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Comparison of Single-Lane Roundabout Entry Degree of Saturation Estimations from Analytical and Regression Models

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Abstract: Roundabout design is an iterative process consisting of a preliminary geometry design, geometry performance checks, and the estimation of intersection functionality (based on the results of analytical or regression models). Since both roundabout geometry design procedures and traffic characteristics vary around the world, the discussion on which functionality estimation model is more appropriate is ongoing. This research aims to reduce the uncertainty in decision-making during this final roundabout design stage. Its two objectives were to analyze and compare the results of roundabout performance estimations derived from one analytical and one regression model, and to quantify the model results' susceptibility to changes in roundabout geometric parameters. For this, 60 four-legged single-lane roundabout schemes were created, varying in size and leg alignment. Their geometric parameters resulted from the assumption of their location in a suburban environment and chosen design vehicle swept path analysis. To compare the models' results, the degree of saturation of roundabout entries was calculated based on presumed traffic flows. The results showed that the regression model estimates higher functionality and that this difference (both between the two models and regression models applied on different schemes) is more pronounced as the outer radius and angle between the legs increase.

Keywords: suburban roundabout design; swept path analysis; geometric parameters; performance estimation; capacity assessment

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1. Introduction

Roundabouts are intersections with a one-way circulatory roadway around a central island. In most countries, the vehicles entering the roundabout should give right-of-way to vehicles in the circulatory lane. Consequently, roundabout operational functionality is directly dependent on the traffic conditions in the circulating traffic flow and indirectly dependent on the geometric design of the roundabout. According to [1–3], single-lane roundabouts are a very good solution for the following transportation engineering demands: for reduced intersection dimensions; for intersections with five or more legs; when there is even distribution of traffic on the intersection legs; for traffic volumes under 25,000 veh/day; for a decrease in the waiting time at the intersection; as a measure to calm traffic, especially in urban areas; and for lowering levels of traffic noise, emissions of harmful gases, and the risk of accidents (due to the low driving speeds of approaching and circulating traffic, and fewer conflict points than at standard intersections). Additionally, single-lane roundabouts are increasingly popular solutions in suburban areas due to their design that provides an easy transition in road category and type (from a dual to a single roadway, i.e., from rural to the urban environment), and the fact that they do not require the installation, maintenance, and operation of signal lights.

Roundabout design is an iterative process consisting of a (1) preliminary geometry design, (2) geometry performance checks, which include the design vehicle swept path, fastest path, and visibility analysis, and (3) assessments of intersection functionality through capacity analysis. Roundabout geometry is primarily influenced by the design vehicle swept path. The design vehicle is a vehicle identified as the least maneuverable vehicle expected to use the intersection [4]—a vehicle of a certain type and dimensions that characterize a group of vehicles and fully correspond to the legal regulations on vehicle dimensions [5], or international recommendations [6]. Design vehicles are often chosen depending on the position of the intersection in the road network and the composition and category of expected vehicles (trucks in industrial zones, buses in urban and suburban areas, etc.) [7]. After confirming the preliminary design through the geometry performance checks, the iterative design process shifts to capacity analysis, to assure that the roundabout geometry satisfies traffic performance criteria. If the capacity value is too low or too high, the geometry needs to be redesigned and the capacity analysis repeated [8].

Numerous models have been created over years to assist road designers and traffic analysts in the assessments of intersection functionality. These models can be broadly classified into three categories: (1) probabilistic, analytical, gap-acceptance models, (2) deterministic, empirical regression, geometric models, and (3) time-dependent, microsimulation models. The final selection of the most appropriate roundabout design is usually based on the results of the analytical or regression model for entry capacity assessment [9–13].

The analytical models were created based on combining the main postulates of traffic flow theory and field-measured driver behaviors. This approach resulted in an analytic formulation of the relationship between field measurements and theoretical performance parameters [14]. They consider traffic flow composition and conflict between vehicles in the circulatory roadway and vehicles entering the roundabout [15]. Probability theory is used to estimate to what extent the vehicles entering a roundabout will be able to use an acceptable gap between two consecutive vehicles in the circulating traffic stream [9,16]. They do not directly quantify the relationship between the capacity and geometric parameters of the roundabout [11,13].

On the other hand, regression models were generated from extensive traffic data collected at roundabout entries. They have established relationships between capacity and geometric design features through statistical multivariate regression analyses to fit mathematical relationships between measured entry capacity, circulating flow, and other independent variables that have an impact on entry capacity [9,14]. They consider not only the circulating and entering but also the exiting traffic flow. The relationship between entry capacity and circulating flow is linear or exponential, depending on the model [8,11].

Simulation models are based on modeling the movements and interactions of individual vehicles on a network consisting of links and nodes or connectors. Vehicle movements are governed by gap acceptance, car-following, lane-changing, and other models, and are typically calculated for each vehicle at every specified time step [8]. In recent years, vehicle movements along a roundabout have been studied within the master equation formalism for stochastic exclusion processes of many-particle systems, i.e., many-body interactions. The finite dimensions of vehicles introduce a natural "quantization" of space, and developed models simulate the stochastic motion of particles (vehicles) along a roundabout through the (totally) asymmetric exclusion process [17,18].

Although designers and analysts would like to perform estimations as completely and correctly as possible, model performance in predicting roundabout entry capacities is limited [19]. Even today, the discussion between analytical and regression models characterizes the general situation regarding the estimation of entry capacity at roundabouts [9,12]. The main issues address the fact that both roundabout geometric parameters and traffic characteristics (volume, vehicle composition, and driver behavior) vary widely across the world [20]. However, according to [10,21], geometric parameters have a much stronger impact on roundabout entry capacity than geographic location or country of origin, i.e., "regional" non-geometric driver behavior. Additionally, among the different factors influencing entry capacity, only the geometric parameters of roundabouts can be quantified and modified, i.e., entirely manipulated by the designers to improve roundabouts' operational performance [11].

The two objectives of the research presented in this paper are to (1) analyze and compare the results of roundabout performance estimations derived from analytical and regression models, and (2) quantify the model results' susceptibility to changes in roundabout geometric parameters. The investigation will be performed on 60 four-legged single-lane roundabouts schemes, varying in size and leg alignment, designed according to the results of the chosen design vehicle swept path analysis. The roundabout performance estimations will be performed under the assumption that the entering traffic at each leg is distributed in three travel directions through the roundabouts, in equal shares. To compare the results of the analytical and regression models, the roundabout entry degree of saturation will be calculated. This is a dimensionless value used as the intersection efficiency indicator in both models. The results of this research will reduce the uncertainty in decision-making during the final roundabout design stage.

2. Materials and Methods

A list of symbols used in the manuscript is given in Table 1.

Table 1. List of symbols used in the manuscript.

Group	Symbol	Parameter
Geometric parameters	R_o	outer radius (m)
	R_i	central island radius (m)
	u	circulatory roadway width (m)
	j	number of roundabout legs, j = 1, . . . , 4
	δ	angle between the roundabout legs (°)
	l	length of the arc between the adjacent roundabout legs (m)
	e_j	entry width (m)
	e_j'	exit width (m)
	R_j	entry radius (m)
	R_{j+1}'	exit radius (m)
	b_j	distance between exiting and entering traffic flows along the center of the circulatory lane (m)
Traffic parameters	i	direction of travel through roundabout, i = 1, . . . , 12
	q_i	traffic flow in the direction i (veh/h)
	Q_i	traffic flow in passenger car units in the direction i (pcu/h)
	f_T	conversion factor for traffic composition (pcu/veh)
	Q_{Cj}	circulating traffic flow (pcu/h)
	Q_{Sj}	exiting traffic flows at leg j (pcu/h)
	Q_{Ej}	entering traffic flows at leg j (pcu/h)
	BC_j	base entry capacity of the roundabout at leg j (pcu/h)
	f_P	capacity reduction factor for pedestrian and cycling traffic flow at roundabouts (-)
	C_{Ej}	entry capacity at leg j (pcu/h)
	C_{mj}	entry capacity for mixed traffic flow at leg j (veh/h)
	q_{mj}	mixed traffic flow at leg j (veh/h)
	$x_{mj,A}$	degree of saturation of entry at leg j according to analytical model (-)
	$x_{mj,R}$	degree of saturation of entry at leg j according to regression model (-)
	α	factor reflecting the impact of exiting traffic on entry capacity by distance b (-)
	β	factor for adjusting circulating flow depending on the number of circulating lanes (-)
	γ	factor for adjusting entry capacity depending on the number of circulating lanes (-)

The geometric parameters of a roundabout are the outer radius (R_o), the central island radius (R_i), the circulatory roadway width (u), the number of legs (j), the angle between the legs (δ), entry width (e_j), exit width (e_j'), entry radius (R_j), and exit radius (R_{j+1}'). The selected R_o is influenced by the location of the roundabout (urban, suburban, rural), roundabout task (e.g., traffic calming), spatial constraints, and the number of circulatory lanes. In this investigation, the roundabout geometric parameters, design vehicle used for swept path analysis, and traffic flow characteristics were defined based on the following assumptions: (1) the roundabouts were to be situated in a suburban environment and

(2) the roundabouts were to act as single-lane traffic-calming devices along the transition path from the rural to the urban environment.

