

Article

Roundabout Entry Capacity Calculation—A Case Study Based on Roundabouts in Tokyo, Japan, and Tokyo Surroundings

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Abstract: The article presents the calculation of roundabout entry capacity as a case study based on roundabouts located in Tokyo, Japan, and Tokyo surroundings. The analysis was conducted as part of the project entitled “Analysis of the applicability of the author’s method of roundabouts entry capacity calculation developed for the conditions prevailing in Poland to the conditions prevailing at roundabouts in Tokyo (Japan) and in the Tokyo surroundings”. The main aim and the research question was whether the author’s model of roundabouts entry capacity calculation constructed for the conditions prevailing in Poland after calibration is suitable to calculate roundabout entry capacity of roundabouts located in Tokyo and in the Tokyo surroundings. In order to perform the calibration in 2019, measurements were taken at the single-lane roundabouts located in Tokyo and Tokyo surroundings. The model calibration revealed that it is possible to evaluate the entry capacity of roundabouts located in Tokyo and in Tokyo surroundings using the author’s model.

Keywords: road traffic engineering; road transport; roundabouts; roundabout entry capacity; gap acceptance theory; traffic streams analysis; driver psychotechnical parameters

1. Introduction

The issue of traffic flow behavior in the roundabout area has repeatedly been the subject of scientific research (e.g., [1–6]). There are various types of models and the resulting methods in the literature used to calculate the capacity of roundabouts and their individual entries. These methods vary depending on the modeling tool used, the geometric and traffic characteristics of the roundabout analyzed, and the computational complexity. The modern models, which were used to develop methods employed to assess roundabout capacity, can be divided into three categories. These are semi-probabilistic models based on the gap acceptance theory used for the main stream of vehicles, empirical models based on the results of empirical data regression analysis, and simulation models based primarily on micro-models of traffic within the intersection with stochastic processes of the presence of vehicles at entries and gap acceptance models. Analytical models adopt the distribution of headways between vehicles in a roundabout circulatory roadway, critical gaps (t_g) and the follow-up times between vehicles entering from the queue at the entry (t_f) adapted to the road (geometric), and traffic conditions at the intersection. The use of estimators, such as the critical gap and follow-up time between the vehicles queuing at the roundabout entry when the headway on the circulatory roadway enables at least two vehicles to enter from the subordinated entry, may result in inaccurate capacity determination. These models use the calibration of empirical data representing selected phenomena and model parameters. The reliability of results depends on the level of model complexity. Analytical models include those presented in the studies [7,8]. Furthermore, statistical models are obtained as a result of regression analysis and correlation of empirical data. Regression and correlation

analysis tools are used to seek independent variables that determine the value of capacity. In these models, all identifiable and measurable capacity determinants are usually sought. The form of the function describing the capacity of a roundabout subordinate entry is then recorded in the following general way:

$$C_{wl} = f(G, S, D, W, T, L, M, E, O), \quad (1)$$

where:

C_{wl} —roundabout entry capacity,

G —a set of geometrical features of a roundabout (e.g., external diameter, width of entries, width of exits, width of the circulatory roadway),

S —a set of characteristics of traffic streams at the intersection (including vehicle traffic volumes at entries, on the circulatory roadway of the intersection in collision areas, pedestrian traffic volumes in the area of the intersection, cyclist traffic volume, traffic directional structure, traffic type structure),

D —a set of characteristics of drivers of vehicles involved in road traffic (e.g., gender, age, personality traits, the motivation of driving, level of fatigue),

W —a set of characteristics describing weather conditions,

T —a set of temporal characteristics (e.g., year, month, day of the week, time, season),

L —a set of characteristics of the location of the intersection (e.g., land development area, outside the land development area, peripheries of the land development area),

M —a set of characteristics of the development of the intersection's surroundings (e.g., strict city center, residential districts, green areas, recreational areas, dense land development),

E —a set of characteristics of environmental restrictions (including the permissible levels of noise of transportation origin, exhaust emission level),

O —other characteristics that are often difficult to identify unambiguously.

In statistical models, the behavior of drivers is represented by a relationship between the way an intersection functions and its characteristics, which are very often geometric. Unfortunately, some of the statistically important parameters, e.g., geometric ones, are difficult to interpret. Models designed based on empirical data have some disadvantages, e.g., the process of collecting data from measurements should take place when the entry capacity is exhausted, but this is difficult to achieve in practice. The reliability of the results depends on the way of representation and the sample size. Therefore, in order to obtain a reliable model, it is necessary to collect a large amount of data with many variants of each examined parameter. The group of statistical models includes models presented, among others, in [9–16].

