.0	68.9
	3 - 1	4.4	11.0	16.0	110.0	41.0	4.1	4.0	5.2	10.0	5.8	0.497	0.888	0.943	35.6	17.6	55.4

- angle of deflection α (k = - 0.6),
- width of splitter island b (k = 0.7),
- radius of central island (including truck apron) R_c (k = 0.9),
- length of splitter island at the entrance a_{1_tran} (k = 0.6).

These correlations are shown in Figure 9. It has also been established that there is no statistically significant correlation between geometric design elements and path radius at the entrance (R_1) and exit (R_3).

Table 3. Poisson coefficients of linear correlation [18]

	e_{ul}	R_{ul}	R_v	α	ϕ	b	v_1	v_2	R_s	e_{iz}	$R_{iz\ (trans)}$	$a_{1\ (trans)}$	$a_{2\ (trans)}$	R_1	R_2	R_3
e_{ul}	**1.0**	**0.7**	0.1	- 0.2	- 0.2	- 0.1	**0.7**	0.2	0.1	**0.8**	0.4	0.4	0.3	0.3	- 0.1	0.3
R_{ul}	**0.7**	**1.0**	0.2	- 0.1	**- 0.7**	0.3	**0.8**	**0.7**	0.2	**0.6**	**0.6**	0.3	**0.5**	0.2	0.0	0.4
R_v	0.1	0.2	**1.0**	**- 0.8**	**- 0.5**	**0.8**	**0.5**	**0.5**	**1.0**	0.4	0.4	**0.6**	**0.6**	0.1	**0.9**	- 0.3
α	- 0.2	- 0.1	**- 0.8**	**1.0**	0.1	- 0.4	- 0.3	- 0.3	**- 0.8**	**- 0.5**	- 0.1	- 0.3	**- 0.5**	0.1	**- 0.6**	0.4
ϕ	- 0.2	**- 0.7**	**- 0.5**	0.1	**1.0**	**- 0.8**	**- 0.6**	**- 0.6**	**- 0.5**	- 0.2	**- 0.7**	**- 0.5**	**- 0.6**	- 0.3	- 0.3	- 0.4
b	- 0.1	0.3	**0.8**	- 0.4	**- 0.8**	**1.0**	**0.5**	**0.7**	**0.8**	0.2	**0.5**	**0.5**	**0.6**	0.1	**0.7**	0.0
v_1	**0.7**	**0.8**	**0.5**	- 0.3	**- 0.6**	**0.5**	**1.0**	**0.6**	**0.5**	**0.7**	**0.5**	**0.6**	**0.6**	0.4	0.3	0.4
v_2	0.2	**0.7**	**0.5**	- 0.3	**- 0.6**	**0.7**	**0.6**	**1.0**	**0.5**	**0.5**	0.4	0.2	**0.5**	0.2	0.4	0.1
R_s	0.1	0.2	**1.0**	**- 0.8**	**- 0.5**	**0.8**	**0.5**	**0.5**	**1.0**	0.4	0.3	**0.6**	**0.6**	0.0	**0.9**	- 0.3
e_{iz}	**0.8**	**0.6**	0.4	**- 0.5**	- 0.2	0.2	**0.7**	**0.5**	0.4	**1.0**	0.4	0.4	**0.5**	0.3	0.2	0.2
$R_{iz\ (trans)}$	0.4	**0.6**	0.4	- 0.1	**- 0.7**	**0.5**	**0.5**	0.4	0.3	0.4	**1.0**	**0.5**	0.3	0.2	0.2	0.3
$a_{1\ (trans)}$	0.4	0.3	**0.6**	- 0.3	**- 0.5**	**0.5**	**0.6**	0.2	**0.6**	0.4	**0.5**	**1.0**	0.2	0.2	**0.6**	0.3
$a_{2\ (trans)}$	0.3	**0.5**	**0.6**	**- 0.5**	**- 0.6**	**0.6**	**0.6**	**0.5**	**0.6**	**0.5**	0.3	0.2	**1.0**	0.3	0.3	- 0.1
R_1	0.3	0.2	0.1	0.1	- 0.3	0.1	0.4	0.2	0.0	0.3	0.2	0.2	0.3	**1.0**	0.1	0.4
R_2	- 0.1	0.0	**0.9**	**- 0.6**	- 0.3	**0.7**	0.3	0.4	**0.9**	0.2	0.2	**0.6**	0.3	0.1	**1.0**	- 0.3
R_3	0.3	0.4	- 0.3	**0.5**	- 0.4	0.0	0.4	0.1	- 0.3	0.2	0.3	0.3	- 0.1	0.4	- 0.3	**1.0**