A plan view of the analyzed 4-legged single-lane roundabouts schemes was created in AutoCAD. The following initial geometric parameters were used (Figure 1a):

- R_o applied in this investigation varied from 13.0 to 20.0 m, with a 0.5 m increment. According to previous research given in [22], these outer radii are commonly used for single-lane roundabouts worldwide. An increment of 0.5 m was chosen to capture the dispersity of the results and to create a sample that is representative, manageable, and easy to present at the same time;
- The roundabout leg alignment was radial, as is standard in the suburban environment [22];
- The axes of legs 1 and 4 intersected at $\delta = 90°$. The axes of legs 1 and 2 intersected at δ ranging from 75° to 90° with 5° increments. This range was defined after considering the condition given in [23], regarding the length of the arc (l) between the adjacent roundabout legs. According to these guidelines, the length of this arc should be longer than 20 m to ensure the efficiency of the roundabout. Namely, a shorter l makes it difficult for drivers to signal the exit of the intersection when turning right due to the very short time to turn on the turn signals;
- There were 15 m long triangular splitter islands designed at each leg with 0.5 m offset from the defined outer edge of the circulatory roadway;
- The initial alignment of 3.25 m wide entry and exit lanes was defined.

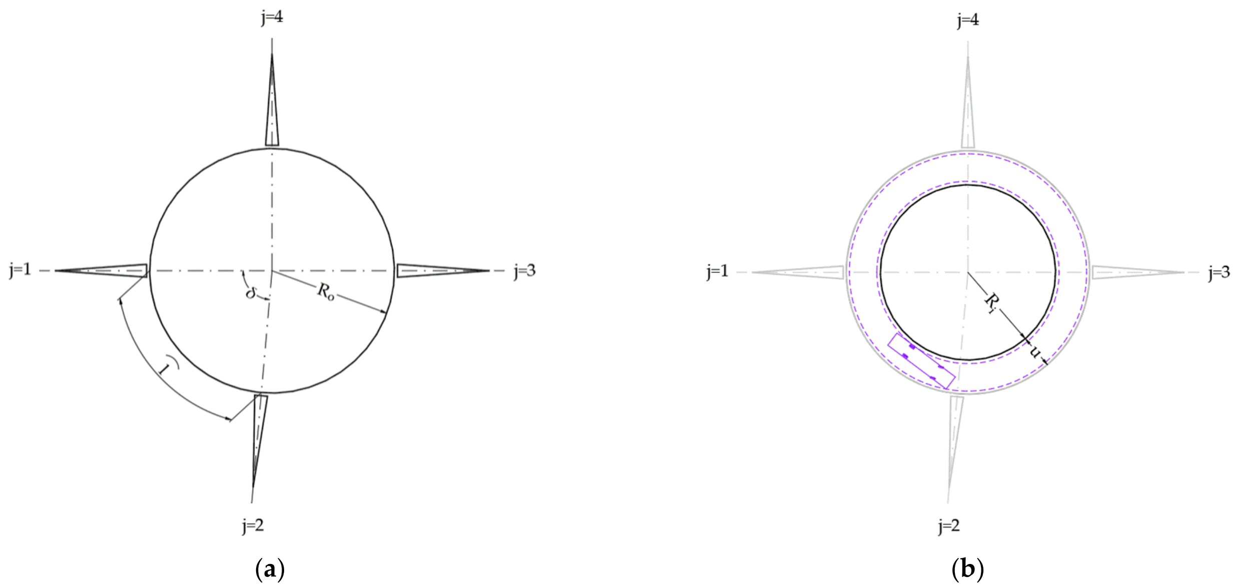
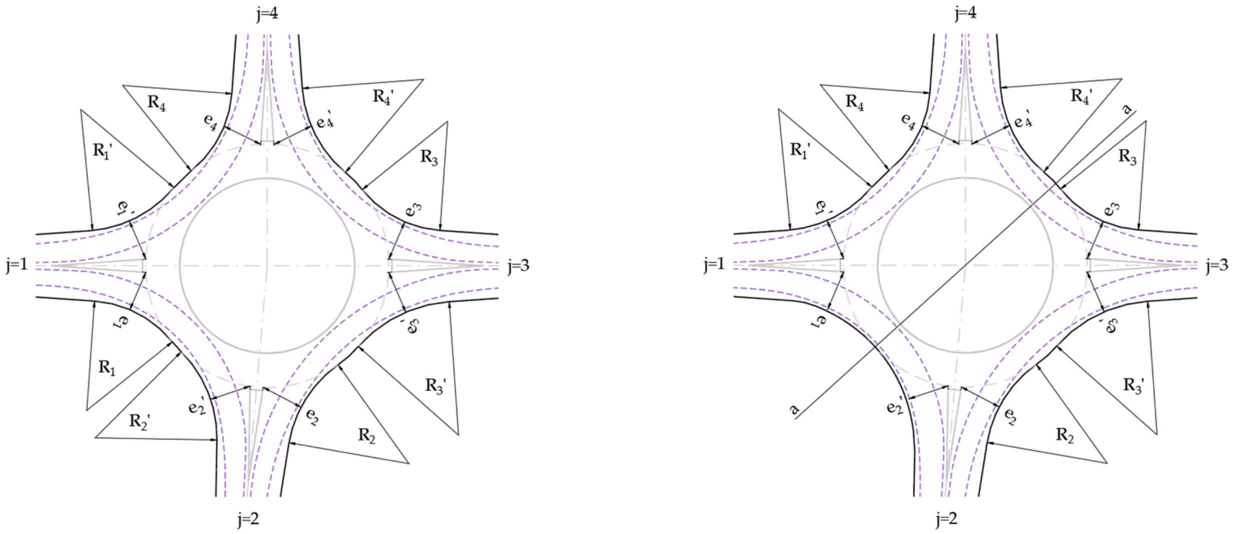


Figure 1. Design of initial geometric parameters: (**a**) the outer radius, legs, and splitter islands; (**b**) the central island radius and the circulatory roadway width defined based on the design vehicle swept path when driving in a full circle.

The geometric parameters R_i, R_j, R_{j+1}', and u resulted from the design vehicle swept path analysis, which was performed in the AutoCAD software add-in Vehicle tracking 2022. The selected design vehicle was a 12 m long bus adopted from the German vehicle library FGSV 2001. The geometric parameters R_i and u (Figure 1b) were defined based on the design vehicle swept path when driving in a full circle [7] while ensuring minimum lateral clearances of 0.5 m [24].

The geometric parameters R_j and R_{j+1}' were defined based on the design vehicle swept path when turning right [24], while ensuring minimum lateral clearances of 0.5 m. Where possible, to achieve wider exits, the roundabout's right roadway edge was designed by considering the condition of $R_{j+1}' \geq R_j + 2$ m (Figure 2a) [25]. Wider roundabout exits are favorable as they enable higher roundabout exit speeds, help minimize the likelihood of congestion and crashes at the exits, provide ease of navigation for long vehicles, and reduce the potential for trailers to track over the outside curb. At roundabouts where it was not possible to design the right roadway edge with radii R_j and $R_{j+1}{}'$ due to leg alignment, a different procedure was applied. Here, the right roadway edge was designed based on the trajectory of the vehicle's right turn movement and lateral clearances of 0.5 m in cross-section a–a (Figure 2b). The geometric parameters e_j and $e_j{}'$ were defined as the shortest distance between the intersection point of the drawn line on the edge of the splitter island and the entry line and the right roadway edge on the roundabout entry and exit (Figure 2).