In the third group of models, i.e., in the group of simulation models, in addition to the elements mentioned in the description of the two above groups of models, the dynamic characteristics of particular vehicles, composite geometric situations, and other factors affecting the processes of the presence and acceptance of gaps in the main stream may be taken into account.

The substantial foundations of the gap acceptance theory for the main stream were developed mainly by W. Siegloch [8], Harders [17], and W. Grabe [18]. One should also mention many valuable works by J.C. Tanner [19,20], N. G. Major and D.J. Buckley [21]. It is most often assumed in models designed based on the gap acceptance theory for the main stream of vehicles that the distribution of gaps in the main stream is exponential (due to its relative simplicity in use compared to complex multi-parametric distributions). This approach has been applied worldwide in a number of models and methods used to calculate roundabout capacity, e.g., in Germany by W. Brilon [22–24], W. Brilon, N. Wu and L. Bondzio [10], W. Brilon and B. Stuwe [25,26], W. Brilon, R. Koenig and R. Troutbeck [27], W. Brilon and M. Vandehey [28]. In Poland, in the studies of J. Chodur [29], it is also the basis of the model on which the method of calculating roundabout capacity was developed [30].

More precise representation of conditions in roundabout traffic streams is possible with the use of models in which the distribution of gaps between vehicles is described using distributions showing

the dependent traffic of vehicles. These models are modifications of the model developed by J.C. Tanner, e.g., models based on the Cowan M3 distribution. J.C. Tanner was the first in 1962 to use the Cowan M3 distribution to describe the time gaps in the traffic flow, and it was only in later years that it began to be used to model the headways between moving vehicles. Its generalized form was used to describe traffic conditions on roundabouts e.g., in Australia by R. J. Troutbeck [31] and R. Akçelik [32], in Sweden by O. Hagring [33], or in Poland by E. Macioszek [34–37].

Although out of the three groups of models described above, models based on the gap acceptance theory for vehicles at entries are considered to be the most reliable (due to the fact that they are models that physically reflect given traffic phenomena), the latest research results, such as [11,12,38], indicate the high accuracy of statistical models in the assessment of roundabout entry capacity. Such models include the models contained in the HCM 2010 (Highway Capacity Manual) method [11] and in the HCM 6th Edition method [12]. The construction of such models required considerable financial outlays to perform numerous empirical studies under conditions of saturation of entries with traffic streams. It is generally accepted that statistical models are not suitable for use in countries other than those for which they were originally developed. The paper presents the effects of the analysis of the applicability of the author's model of the calculation of single-lane roundabout entry capacity (referred to as the E. Macioszek model) developed for the conditions prevailing in Poland to the conditions prevailing at single-lane roundabouts located in Tokyo and in Tokyo surroundings. The present research has been financed from the funds of the Polish National Agency for Academic Exchange as part of the project within the scope of the Bekker Programme. The project has the title "Analysis of the applicability of the author's method of roundabouts entry capacity calculation developed for the conditions prevailing in Poland to the conditions prevailing at roundabouts in Tokyo (Japan) and in the Tokyo surroundings".

2. The E. Macioszek Model

The E. Macioszek model was designed based on empirical data obtained from measurements taken at roundabouts in Poland in 2004–2013. The model is constructed to calculate the value of initial capacity of single-lane roundabouts, two-lane roundabouts, and turbo roundabouts under the ideal conditions at the roundabout, i.e., without the influence of pedestrians and heavy traffic. The value of actual capacity of roundabout entry can then be calculated using data about pedestrians and heavy traffic volumes. This model is based on the gap acceptance theory with an empirical basis. A detailed description of the model as well as detailed data about the model parameters can be found in [39]. In the modeling process, a stepwise function of gap acceptance by vehicle drivers entering the roundabout circulatory roadway is assumed. The model uses two different circulating stream headway distributions according to the range of the circulating flow rate (Q_{nwl}). There are:

- for $Q_{nwl} \leq 100$ Pcu/h—shifted exponential distribution, and
- for $Q_{nwl} > 100$ Pcu/h—Cowan M3 distribution.