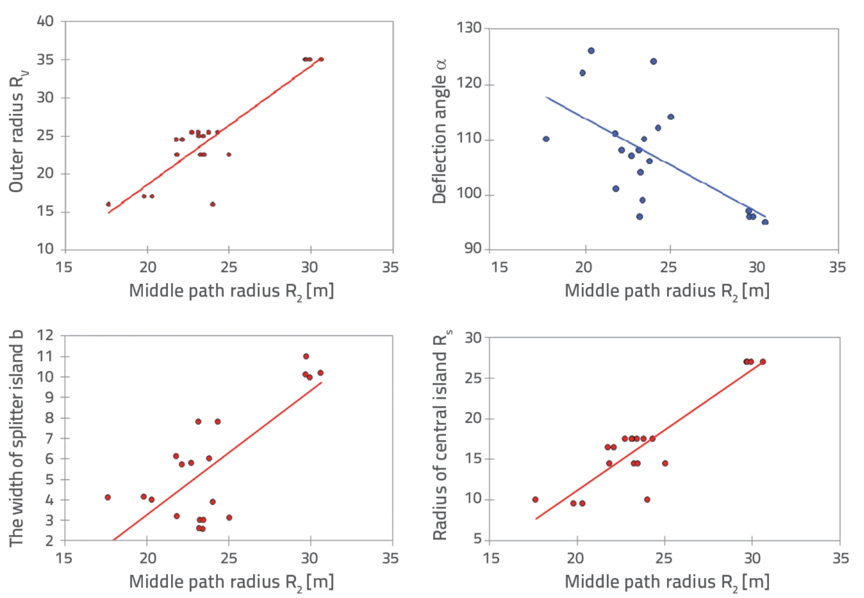

Figure 9. Correlation between path radius in the middle R_2 and individual geometric design elements of the roundabout [18]

The method of gradual regression, involving gradual expansion and complete reduction of model dimensions during selection of independent variables, was applied for the multiple linear regression model. All variables (all geometric elements of the roundabouts) were considered by this method irrespective of the correlation strength, and the significance of each variable was re-examined in each step.

Regardless of the strength of linear correlation, four variables were selected using the method of gradient regression for the model of the path radius in the middle of the intersection:

- angle deflection α,
- entrance angle ϕ,
- radius of central island (including truck apron) R_c,
- length of splitter island at the exit a_{2_trans}.

The correlation matrix between the selected independent variables (α, ϕ, R_c, a_{2_trans}) and the dependent variable R_2 is shown in Table 4.

Table 4. Correlation matrix between independent variables and dependent variable [18]

	α	ϕ	R_s	a_{2_trans}	R_2
α	1	0.080	**- 0.814**	**- 0.526**	**- 0.620**
ϕ	0.080	1	**- 0.459**	**- 0.600**	- 0.308
R_s	**- 0.814**	**- 0.459**	1	**0.592**	**0.905**
a_{2_trans}	**- 0.526**	**- 0.600**	**0.592**	1	**0.299**
R_2	**- 0.620**	- 0.308	**0.905**	0.299	1

One of basic assumptions of the multiple linear regression is the absence of multi-collinearity between independent variables. This assumption was verified by determining the variance inflation factor (VIF) (VIF), which is the most frequently used indicator of multi-collinearity. The variance inflation factor and tolerance sizes are given by the expressions (2) and (3):

$$VIF_j = \frac{1}{1-R_j^2} \qquad j = 1, 2, \ldots, k \tag{2}$$

$$TOL_j = \frac{1}{VIF_j} \qquad TOL_j = 1 - R_j^2 \tag{3}$$

In this expression, R^2_j is the determination coefficient for the multiple linear regression model in which j is the regression variable acting as a dependent variable, and the remaining (k-1) regressor variables are acting as independent variables. A multicollinearity problem is present if VIF_j is greater than 5 or TOLj is <0.2. Table 5 shows variance inflation factors and tolerance sizes for the model with the above chosen four independent variables (α, ϕ, R_c, a_{2_trans}) and a dependent variable R_2.