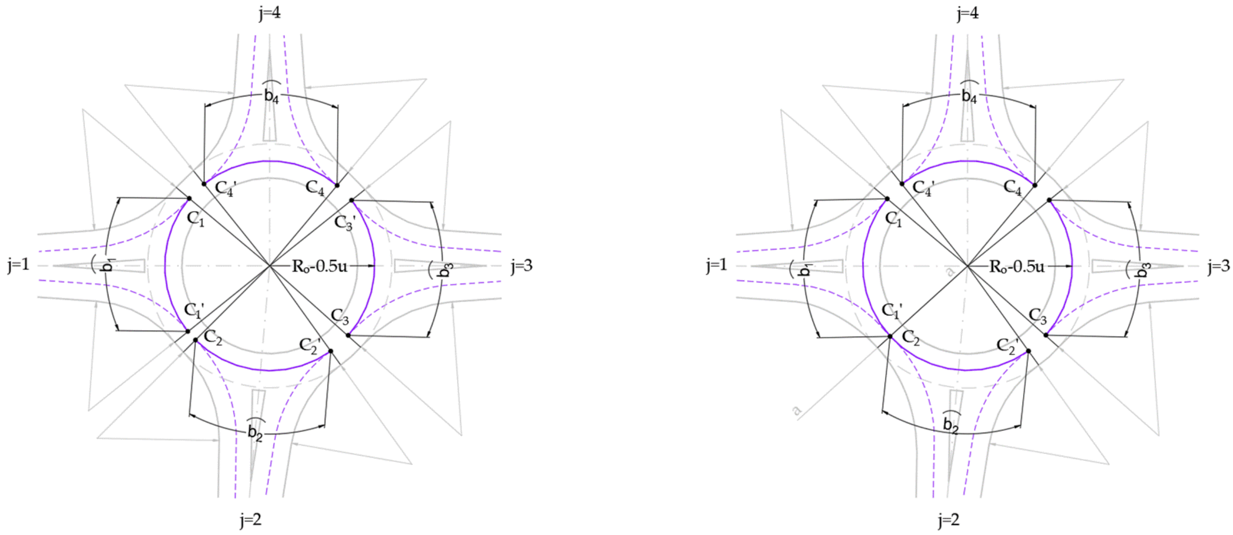


(**a**) (**b**)

Figure 2. Roadway right edge design based on the trajectory of the vehicle's right-turn movement: (**a**) defined by entry radius and exit radius; (**b**) defined by the trajectory of the design vehicle.

The two observed models for the roundabout entry degree of saturation calculation differ in the utilization of the abovementioned geometric parameters. The analytical HBS 2015 model, given in [26], uses only R_o as an input for calculation. The regression Swiss Bovy model, given in [1], considers the influence of conflicting traffic on the circulatory roadway that is exiting the roundabout at the same leg as the observed entry. The influence of conflicting traffic on the circulatory roadway is defined as the distance between exiting and entering traffic flows along the center of the circulatory lane (b_j) [8], i.e., it considers the joint influence of geometric parameters R_o, R_i, and δ.

Parameter b_j was defined through the following procedure. First, the lines from the center of the outer radius R_o to the center of the radii R_j and $R_j{}'$ were drawn (Figure 3a). At roundabouts where it was not possible to design the right roadway edge with radii R_j and $R_{j+1}{}'$, the line from the center of the outer radius R_o perpendicular to the trajectory of the vehicle's right turn movement was drawn (Figure 3b). Then, a circle of radius R_o—u/2 was constructed from the R_o center. Traffic stream conflicting points, exiting point (C) and entering point (C′), were defined as intersections of these entities. The distance between exiting and entering traffic streams along the center of the circulatory lane, i.e., the length of the circular arc between conflicting points $b_{j,}$ was then measured.



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

Figure 3. Defining the distance b along the center of the circulatory lane, for roadway right edge design defined by the: (**a**) entry and exit radius; (**b**) design vehicle trajectory.

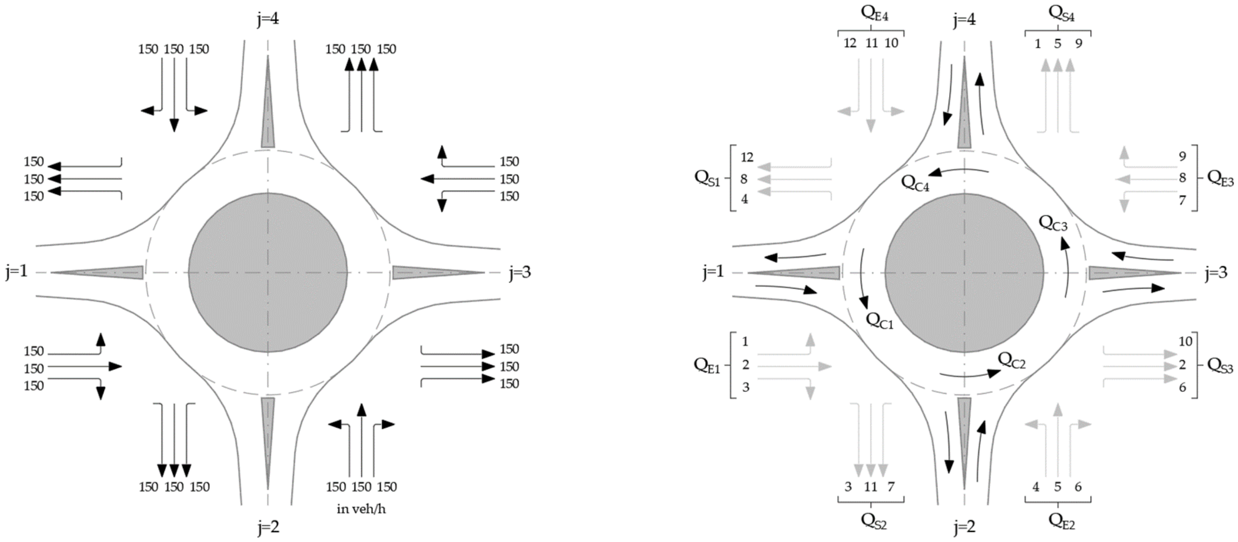
Once designed, the geometric parameters R_i, u, e_j, e_j', and b_j were systematized according to the R_o and δ. When designing a roundabout according to the previously described procedure, it should be noted that the results depend on the experience and subjective approach of the designer. Therefore, to better present the influence of the chosen R_o and δ on the designed parameters, regression analysis was performed, and best-fit curves with a coefficient of determination larger than 0.99 were created. Second-degree polynomial curves were used to describe R_i and u as a function of R_o, and third-degree polynomial curves were used to describe e_j, e_j', and b_j as a function of R_o for different δ. Additionally, the average difference between b_j (j = 1, 2, and 3) for δ = 90° and b_j (j = 1, 2, and 3) for δ = 85°, 80°, and 75° was calculated.

The entry degree of saturation (x_{mj}) was defined as the ratio of entering traffic flow and entry capacity. According to [14], sustainable values of x_{mj} range from 0.0 to 1.0 (values above 1.0 indicate an excess of entering traffic demand over entry capacity). x_{mj} was calculated for each designed scheme considering the following simplifications and assumptions on traffic flow volume, distribution, and composition:

- Three travel directions through the roundabout were considered at each roundabout entry (j = 1, . . . , 4): right turn, straight passage, and left turn (i = 1, . . . , 12).
- Traffic flow q_i at each entry (j = 1, . . . , 4) in each travel direction (i = 1, . . . , 12) was 150 veh/h, adding up to a total of 1800 veh/h passing through the roundabout (Figure 4a).
- The influence of pedestrian and bicycle traffic on roundabout capacity was not considered.
- The influence of heavy vehicles on the traffic flow quality was considered through the homogenization of traffic flows q_i. Flat-rate conversions of each q_i from vehicles per hour (veh/h) to Q_i in passenger car units per hour (pcu/h) were made by using a conversion factor of f_T = 1.1, prescribed by [26] in case of lacking real data on flow composition:

$$Q_i = f_T \cdot q_i, \quad (1)$$

where Q_i is homogenized traffic flow in the direction i (pcu/h), f_T is conversion factor (set to 1.1), and q_i is traffic flow in the direction i (veh/h).



(a) (b)

Figure 4. Traffic flows at a four-legged roundabout: (**a**) each entry in each travel direction, in veh/h; (**b**) entering, exiting, and circulating the roundabout.

The same procedure for determining the entering, exiting, and circulating traffic flows given in [26] was used for both the analytical and regression models. Based on assumed traffic conditions, 12 entering and exiting traffic flows Q_i for each travel direction (i = 1, . . . , 12) were calculated. Then, the entering traffic flows Q_{Ej}, exiting traffic flows Q_{Sj}, and the circulating traffic flow Q_{Cj} (traffic flow in the circulatory roadway, i.e., the main flow, which has priority over the ones entering the circulatory roadway) were calculated for each leg (j = 1, . . . , 4) according to Figure 4b and Table 2.