The model used to calculate the initial capacity of a single-lane roundabout entry has the following form:

$$C_{owl} = \begin{cases} \frac{1.03 \cdot Q_{nwl} \cdot e^{-\left[\frac{Q_{nwl}}{3600 - Q_{nwl} \cdot t_p} \cdot (t_g - t_p)\right]}}{1 - e^{-\left[\frac{Q_{nwl}}{3600 - Q_{nwl} \cdot t_p} \cdot t_f\right]}} & \text{for } Q_{nwl} \leq 100 \left[\frac{Pcu}{h}\right] \\ \frac{1.03 \cdot Q_{nwl} \cdot \phi \cdot e^{-\left[\frac{\phi \cdot Q_{nwl}}{3600 - Q_{nwl} \cdot t_p} \cdot (t_g - t_p)\right]}}{1 - e^{-\left[\frac{\phi \cdot Q_{nwl}}{3600 - Q_{nwl} \cdot t_p} \cdot t_f\right]}} \left[\frac{Pcu}{h}\right] & \text{for } Q_{nwl} > 100 \left[\frac{Pcu}{h}\right] \end{cases}, \quad (2)$$

where:

C_{owl} —the initial capacity for single-lane roundabout entry [Pcu/h],

Q_{nwl} —the traffic volume on roundabout circulatory roadway [Pcu/h],

t_g —critical gap [s],

t_f —follow-up time [s],

t_p —minimum headway between vehicles moving on roundabout circulatory roadway [s],

ϕ —the proportion of unbunched vehicles for the circulating stream ($\phi \in (0, 1)$)[–].

The summary of research data from single-lane roundabouts in Poland used for calibrating the capacity model is presented in Table 1.

Table 1. The brief of research data from single-lane roundabouts used for calibrating the capacity model.

Parameter	Single-Lane Roundabout
External diameter [m]	26.0–45.0
Central island diameter [m]	15.0–26.0
Circulating road width [m]	4.0–10.0
Total entry width [m]	3.0–4.0
Entry radius [m]	6.0–15.0
Total exit width [m]	4.0–4.75
Exit radius [m]	12.0–15.0
Number of intersection arms	4
Existence of splitter island	Yes, at all entries
Critical gaps [s]	3.16–6.05
Follow-up times [s]	2.50–3.08
Follow-up headway/critical gap ratio [–]	0.51–0.79
Traffic volume on circulatory roadway [Veh/h]	120–690
Total traffic volume on roundabout entry [Veh/h]	186–794

Figure 1 shows the initial capacity of single-lane roundabout entry calculated from the E. Macioszek model as a function of traffic volume on the roundabout circulatory roadway. The curves are presented for extreme values of observed data for the external diameter (D_i) and circulatory roadway width (w_c).

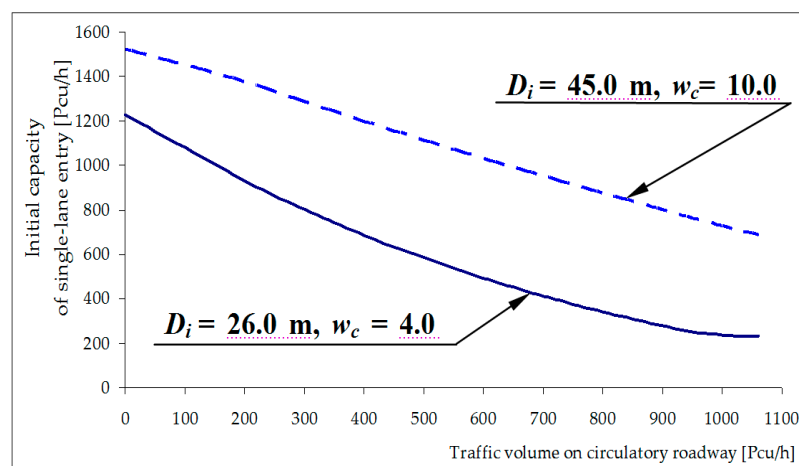


Figure 1. The initial capacity of single-lane roundabout entry calculated from the E. Macioszek model.

3. Roundabouts in Japan

Although roundabouts are popular and often designed in many countries in Europe, North America, Australia, and New Zealand, they are not a popular kind of intersections in Japan. The vast majority of intersections in Japan are controlled by traffic lights. The first roundabout in Japan was built in 2012 (by comparison, the first roundabout in the USA was designed in 1905 in New York City, whereas the first roundabout in Europe was built in 1905 in Paris. Both these roundabouts are still under operation). Some of the first roundabouts built in Japan included:

- 2012—Iida city and Karuizawa city in Nagano Prefecture—6 intersections were converted into roundabouts,
- 2013—Yaizu city in Shizuoka Prefecture—2 intersections were converted into roundabouts,
- 2013—Moriyama city in Shiga Prefecture—2 intersections were converted into roundabouts.

According to data [40], 38 roundabouts were built in Japan in 2014, 49 in 2015, while according to Japan Ministry of Land, Infrastructure, Transport, and Tourism [41], there are currently about 140 of them in 32 Japanese prefectures (Figure 2). Roundabouts are primarily sited in residential areas as well as in suburban areas and further on in urban areas (Figure 3). There are only single-lane roundabouts.