Table 5. Variance inflation factors and tolerance values [18]

	α	ϕ	R_s	a_{2_trans}
Tolerance	0.174	0.324	0.173	0.392
VIF	**5.744**	3.084	**5.782**	2.550

Table 5 shows that there is a possibility of multicollinearity since VIF = 5.744 > 5 (for variable α) and VIF = 5.782 > 5 (for variable R_c). Therefore, this model, which includes four independent variables (α, ϕ, R_s, a_{2_trans}) and a dependent variable R_2, was discarded from further analysis.

A multiple regression model for the vehicle path radius in the middle of the roundabout, which considers three independent variables (α, R_c, a_{2_trans}) and the dependent variable R_2 is considered in the following section. The entrance angle variable ϕ was discarded from further analysis since Poisson's coefficient of linear correlation showed a very poor connection to path radius in the middle R_2. The correlation matrix between the three independent variables and the path radius in the middle is shown in Table 6. Table 7 shows variance inflation factors and tolerance sizes, which confirm that in this case there is no possibility of multicollinearity.

Table 6. Correlation matrix between independent variables and dependent variable [18]

	α	R_s	$a_{2-trans}$	R_2
α	1	**- 0.814**	**- 0.526**	**- 0.620**
R_s	**- 0.814**	1	**0.592**	**0.905**
a_{2_trans}	**- 0.526**	**0.592**	1	0.299
R_2	**- 0.620**	**0.905**	0.299	1

Table 7. Variance inflation coefficients and tolerance sizes [18]

	α	Rs	$a_{2-trans}$
Tolerance	0.335	0.301	0.644
VIF	2.987	3.326	1.552

For the model with the chosen independent variables (α, R_s, a_{2_trans}) and the dependent variable R_2, it was established by the Durbin-Watson test (DW test) that there is no autocorrelation of errors of the relation e_i. The null hypothesis of the test states that there is no auto-correlation between the errors. The null hypothesis is accepted if the following is valid (4):

$$d > d_{upper} \text{ ori } d < (4 - d_{upper}) \tag{4}$$

where

d - test size

d_U - critical values, sampling-distribution values.

In case of the above model, the applied DW test, i.e. the calculated value of the test d_{stat}, does not satisfy the expression (4) which is a condition for the absence of autocorrelation. The value of the d_{stat} test is between the limit values ($d_{lower} \leq d_{stat} \leq d_{upper}$, Table 8), which prevents us from concluding that there is an autocorrelation of errors of the relation ei.

Table 8. Results of DW test for autocorrelation [18]

Test size - d_{stat}	1.648649
Lower critical value - d_{lower}	0.99755
Upper critical value - d_{upper}	1.67634

Given the impossibility of making conclusion about the autocorrelation error, the mentioned model with three independent variables (α, R_c, a_{2_trans}) and the dependent variable R_2 was rejected.

Only two independent variables were chosen for the final model of multiple linear regression: angle of deflection α and radius of central island (including truck apron) R_c, and path radius in the middle R_2 as the dependent variable. Basic assumptions of the multiple regression model, and the representativeness of this model, are examined below.

Linearity

Pearson correlation coefficient values shown in the correlation matrix (Table 9) confirmed the first hypothesis of the multiple regression model, since the t-test for all coefficients showed that the corresponding p-values are <0.05 and that the null hypothesis about non-existence of linear correlation should be rejected.