Table 2. Calculation of entering, exiting, and circulating traffic flow.

Leg j	Q_{Ej} (pcu/h)	Q_{Sj} (pcu/h)	Q_{Cj} (pcu/h)
1	$Q_{E1} = Q_1 + Q_2 + Q_3$	$Q_{S1} = Q_4 + Q_8 + Q_{12}$	$Q_{C1} = Q_7 + Q_{10} + Q_{11}$
2	$Q_{E2} = Q_4 + Q_5 + Q_6$	$Q_{S2} = Q_3 + Q_7 + Q_{11}$	$Q_{C2} = Q_1 + Q_2 + Q_{10}$
3	$Q_{E3} = Q_7 + Q_8 + Q_9$	$Q_{S3} = Q_2 + Q_6 + Q_{10}$	$Q_{C3} = Q_1 + Q_4 + Q_5$
4	$Q_{E4} = Q_{10} + Q_{11} + Q_{12}$	$Q_{S4} = Q_1 + Q_5 + Q_9$	$Q_{C4} = Q_4 + Q_7 + Q_8$

Once the circulating, entering, and exiting traffic flows were established, the x_{mj} was calculated through the following analytical and regression model procedures.

In the analytical model, the circulating flow Q_{Cj} was used as an input variable for determining the base capacity of the approach BC_j. BC_j values for the roundabout with one circulatory lane and the outer radius of roundabout R_o were determined from the chart in Figure 5 [26]. As the chart gave data only for roundabouts with outer radii R_o of 13.5, 15, 17.5, and 20 m, for other investigated R_o values, BC_j was defined through interpolation.

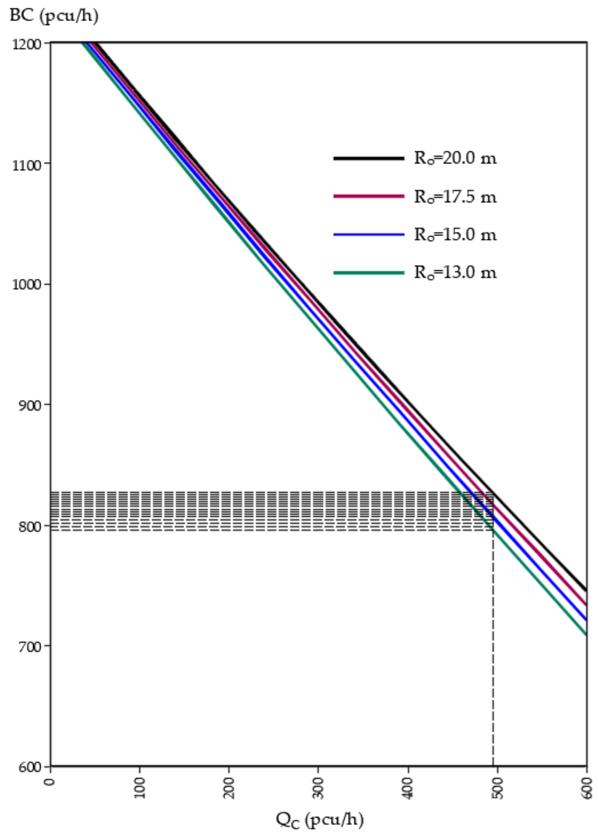


Figure 5. Base capacity at single-lane roundabouts as a function of outer radius.

Roundabout entry capacity C_{Ej} was calculated as

$$C_{Ej} = BC_j \cdot f_p, \quad (2)$$

where C_{Ej} is roundabout entry capacity considering the impact of pedestrian crossings (pcu/h), BC_j is the base entry capacity of the roundabout according to Figure 5 (pcu/h), and f_p is the capacity reduction factor for pedestrian and cycling traffic flow at roundabouts. In this investigation, the influence of pedestrian and bicycle traffic on entering traffic flow was neglected and the f_p factor was set to 1.0. The value of entry capacity C_{Ej} was, therefore, equal to base capacity BC_j.

To determine the degree of saturation x_{mj}, it was necessary to back-calculate the entry capacity values C_{Ej} from passenger car units to vehicles per hour. The entry capacity C_{mj} for the mixed traffic flow was then calculated as

$$C_{mj} = \frac{C_{Ej}}{f_T}, \quad (3)$$

where C_{mj} is the entry capacity for mixed flow (veh/h), C_{Ej} is the entry capacity (pcu/h), and f_T is the conversion factor for traffic composition set to 1.1 because of the absence of real data on flow composition.

Mixed traffic flow q_{mj} in vehicles per hour was then calculated on each leg's entry by summing up the three traffic flows q_i with different directions of travel (right turn, straight passage, and left turn). $x_{mj,A}$ was calculated as the ratio of entering mixed traffic flow q_{mj} in vehicles per hour and entry capacity C_{mj} in vehicles per hour:

$$x_{mj,A} = \frac{q_{mj}}{C_{mj}}, \quad (4)$$

where $x_{mj,A}$ is the entry degree of saturation according to the analytical model, q_{mj} is mixed traffic flow on legs' entry (veh/h), and C_{mj} is entry capacity (veh/h).

In the regression model, entry capacity C_{Ej} in passenger car units per hour was defined as [1]

$$C_{Ej} = \frac{1}{\gamma}\left[1500 - \frac{8}{9}\cdot\left(\beta\cdot Q_{Cj}+\alpha\cdot Q_{Sj}\right)\right], \quad (5)$$

where C_{Ej} is entry capacity (pcu/h), Q_{Cj} is circulating traffic flow in front of the leg being considered (pcu/h), Q_{Sj} is exiting traffic flow on the same leg as the entry (pcu/h), α is a factor reflecting the impact of exiting traffic on entry capacity by distance b_j, β is a factor for adjusting circulating flow depending on the number of circulatory lanes, and γ is a factor for adjusting entry capacity depending on the number of circulatory lanes.

Conflict factor α was determined from the chart in Figure 6 for measured distance b_j and middle curve. The factors β and γ were set to 1.0, as single-lane circulatory roadways were investigated [1].

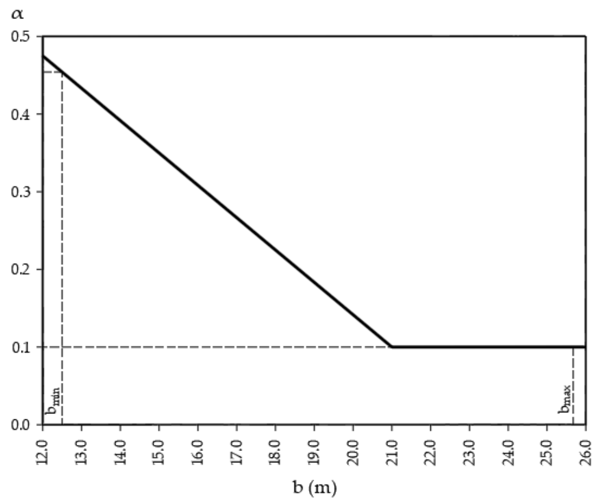


Figure 6. Conflict factor reflecting the impact of exiting traffic on entry capacity by the distance between exiting and entering traffic streams along the center of the circulatory lane.

The degree of saturation of entry was defined as

$$x_{mj,R} = \frac{\gamma\cdot Q_{Ej}}{C_{Ej}}, \quad (6)$$

where $x_{mj,R}$ is the entry degree of saturation according to the regression model, γ is a factor for adjusting entry capacity depending on the number of circulatory lanes (set to 1.0), Q_{Ej} is entering traffic flow (pcu/h), and C_{Ej} is entry capacity (pcu/h).

To present the influence of R_o and δ on calculated x_{mj}, regression analysis was performed, and best-fit curves for x_{mj} values were created. Second-degree polynomial curves with a coefficient of determination larger than 0.99 were used to visualize the trend.

To further quantify the impact of the application of different models in the roundabout design process, the reversed calculation of traffic flow at each leg was performed according to the regression model methodology. The calculation was based on the condition that the intersection enables the same level of saturation as previously defined by the analytical model (i.e., for the previously determined values of $x_{mj,A}$). With this reversed calculation, the potential traffic flow volume in veh/h was determined for each roundabout, summarized, and compared with the input total flow rate of 1800 veh/h.

3. Results

The results of the roundabout geometric design showed that to simultaneously fulfill two roundabout design conditions (regarding preferred arc length and the roundabout's right roadway edge design, Table 3) values of R_o for different δ should be (1) $R_o \geq 13.5$ m for δ = 85°, (2) $R_o \geq 16.5$ m for δ = 80°, and (3) $R_o \geq 19.0$ m for δ = 75°.