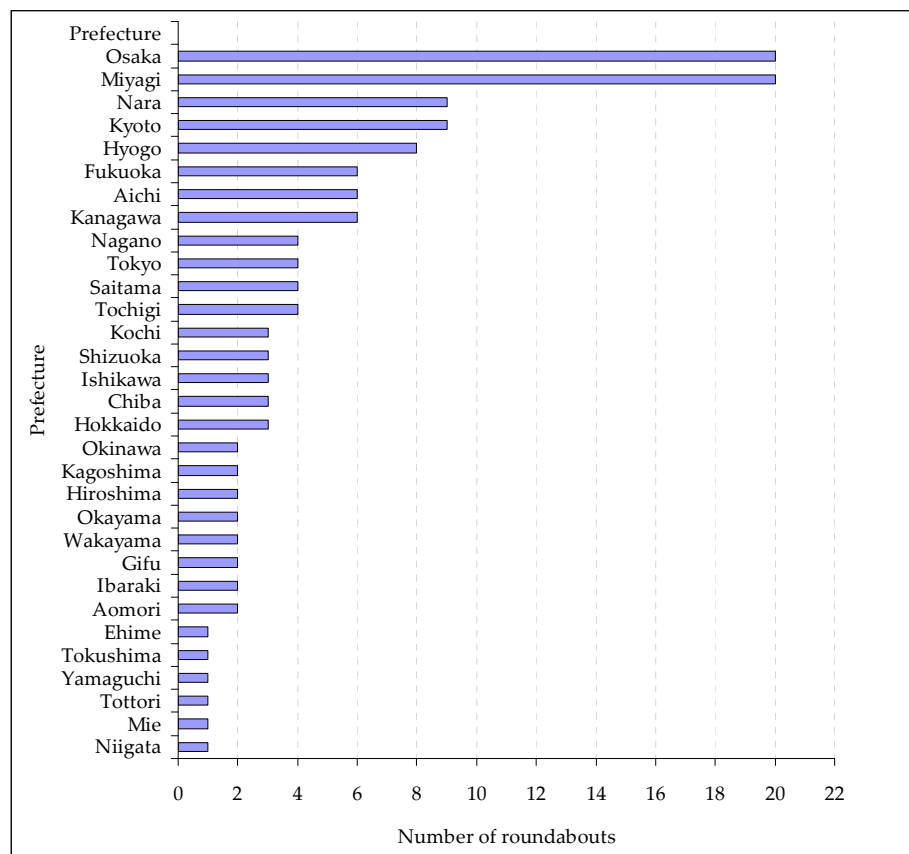
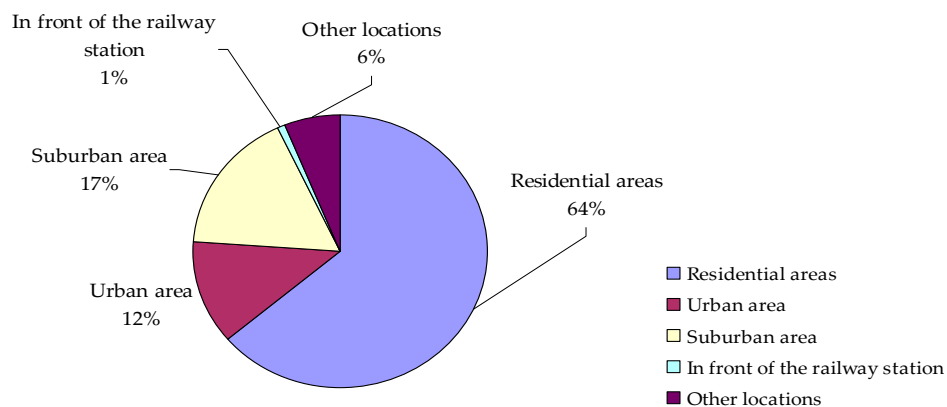
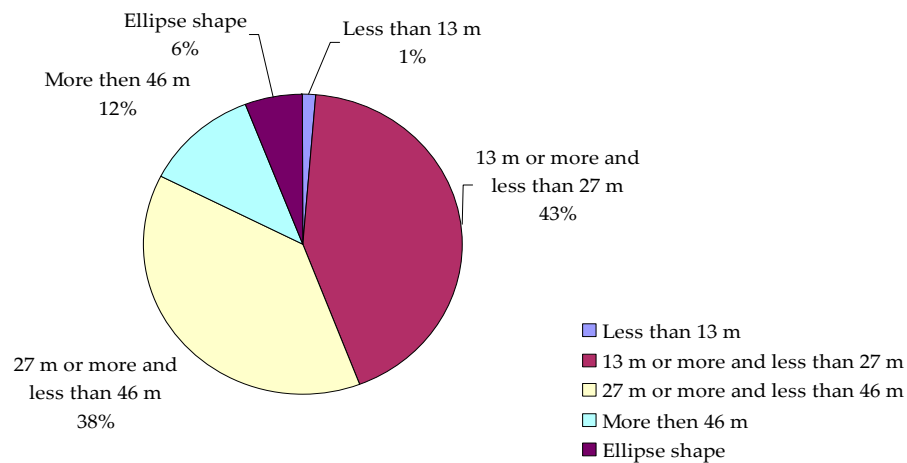


Figure 2. Roundabouts in different prefectures in Japan. Source: own research based on [41].