Table 9. Correlation matrix between independent variables and dependent variable [18]

	α	R_s	R_2
α	1	**- 0.814**	**- 0.620**
Rs	**- 0.814**	1	**0.905**
R_2	**- 0.620**	**0.905**	1

Normal distribution of dependent and random variable e

The K-S test was used to verify normal distribution of residual deviations and dependent variable. The test results are shown in Table 10. These results (p-values greater than 0.05) indicate the acceptance of null hypothesis that the data are coming from normal distribution.

Table 10. Results of K-S test for normality of distribution of residual variances and variable R_2 [18]

	R_2	R_{2_pred}	Residual deviations	Standardized residuals
p - values	0.291	0.330	0.991	0.990
α - level of significance	0.05	0.05	0.05	0.05

Homoscedasticity

Once the above mentioned two conditions of multiple linear regression are met, the assumption of fulfilment of the condition of homoscedasticity, i.e., assumptions that relation errors e_i have the same variance, are verified as shown below. In order to verify this assumption, the analysis of residual deviations was compared in relation to independent variables (Figure 10), and in relation to regressive values R_{2_pred} (Figure 11).

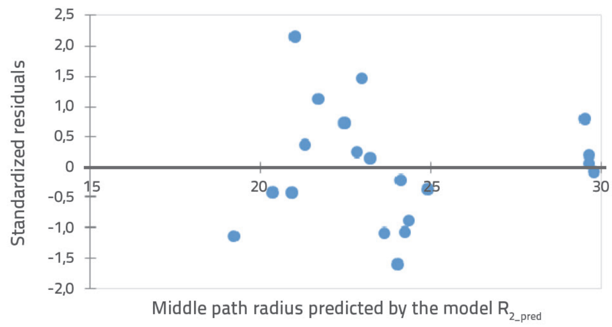

Figure 11. Residual deviations as related to regression values R_{2_pred} [18]

Figures 10 and 11 show that residual deviations are randomly (erratically) arranged around the x-axis and that there is no pronounced trend. Spearman correlation coefficient values as well as t-test values (p-values) (Table 11) confirm that there is no statistically significant correlation between independent variables and residual deviations and regression values and residual deviations.

Table 11. Spearman correlation coefficients and t-test values (p-value) [18]

	Regression values (R_{2_pred}) – stand. residual deviations	Independent variables (α) – stand. residual deviations	Independent variables (R_c) – stand. residual deviations
Spearman correlation coefficient	- 0.059	- 0.234	- 0.026
p - values	0.806	0.320	0.912

Autocorrelation

The condition of non-existence of auto-correlation of errors of the relation was verified by the DW test according to expression (4). These test results (shown in Table 12) confirm the mentioned linear regression assumption.

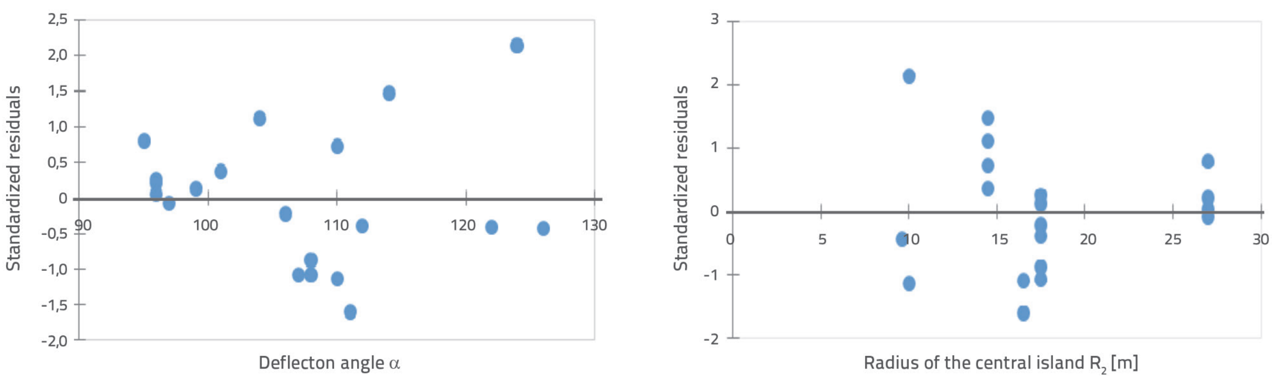

Figure 10. Residual deviations as related to independent variables [18]

Table 12. DW test results [18]

Test size - d	2.090617
Lower critical value - d_L	1.1004
Upper critical value - d_u	1.53668

Multicollinearity

The requirement of non-existence of multicollinearity was verified by determining the variance inflation factor and the tolerance size (Table 13). It was established that there is no multicollinearity between the chosen variables.