Table 3. Overview of two roundabout design conditions' fulfillment (marked with +): Condition 1 ($l \geq 20$ m)/Condition 2 ($R_{j+1} \geq R_j + 2$ m).

R_o (m)	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5	18.0	18.5	19.0	19.5	20.0
δ = 90°	+/+	+/+	+/+	+/+	+/+	+/+	+/+	+/+	+/+	+/+	+/+	+/+	+/+	+/+	+/+
δ = 85°	−/+	+/+	+/+	+/+	+/+	+/+	+/+	+/+	+/+	+/+	+/+	+/+	+/+	+/+	+/+
δ = 80°	−/−	−/−	−/−	+/−	+/−	+/−	+/−	+/+	+/+	+/+	+/+	+/+	+/+	+/+	+/+
δ = 75°	−/−	−/−	−/−	−/−	−/−	+/−	+/−	+/−	+/−	+/−	+/−	+/−	+/+	+/+	+/+

Considering the fulfillment of the abovementioned conditions (Table 3), designing a roundabout with a δ ≤ 75° is not recommended. However, the roundabout design that does not consider these two design conditions could be applied in the suburban environment because of the spatial limitations. Therefore, calculations of the x_{mj} were performed for all 60 designed roundabouts, based on the calculated traffic flow volumes shown in Figure 7.

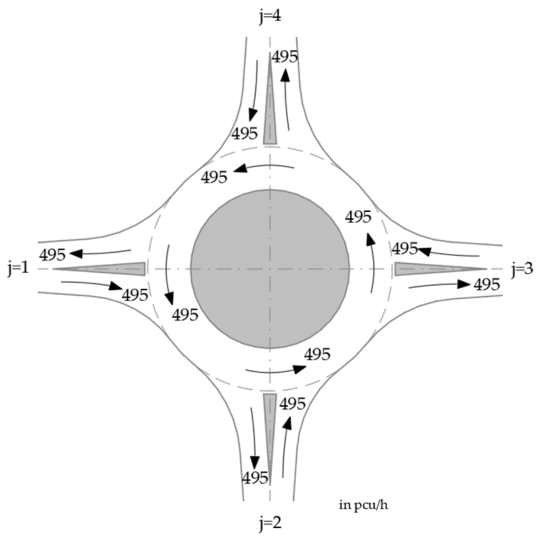


Figure 7. Calculated values of entering, exiting, and circulating traffic flow in pcu/h.

The resulting values of the geometric parameters of the 60 designed roundabouts schemes are shown with their best-fit curves in Figures 8, 9a, 10, 11 and 12a.

As shown in Figure 8, R_i, e_j, e_j', and b_j were proportional to R_o, and u values were inversely proportional. The change in e_1 was (1) proportional to δ, (2) identical for δ = 90 and 85°, (3) identical for δ = 80 and 75° at R_o = 13.0 m, and (4) identical for δ = 90, 85, and 80° at $R_o \geq 19.0$ m. The change in e_2 was inversely proportional to δ at $R_o \geq 14.0$ m. The change in e_2' and e_3' at $R_o \geq 16.0$ m showed an uneven trend for different δ. As expected, δ did not affect the entrance and exit widths e_3, e_4, e_1', and e_4'.

As shown in Figures 9a, 10, 11 and 12a, the trend of b_j increasing for different δ corresponded to those of e_j and e_j'. Thus, the change in b_1 (1) was proportional to δ and (2) was identical for δ = 90 and 85°. The change in b_2 was inversely proportional to δ at $R_o \geq 14.0$ m. δ had a negligible effect on the values of b_3 at $R_o < 16$ m. The change in δ had no effect on the values of b_4. Extreme values of b_j were observed for δ = 75° and R_o = 13.0 m (b_1 = 12.5 m) at leg 1, and R_o = 20.0 m (b_2 = 25.7 m) at leg 2.

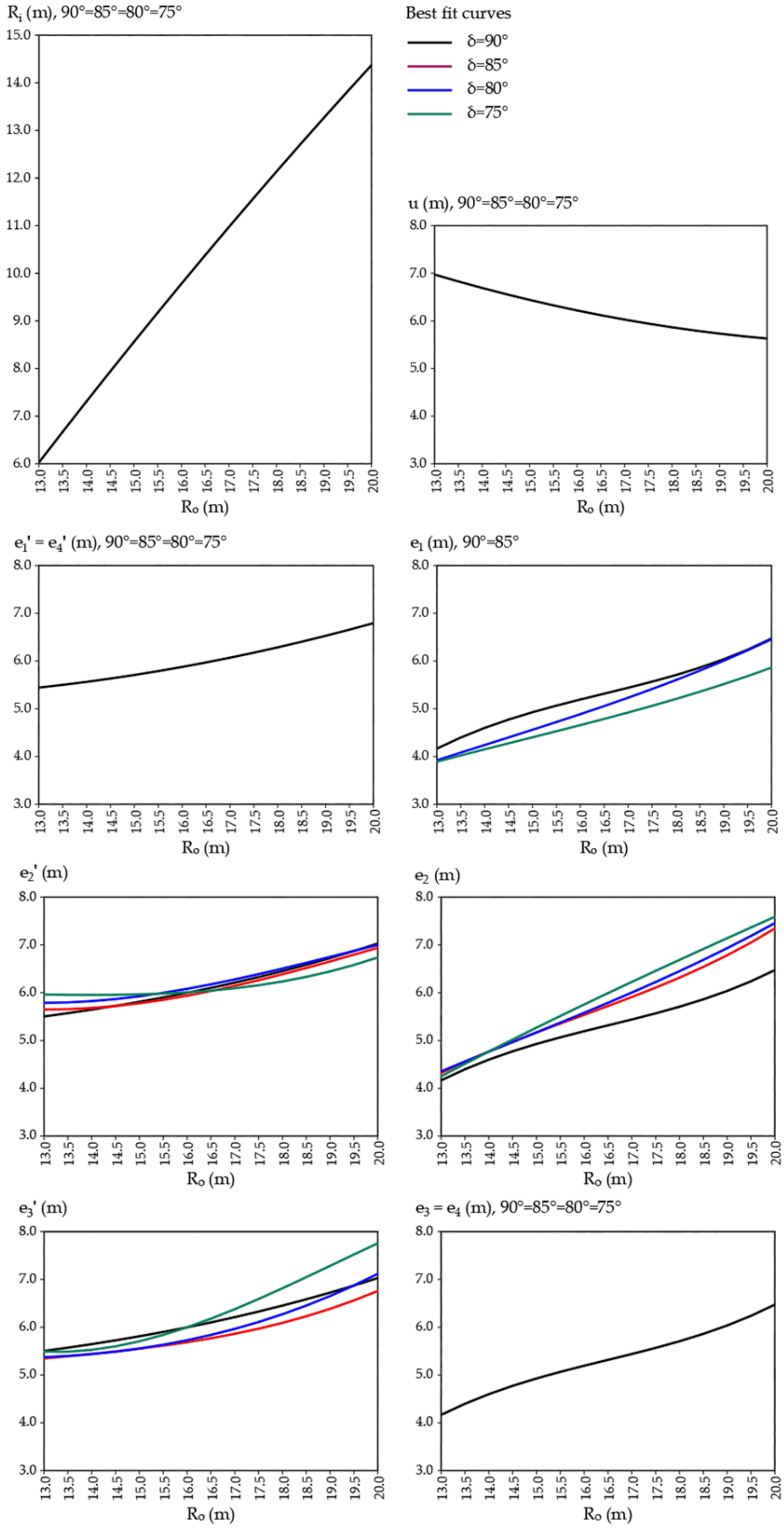


Figure 8. Geometric parameters R_i, e_j, e_j', and u as a function of R_o for different δ.