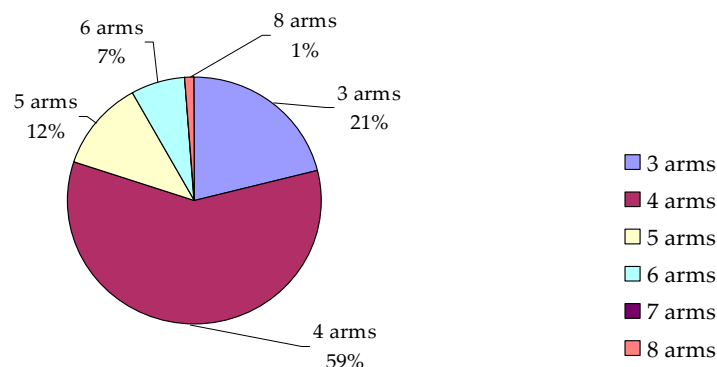


(a)

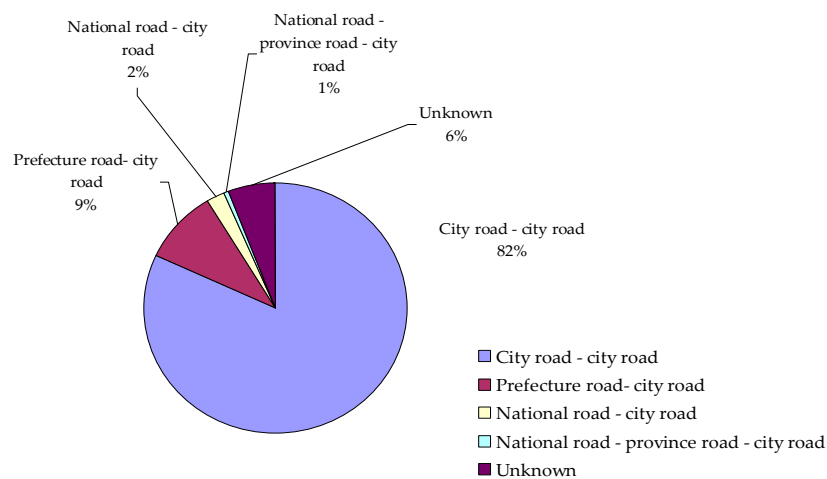
Figure 3. Cont.



(b)



(c)



(d)

Figure 3. Selected roundabouts classification in Japan, according to: (a) location; (b) external diameter; (c) the number of roundabout arms; (d) types of intersecting roads. Source: Own research based on [41–45].

Although roundabouts have been operating within the transport network in Japan since 2012, they are still not very popular and are not much liked by the Japanese. However, the reason for their

use is the fact that they allow for smooth driving on intersections in crises such as earthquakes that occur quite frequently in Japan, which is usually impossible during breakdowns at intersections with traffic lights caused by earthquakes.

4. Roundabouts Entry Capacity Calculation—Case Study Based on Roundabouts in Tokyo and Tokyo Surroundings

In order to analyze the applicability of the author's model of roundabout entry capacity calculation developed for the conditions prevailing in Poland to the conditions prevailing at roundabouts in Tokyo and in Tokyo surroundings, examinations of traffic streams were performed for vehicles moving around 6 single-lane roundabouts located in and around Tokyo using digital cameras from February to April 2019. These were the following roundabouts:

- Minami Hanyu roundabout,
- Sakuragaoka roundabout,
- Suzaka Nagano roundabout
- Hitachi Taga roundabout,
- Iida Nagano 1 roundabout,
- Iida Nagano 2 roundabout.

Over the empirical measurements, the following features of traffic flows were identified:

- traffic volumes at roundabout entries at 15-min intervals,
- traffic volumes on the circulatory roadways of roundabouts at 15-min intervals,
- headways rejected and accepted by particular drivers at roundabout entries, which then were the basis for determination of critical gaps (t_g),
- follow-up times (t_f) for drivers of vehicles from entries,
- headways between vehicles on the circulatory roadway (t_p),
- vehicle type structure,
- vehicle direction structure,
- empirical capacity.