Table 13. Variance inflation factors and tolerance sizes for final model [18]

	α	R_s
Tolerance	0.338	0.338
VIF	2.960	2.960

Since all assumptions of the multiple linear regression model have been met, the analytic expression of the model for the vehicle path radius in the middle of the roundabout can be defined as follows (5):

$$R_{2\_pred} = -2{,}036 + 0{,}128 \cdot \alpha + 0{,}719 \cdot R_s \quad (5)$$

where:

R_{2_pred} - the radius of the vehicle path in the middle of the roundabout [m]

α - the deflection angle [°]

R_s - the radius of the central island (including the truck apron if there is one) [m].

The corrected determination coefficient R^2_{adj} = 0.842 for the obtained model of path radius in the middle of the intersection confirms that 84.2% of the relation between the observed variables can be explained by the multiple linear regression model. In order to confirm validity of the developed model for the radius of vehicle path through the roundabout, additional measurements were carried out at the roundabout that was not used for model development (Table 14). By its features, the selected roundabout corresponds to geometric design elements of ten roundabouts that were used for development of the model. Opposite axes of the intersection form an angle of 180°, and the axes of intersection legs are straight or curved by a minimum radius of 250 m in the narrower intersection zone, and are approximately horizontal. The intersection is suburban, and hence the impact of cyclists and pedestrians on the movement of vehicles in the intersection zone is eliminated. All of the above corresponds to the criteria that were used when choosing intersections (ten of them) for development of the model. Based on analytic expression of the model for vehicle path radius through the roundabout (5), the radius of the vehicle path is calculated in the middle of the intersection, separately for each straight direction of the roundabout:

- direction 1-3 (za α = 107° i Rc = 14 m) R_{2_pred} = 21.71 m
- direction 3-1 (za α = 108° i Rc = 14 m) R_{2_pred} = 21.84 m

By their values, experimentally determined radii R_{1-3} = 21.5 m and R_{3-1} = 21.51 m (Table 14) are within the range of 55% of the path radius value (Figure 8) based on which the model was developed, as well as the values calculated by the model.

The calculated radius of vehicle path in the middle of the roundabout was compared to the average radius of vehicle path in the middle of the roundabout, separately determined for 32 passes in direction 1-3, and 30 passes in direction 3-1 (Table 14).

Table 14. Data required for model validation [18]

	Data from GNSS device	**Geometric data**	
	Middle path radius R_2 [m]	**Deflection angle α [°]**	**Radius of central island R_s [m]**
Direction 1 - 3	21.50	107	14
Direction 3 - 1	21.51	108	14

The t-test results (p-values) shown in Table 15 confirm that there is no statistically significant difference between the average path radius value and the one calculated by the model.

Table 15. t-test results for comparison of average path radius values in the middle of the roundabout and the values calculated by the model [18]

	Direction 1 - 3	Direction 3 - 1
p - value	0.322	0.119
α - level of significance	0.05	0.05

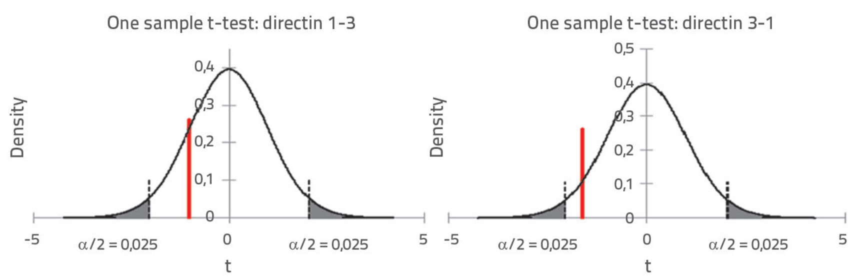

Figure 12. t-test results for comparison of average radius path value and value determined by model [18]: a) direction 1-3; b) direction 3-1

The t-test results are also confirmed graphically, as shown in Figure 12.