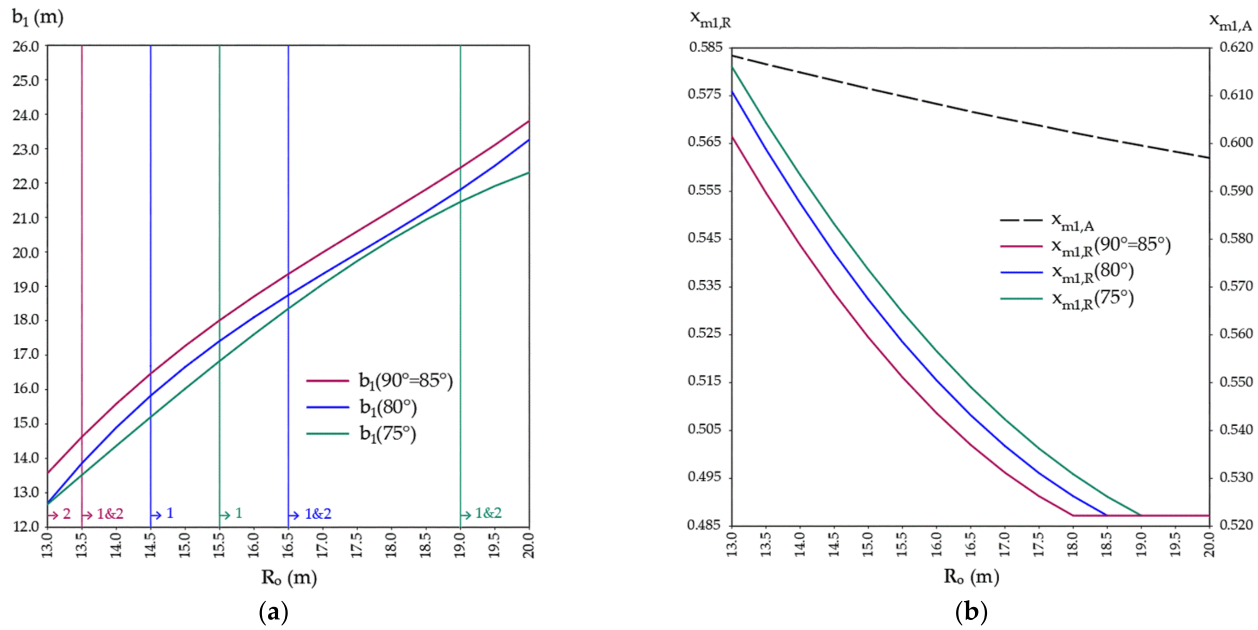


Figure 9. Investigated parameters at leg 1 as a function of R_o for different δ, considering the application of design conditions 1 and 2: (**a**) geometric parameter b_1; (**b**) traffic parameter x_{m1}.

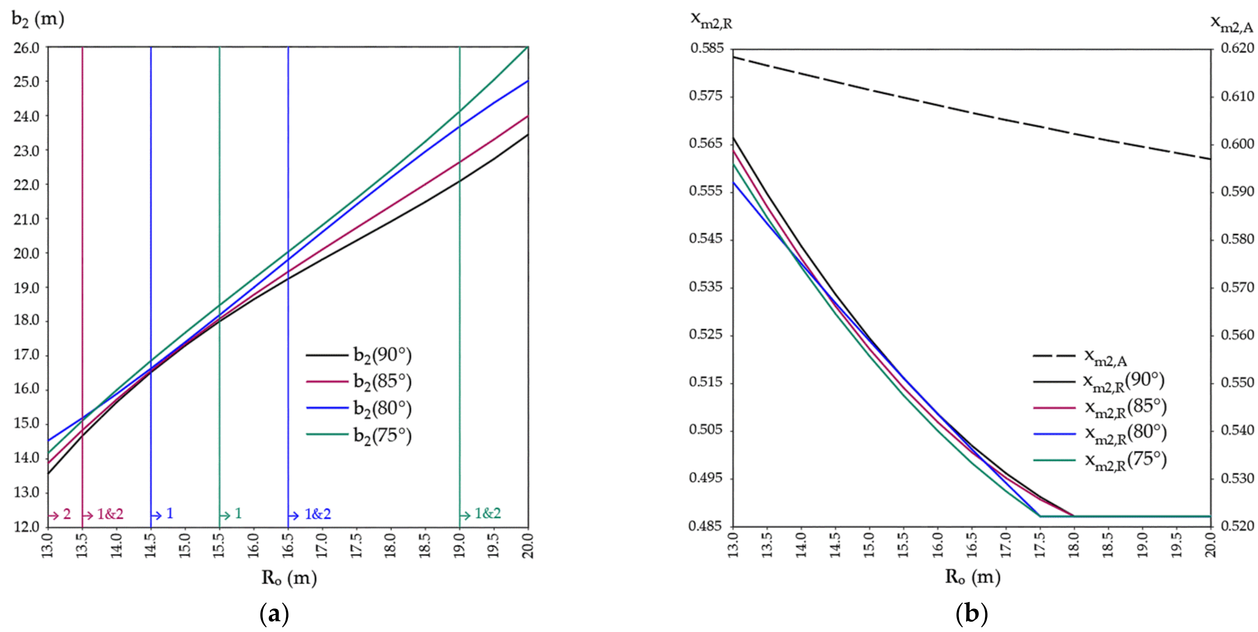


Figure 10. Investigated parameters at leg 2 as a function of R_o for different δ, considering the application of design conditions 1 and 2: (**a**) geometric parameter b_2; (**b**) traffic parameter x_{m2}.

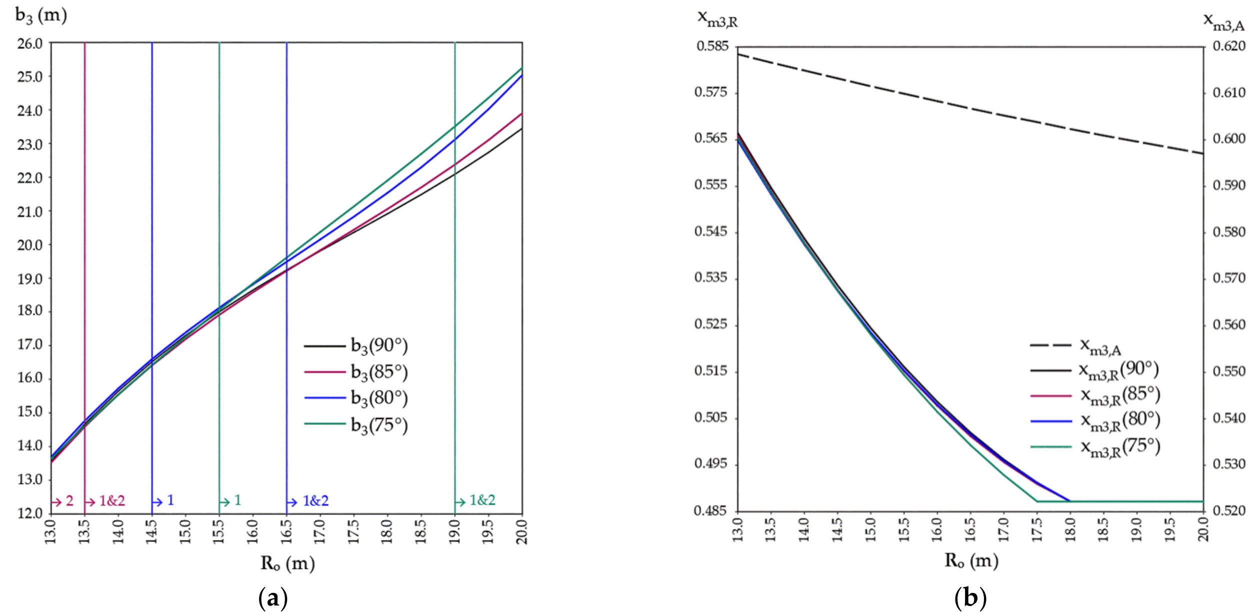


Figure 11. Investigated parameters at leg 3 as a function of R_o for different δ, considering the application of design conditions 1 and 2: (**a**) geometric parameter b_3; (**b**) traffic parameter x_{m3}.