The outer diameter of intersections (D_i) ranged from 24.0 to 37.0 m, whereas the roundabout roadway (w_c) was between 4.0 and 5.0 m. The traffic was characterized by the volume ranging from 14 to 951 Pcu/h. There was between 0.1% and 10.0% of heavy vehicles recorded in the traffic stream. The measurements were performed under convenient weather conditions for traffic (no precipitation, good visibility). In each case, the measuring stands were located in places as inconspicuous as possible to the drivers (Figure 4). The number of samples for further analyses was selected from the Lapunov formula with the level of significance set at 0.05.

The trajectories of the vehicles on the circulatory roadway and those at the entry were analyzed using the Traffic Analyzer image processing system [46]. The position of vehicles was extracted in 0.5 s intervals, and then, the position coordinates were converted into a global coordinate system by the projective transformation. The vehicle trajectories transformed were smoothened by the Kalman smoothing method [47–49].

The analysis of the applicability of the E. Macioszek model of roundabouts entry capacity calculation developed for the conditions prevailing in Poland to the conditions prevailing at roundabouts in Tokyo and in the Tokyo surroundings consisted in determining the forms of functions representing the parameters of the E. Macioszek model. These were functions that characterized:

- critical gaps (t_g),
- follow-up times (t_f) for drivers of vehicles from entries,
- minimum gaps between vehicles moving on roundabout circulatory roadways (t_p).

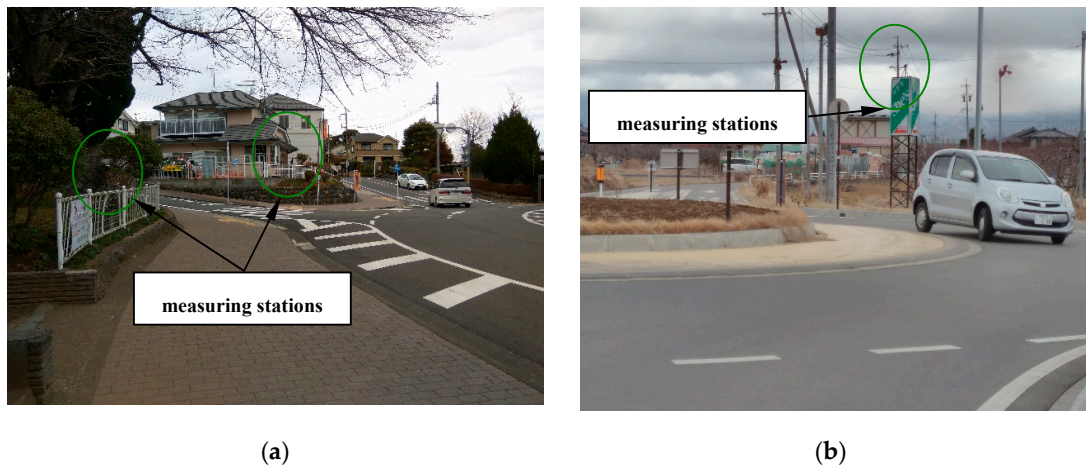


Figure 4. Examples of the location of measuring stations.

Due to the fact that the E. Macioszek model is based on the gap acceptance theory and the function of stepwise acceptance of the headways, it was also necessary to conduct analyses in order to determine the form of the function of the distribution of headways between vehicles moving on the circulatory roadway of a roundabout. The data obtained in this way allowed for the calibration of the E. Macioszek model to the conditions prevailing at roundabouts in Tokyo and in the Tokyo surroundings and then for the verification of the model using the measured empirical capacity.

4.1. The Choice of the Distribution of Headways Between Vehicles on the Circulatory Roadway of a Roundabout

The main objective of the analysis in this research area was to assess the usefulness of theoretical models of a random variable to describe the headways between vehicles on the circulatory roadways of roundabouts. The following theoretical distributions were used for the statistical analysis consisting in the verification of the zero hypothesis (H_0) of the compatibility of the empirical distribution of headways with the hypothetical distribution of the known form of $F(t)$ distribution: exponential distribution, Erlang distribution, gamma distribution, log-normal distribution, exponential shifted distribution, Cowan M3 distribution.