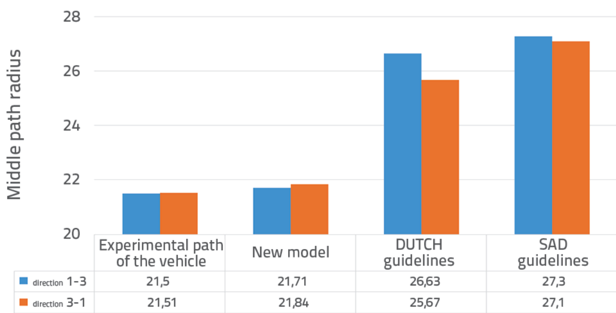

Figure 13. Difference between path radius in the middle determined by the model and the average value obtained by field tests

The results obtained using the new model were compared to the average vehicle path radius obtained by field testing, and to the results obtained by applying the Dutch model (expression 1) and the vehicle path construction method according to the US guidelines (Figure 3 left). Small differences between the radius determined by the new model and the one obtained in the field test in the middle of the intersection (Figure 13) are the result of a very well-explained connection between the variables observed by the multiple linear regression model (corrected coefficient of determination $R^2 = 0.84$).

4. Conclusion

Most guidelines for the roundabouts analysed in this paper provide recommendations for forming the vehicle path through roundabouts by defining safety distances from raised curbs and marked lines of pavements or islands. Safety distances in the vehicle path development models vary from 1 m to 1,5 m. The experimentally determined paths differ significantly from recommendations given in the analysed guidelines, which was an incentive for further research, i.e., for the development of an original vehicle path model for roundabouts, as presented in this paper. For this purpose, detailed experimental tests were carried out on a total of ten selected roundabouts. The data on geometric design elements of roundabouts, as well as the data on the radii of the vehicle path through a roundabout, were obtained to this effect. A model for calculating the vehicle path radius in the middle of a roundabout was developed using the multiple regression analysis. This model is based on strong correlation with specific geometric elements of roundabouts. Statistical data analysis did not confirm significant correlations between geometric design elements and path radius at the entrance (R_1) and exit (R_3). Therefore, these models were not developed. Deflection angle (α) for the observed straight movement of the vehicle, and the radius of the central island R_s (which also includes the width of truck apron, and that of the central island, if any), were chosen as the parameters that best explain linear relation with path radius in the middle of the roundabout by applying the gradual model expansion method. The corrected determination coefficient $R^2_{adj} = 0.842$ for the obtained model of the path radius in the middle of the intersection confirms that 84.2 % of the connection between the path radius in the middle, the angle of deflection, and the radius of the central island, is explained by the multiple linear regression model, and can be considered as highly reliable. Model validation was carried out on the basis of field tests conducted at the roundabout that was not used in the model development tests. Statistical tests confirm that for the level of significance $\alpha = 0.05$ the values of the calculated vehicle path radii in the middle of the roundabout, and the average values of the radii determined on the basis of field tests, do not differ, i.e. that it is necessary to accept the null hypothesis stating that there is no statistically significant difference between the observed radii.

The vehicle path model for the middle of the roundabout was developed and validated for roundabouts with the central island radius ranging from 9.5 to 27 m, and for angles of deflection varying from 95° to 126°. The model can however be used for the central island radii and deflection angles that deviate from the mentioned values, but subject to additional validation.

The developed model of vehicle path in the middle of the roundabout represents the basis for further research of the vehicle speed model at roundabouts, and thus constitutes a contribution to the efforts for optimizing the roundabout design procedure in terms of meeting appropriate safety and capacity requirements.

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