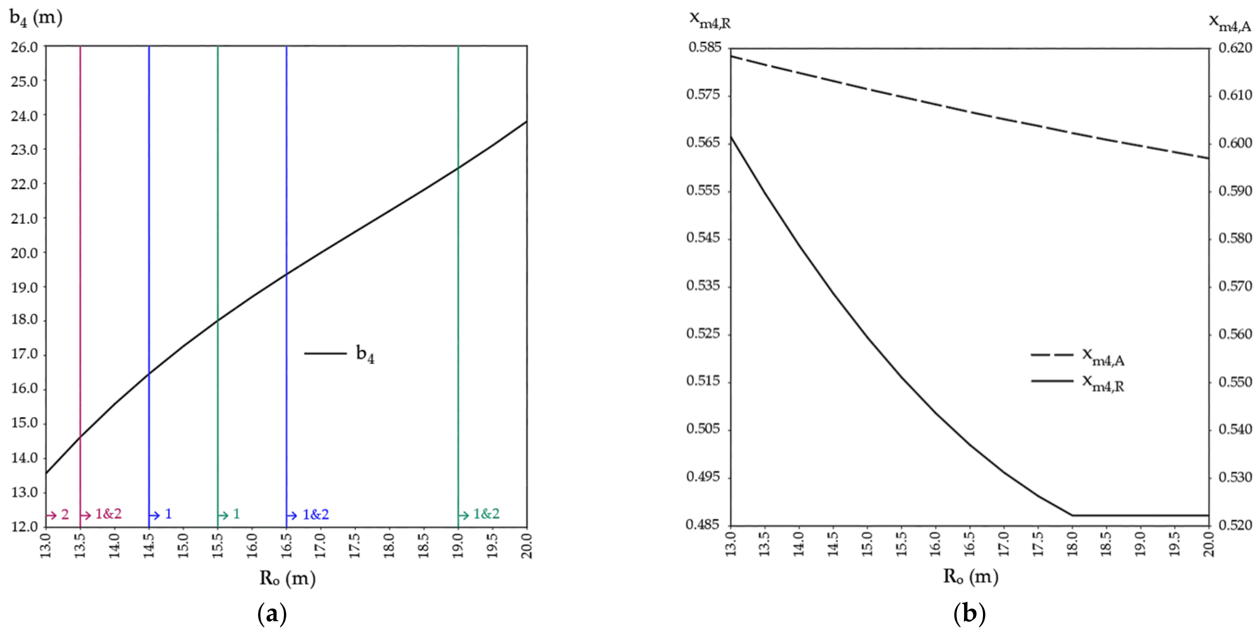


Figure 12. Investigated parameters at leg 4 as a function of R_o for different δ, considering the application of design conditions 1 and 2: (**a**) geometric parameter b_4; (**b**) traffic parameter x_{m4}.

The results of the calculation of the entry degree of saturation with dependence on the R_o of roundabouts and δ according to the analytical model ($x_{mj,A}$) and regression model ($x_{mj,R}$) showed that x_{mj} values were inversely proportional to R_o. $x_{mj,R}$ values followed the observed trend of b_j for all analyzed δ at each roundabout leg (Figures 9b, 10, 11 and 12b). For $R_o \leq 16.5$ m, an established trend showed a more rapid decrease in b_j and, consequently, in $x_{mj,R}$. On the other hand, for $R_o \geq 19.0$ m, it can be stated that the differences in the right roadway edge design, regardless of δ, do not affect $x_{mj,R}$. The values of $x_{mj,A}$ decreased at a lower and uniform rate as R_o increased. $x_{mj,A}$ values were higher than $x_{mj,R}$ by, on average, 16%. The average difference between $x_{mj,A}$ and $x_{mj,R}$ varied between 0.088 and 0.100. These extreme differences were observed for δ = 75°, at leg 1 and leg 2, respectively. At each leg, the average observed difference between the calculated $x_{mj,R}$ for δ = 90° and $x_{mj,R}$ for the other δ values amounted to (1) 0.3% at leg 2 for δ = 85°, (2) 1.1% at leg 1, and 0.4% at leg 2 for δ = 80°, (3) 1.7% at leg 1, 0.5% at leg 2, and 0.2% at leg 3 for δ = 75°.

Figure 13 shows the average difference between b_1, b_2, and b_3 for δ = 90° and b_1, b_2, and b_3 for δ = 85°, 80°, and 75°, respectively. The change in these differences in b_j values is linear. As expected, b_1 shortened as δ decreased. The opposite is true for b_2 and b_3. The main reason for this is the design of the right roadway edge based on the design vehicle swept path analysis. Namely, on the roundabout exit at legs 2 and 3, the body of the design vehicle swept a wider surface than on the roundabout entry at leg 1, and this surface was ever wider as δ decreased. Therefore, the designed exit radii R_2' and R_3' were significantly larger than the recommended ones and, consequently, the distances b_2 and b_3 were inversely proportional to δ.

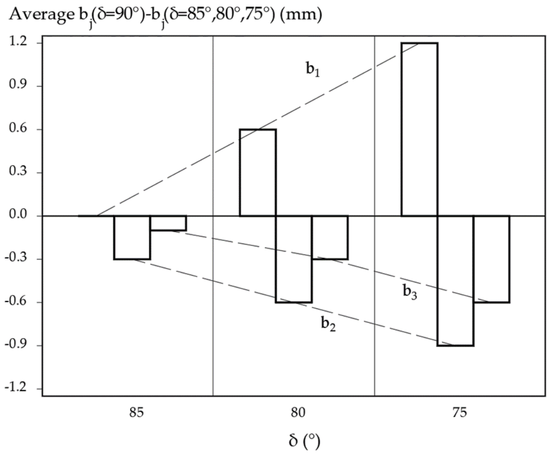


Figure 13. The average difference between b_1, b_2, and b_3 for δ = 90° and b_1, b_2, and b_3 for δ = 85°, 80°, and 75°.

The results of the reversed calculation of traffic flow at each leg according to the regression model methodology showed that, at a given roundabout, the application of the regression model gives the same x_{mj} results as the analytical one for 6% to 15% higher traffic flows q_i. The difference in traffic flow values obtained through this calculation is shown as a percentage concerning the initial total value of 1800 veh/h (Figure 14).

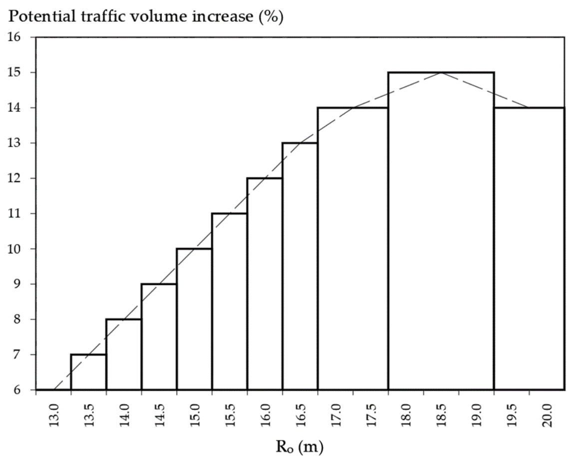


Figure 14. Results of the reversed calculation of traffic flow—the difference in traffic flow values shown as the percentage of the initial 1800 veh/h.

4. Discussion and Conclusions

The iterative process of roundabout design requires shifting between geometry design and capacity analysis, to ensure that chosen roundabout geometry satisfies the desired traffic performance criteria. The quality of traffic flow on the roundabout is indirectly dependent on its geometric parameters, and should be estimated during roundabout design through calculation models or simulations. In this investigation, a comparison of the analytical and empirical models for single-lane roundabout entry degree of saturation estimation was performed on 60 designed four-legged roundabout schemes.

When designing a single-lane roundabout based on the design vehicle swept path analysis, the choice of geometric parameters and the capacity calculation model influences the roundabout performance evaluation results. The observed models differ in the utilization of the geometric parameters: (1) the analytical model uses only the roundabout outer radius as an input for calculation, while (2) the regression model considers the influence of conflicting traffic on the circulatory roadway defined by the distance between exiting and entering traffic flows along the center of the circulatory lane, i.e., it considers the joint influence of roundabout outer radius, the central island radius, and the angle between the roundabout legs.

The results of the geometric and traffic parameters analysis showed that the central island radius and entry capacity are proportional to the outer radius. At the same time, the circulatory roadway width and the entry degree of saturation are inversely proportional to the outer radius. This is in line with the conclusions given in [27], which state that circulatory roadway width significantly influences capacity. As can be seen from our results, the influence of the circulatory roadway width, derived from the design vehicle swept path, on capacity is counterintuitive; narrower circulatory roadways on roundabouts with a larger outer radius enabled higher entry capacity, i.e., lower entry degree of saturation.

According to [11], entry width has a positive correlation with entry capacity. According to [27], the distance between the entry and exit has a greater impact on the entry capacity than the entry radius. The results of our investigation show that an increase in entry width is directly linked with an increase in outer radius value and the design of the right roadway edge derived from the design vehicle swept path, and that it decreases the roundabout entry degree of saturation in the regression model. A larger outer radius in the analytical model results in a lower degree of saturation. A larger outer radius and a greater distance between the conflicting points (dependent not only on radius but also on the width of the circulatory roadway and entry and exit widths) in the regression model result in a lower degree of saturation.