Tests of compatibility of model distributions with the real distributions were performed with the χ^2 Pearson's test, assuming the significance level $\alpha = 0.05$. The analyses were carried out independently for 20 classes of traffic volumes with the span of 50 PCU/h. The test statistics were in the form:

$$\chi_{emp}^2 = \sum_{i=1}^k \frac{(n_i - n_i^t)^2}{n_i^t}, \quad (3)$$

$$n_i^t = Np_i^t, N = \sum_{i=1}^k n_i, \quad (4)$$

$$p_i^t = P_F \{X \text{ adopted the value of class } i\}, \quad (5)$$

$$\text{Critical value } \chi^2(\alpha; k - u - 1), \quad (6)$$

where:

k —the number of classes,

n_i —class size,

u —the number of unknown parameters of the hypothetical distribution F ,

$n_i^t = Np_i^t$ —theoretical (hypothetical) numbers,

α —the significance level.

If $\chi_{emp}^2 > \chi^2(\alpha; k - u - 1)$, the H_0 hypothesis of the compatibility of empirical distribution with theoretical distribution was rejected. The calculations were performed using the Statgraphics software. They were performed independently for two states of the vehicle type structure, i.e., with and without heavy vehicles, including passenger car units.

The conversion factor for heavy vehicles was used to determine the traffic volumes in passenger car units per hour [Pcu/h]. It was determined based on the author's own research as follows:

$$E = \frac{\overline{dt_{pc-hv}}}{\overline{dt_{pc-pc}}}, \quad (7)$$

where:

E —the conversion factor for heavy vehicles [–],

$\overline{dt_{pc-hv}}$ —average gap between passenger car and heavy vehicle on the roundabout circulatory roadway [s],

$\overline{dt_{pc-pc}}$ —average gap between two passenger cars on the roundabout circulatory roadway [s].

The value of conversion factor for heavy vehicles (trucks and buses) to passenger car units was obtained as $E = 2.10$. Table 2 contains the results of testing of the compatibility of individual, accepted model distributions with the empirical distributions at the significance level $\alpha = 0.05$ for individual ranges of traffic volume. A positive result (marked with “+” in Table 2) was found to be the one for which there were no grounds to reject the H_0 hypothesis about the compatibility of the empirical distribution with the selected hypothetical distribution for all the intersections tested. Furthermore, a negative result (marked with “–” in Table 2) was considered to be a result for which at least one of the intersections tested had grounds to reject the zero hypothesis. Given that there are no grounds for rejecting the H_0 hypothesis, there is no reason to question the compatibility of the spacing distribution between vehicles on the circulatory roadway of a roundabout with the adopted hypothetical distribution. The test is designed in such a way that as the value of the statistic χ^2 gets closer to zero, the H_0 hypothesis becomes more reliable.

The analyses revealed that for small values of traffic volume (0–200 Pcu/h), the theoretical distributions in most of the examined cases met the statistical conditions with the sufficient accuracy. It was also found that in many cases, the distributions such as: exponential, shifted exponential, log-normal, and gamma distribution can also describe the average traffic volume of vehicles passing through a given road section (~200–400 Pcu/h). This is consistent with the results of the studies published by C. Bennett [50], S. Yin et al. [51], E. Chevallier and L. Leclercq [52], or R. Rupali and P. Saha [53]. However, from a traffic volume of approximately 400 Pcu/h, vehicle traffic is mainly not smooth and these distributions (except for Cowan M3 and shifted exponential distribution) do not meet the test condition χ^2 . According to the literature [54,55], in situations of high traffic volume, the distribution of headways between the vehicles on the circulatory roadways is mostly described by exponential shifted distribution or complex distributions, such as the Hyperlang distribution, which is a weighted sum of the shifted exponential and the Erlang distributions or the Cowan M3 distribution.

The aggregate results of the statistical tests presented in Table 2 prove that the most useful theoretical distribution to describe the time headways between vehicles on the circulatory roadway of a roundabout is the exponential shifted distribution. This is because it yields correct results for the entire range of traffic volumes and for all roundabouts. Positive test results for all roundabouts and traffic volumes greater than 250 Pcu/h were also obtained for the Cowan M3 distribution. Figure 5 presents a comparison of the accuracy of the description of empirical headway distributions for the distributions tested. The quotient of the mean value χ^2 calculated from the study and the critical value was used to assess accuracy. As the value of this quotient gets closer to zero, the description becomes more accurate. Furthermore, a value above 1.0 indicates a negative result of the compatibility of the empirical distribution with the model distribution.

Table 2. The outcome of the accuracy analysis of fit for the empirical and theoretical distributions on a significance level $\alpha = 0.05$ (where: “+” lack of reasons for rejecting the null hypothesis H_0 about compliance of the empirical distribution with the theoretical distribution for all investigated roundabouts, “-” there are reasons for rejecting the null hypothesis H_0 for at least one test roundabout).