In general, for all the observed combinations of geometric parameters, the regression model results in lower values of roundabout entry degree of saturation. This difference is more pronounced as the outer radius and angle between the roundabout legs increase. This implies that it is possible to justify the chosen roundabout geometric parameters by choosing the capacity analysis model, which will allow higher traffic flow volumes. Namely, the results of the investigation showed that it is possible to increase the traffic flows that could be processed at a given roundabout from 6% to 15% if the regression model is applied instead of the analytical one during roundabout performance evaluation. From the perspective of the time in which the roundabout is expected to satisfy the desired performance criteria and considering that the average annual increase in motor vehicles' number in Europe is 2% (according to the European Automobile Manufacturers' Association), it could be said that the application of the regression model could extend the expected service life of a roundabout by 3 to 7 years.

For further research, the results of this investigation will be compared to and validated by roundabout entry degree of saturation calculations performed with data from field measurements. Additionally, it is planned to reverse-calculate the distance between exiting and entering traffic flows along the center of the circulatory lane for $x_{m,R} = 0.85$, which is defined as the maximum entrance degree of saturation [28]. This will allow the investigation of how this distance affects other roundabout geometric parameters and traffic flows.

The described approach to roundabout capacity model comparison and appropriateness evaluation could be applied to more complex roundabout setups, i.e., to roundabouts with two-lane approaches, two-lane circulatory roadways, different leg numbers and alignments, and the presence of pedestrian and cyclist flow. This investigation could be also conducted for urban areas where spatial and territorial constraints are more stringent, i.e., for roundabouts with minimal outer radii of 6.5 m and with leg alignments defining the minimum distance between exiting and entering traffic flows along the center of the circulatory lane of 9 m.

The investigation presented in this paper has shown that (1) the applied regression model estimates a higher roundabout traffic performance than the analytical one, and (2) this difference (both between the two models and regression models applied on different schemes) is more pronounced as the outer radius and angle between the legs increase. To conclude, the regression model is more suitable for application in suburban roundabout design, i.e., for environments with spatial limitations, and where performance evaluation demands higher traffic flow volumes to be processed through the roundabout. On the other hand, due to its simplicity, the analytical model should be applied in rural areas with more heterogenic and time-variable traffic flows, and for road network planning purposes, preliminary roundabout design, and robust capacity estimations.

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References

1. Ministry of Transport. *Roundabouts—Application and Design: A Practical Manual*; Ministry of Transport, Public Works and Water Management, Partners for Roads: Amsterdam, The Netherlands, 2009.
2. Alozi, A.R.; Hussein, M. Multi-criteria comparative assessment of unconventional roundabout designs. *Int. J. Transp. Sci. Technol.* **2021**, *11*, 158–173. [CrossRef]
3. *CROW: Eenheid in Rotondes*; CROW Publication no.126; CROW: Ede, The Netherlands, 1998; Available online: https://nmfv.dk/wp-content/uploads/2012/06/RDC_Netherlands.pdf (accessed on 15 March 2023).
4. Ahac, S.; Ahac, M.; Džambas, T.; Dragčević, V. The Design Vehicle Steering Path Construction Based on the Hairpin Bend Geometry-Aplication in Roundabout Design. *Appl. Sci.* **2022**, *12*, 11019. [CrossRef]
5. Regulation on technical conditions of vehicles in road traffic (Official Gazette, no. 85/16, 24/17, 60/20). Available online: https://narodne-novine.nn.hr/clanci/sluzbeni/2016_09_85_1864.html; https://narodne-novine.nn.hr/clanci/sluzbeni/2017_03_24_547.html; https://narodne-novine.nn.hr/clanci/sluzbeni/2020_05_60_1224.html (accessed on 15 March 2023).
6. Directive 96/53/EC and Directive 2002/7/EC. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:01996L0053-20150526&from=EN (accessed on 15 March 2023).
7. Građevinski fakultet Sveučilišta u Rijeci. *Smjernice za Projektiranje Kružnih Raskrižja na Državnim Cestama*; Građevinski fakultet Sveučilišta u Rijeci: Rijeka, Croatia, 2014.
8. Yap, Y.H.; Gibson, H.M.; Waterson, B.J. An International Review of Roundabout Capacity Modelling. *Transp. Rev.* **2013**, *33*, 593–616. [CrossRef]
9. Guiffre, O.; Granà, A.; Tumminello, M.L. Exploring the uncertainty in capacity estimation at roundabouts. *Eur. Transp. Res. Rev.* **2017**, *9*, 18. [CrossRef]
10. Johnson, M.T.; Lin, T. Impact of Geometric Factors on the Capacity of Single-Lane Roundabouts. *Transp. Res. Rec. J. Transp. Res. Board* **2018**, *2672*, 10–19. [CrossRef]
11. Zacharia, A.B.; Madhavan, H.; Anjaneyulu, M.V.L.R. Geometric factors influencing entry capacity of roundabouts under heterogeneous traffic conditions. *Arch. Transp.* **2019**, *49*, 87–101. [CrossRef]
12. Pompigna, A.; Guerrieri, M.; Mauro, R. New Extensions and Applications of the Modified Chumanov Model for for Calculating Entry Capacity of Single-Lane Roundabouts. *Sustainability* **2020**, *12*, 6122. [CrossRef]

13. Žura, M. Roundabout Capacity Estimation Model Considering Driver Behaviour on the Exiting and Entry Flows. *Promet – Traffic Transp.* **2022**, *34*, 397–405. [CrossRef]
14. Transportation Research Board, Roundabouts. In *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis*; Transportation Research Board (TRB): Amsterdam, The Netherlands, 2016.
15. Hamim, O.F.; Hadiuzzaman, M.; Hossain, S. Developing empirical model with graphical tool to estimate and predict capacity of rural highway roundabouts. *Int. J. Transp. Sci. Technol.* **2021**, *11*, 726–737. [CrossRef]
16. Batra, V.; Anand, V.; Prakash, V.; Mangal, V.; Kumar, N. A Review of Capacity, Critical Gap and Follow-up Time on an Unsignalised Intersections in Bangalore City. *Int. J. Innov. Sci. Res. Technol.* **2020**, *5*, 912–917.
17. Foulaadvand, M.E.; Maass, P. Phase transitions and optimal transport in stochastic roundabout traffic. *Phys. Rev. E* **2016**, *94*, 012304. [CrossRef] [PubMed]
18. Nava, A.; Giuliano, D.; Papa, A.; Rossi, M. Traffic models and traffic-jam transition in quantum (N+1)-level systems. *SciPost Phys.* **2022**, *Core 5*, 022. [CrossRef]
19. Song, Y.; Hu, X.; Lu, J.; Zhou, X. Analytical approximation and calibration of roundabout capacity: A merging state transition-based modeling approach. *Transportation Res. Part B Methodol.* **2022**, *163*, 232–257. [CrossRef]
20. Anagnostopoulos, A.; Kehagia, F.; Aretoulis, G. Application of Artificial Neural Network for Modelling and Predicting Roundabout Capacity. In Proceedings of the 8th Road Safety & Simulation International Conference, Athens, Greece, 8–10 June 2022.
21. Johnson, M.T.; Hale, D.K. A Case for Geometrically-Based Roundabout Capacity Equation Modeling. In Proceedings of the 5th International Symposium on Highway Geometric Design, Vancouver, BC, Canada, 22–24 June 2015.
22. Ahac, S.; Dragčević, V. Geometric Design of Suburban Roundabouts. *Encyclopedia* **2021**, *1*, 720–743. [CrossRef]
23. *Plangleiche Knoten–Kreisverkehre*; (RVS 03.05.14); Österreichische Forschungsgesellschaft Straße-Schiene-Verkehr (FSV): Wien, Austria, 2010.
24. Ahac, S. Design of Suburban Roundabouts Based on Rules of Vehicle Movement Geometry. Ph.D. Thesis, University of Zagreb, Zagreb, Croatia, April 2014.
25. Rodegerdts, L.; Bansen, J.; Tiesler, C.; Knudsen, J.; Myers, E.; Johnson, M.; Moule, M.; Persaud, B.; Lyon, C.; Hallmark, S.; et al. *NCHRP Report 672: Roundabouts: An Informational Guide*, 2nd ed.; Transportation Research Board: Washington, DC, USA, 2010.
26. Voss, T. HBS 2015 Teil S5 Knotenpunkte ohne Lichtsignalanlage, Germany. 2015.
27. Yap, Y.H.; Gibson, H.M.; Waterson, B.J. Models of Roundabout Lane Capacity. *J. Transp. Eng.* **2015**, *141*, 1–12. [CrossRef]
28. Šurdonja, S.; Deluka-Tibljaš, A.; Babić, S. Optimization of roundabout design elements. *Tech. Gaz.* **2013**, *20*, 533–539.