Traffic Volume Range [Pcu/h]	Theoretical Distribution Type					
	Exponential	Gamma	Erlang	Lognormal	Shifted Exponential	Cowan M3
0–50	+	+	+	+	+	-
50–100	+	+	+	+	+	-
100–150	+	+	+	-	+	-
150–200	+	+	+	-	+	-
200–250	-	+	-	-	+	-
250–300	+	+	-	+	+	+
300–350	+	+	-	+	+	+
350–400	+	+	-	-	+	+
400–450	+	-	-	-	+	+
450–500	-	-	-	-	+	+
500–550	-	-	-	-	+	+
550–600	-	-	-	-	+	+
600–650	-	-	-	-	+	+
650–700	-	-	-	-	+	+
700–750	-	-	-	-	+	+
750–800	-	-	-	-	+	+
800–850	-	-	-	-	+	+
850–900	-	-	-	-	+	+
900–950	-	-	-	-	+	+
950–1000	-	-	-	-	+	+

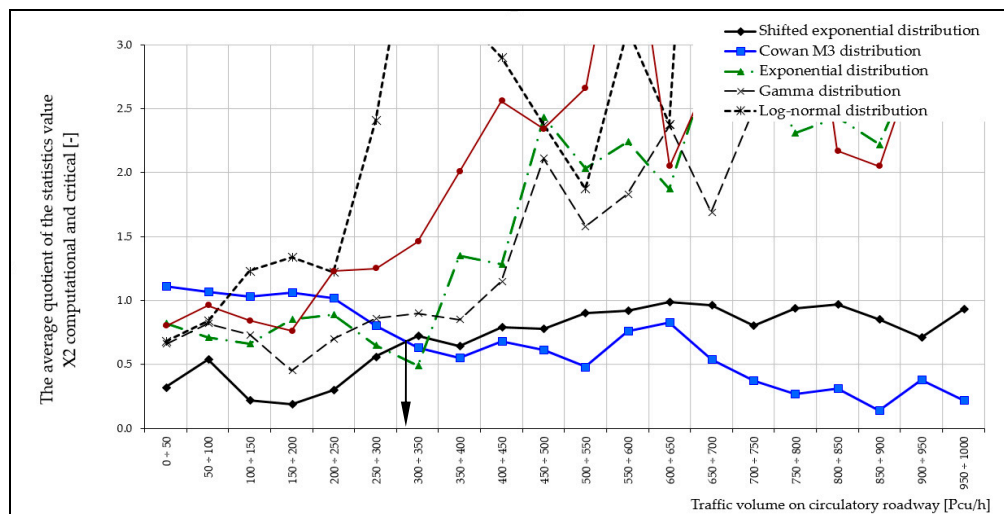


Figure 5. Relative values of χ^2 statistic for theoretical distribution gaps between vehicles on the roundabout circulatory roadway.

The results of the analyses contained in Figure 4 confirm very high usefulness of the shifted exponential distribution for describing the time headways between vehicles. It should be emphasized that the quotient $\frac{\chi^2}{\chi^2_{critical}}$ obtained for this distribution in all tested ranges of traffic volume is very low, which proves the high accuracy of the description of actual headways. Similar results in terms of accuracy of the description of the analyzed distribution are obtained only for traffic volumes of above 250 Pcu/h when Cowan M3 distribution is used.

4.2. The Minimal Headways between Vehicles on the Circulatory Roadway of a Roundabout

One of the very important parameters of the distribution of headways between vehicles on the circulatory roadway of a roundabout is the minimum headway t_p . The minimum headway between vehicles on the roadway of a roundabout plays an important role in calculating the capacity of the subordinate entries of roundabouts. According to the literature [33], the minimum observed value of the distance between vehicles ranges from 0.5 to 2.5 s. Gaps shorter than 1.0 s occur at intersections or multi-lane roads and are observed between vehicles travelling in different lanes. According to R. Akçelik and E. Chung [54] or V. Statens [56], for roundabouts with one lane on the roundabout roadway, the minimum headway t_p ranges from 1.5 to 2.0 s and often is 1.8 s. Furthermore, some studies, e.g., [55], specify that the minimum values of t_p headway greater than 2.0 s for roundabouts are rare.

Considering the values obtained from the author's own tests, it can be stated that the minimum headway ranges from 2.31 to 5.74 s and clearly depends on the traffic volume. On the basis of data presented on Figure 6, it can be concluded that stabilization of the minimum values of t_p headway exists for higher traffic volume on roundabout circulatory roadway which results from a significant increase in the likelihood of vehicles rear impacts. In cases of high traffic volumes, vehicles are moving in columns one vehicle after another, and the headways between vehicles are constants or they are similar values to each other. So, in these road traffic conditions, minimum values of t_p headway should be sought. Considering the results of our own research, it was calculated that the average value of t_p headway is equal to 2.45 s (for non-free traffic conditions).

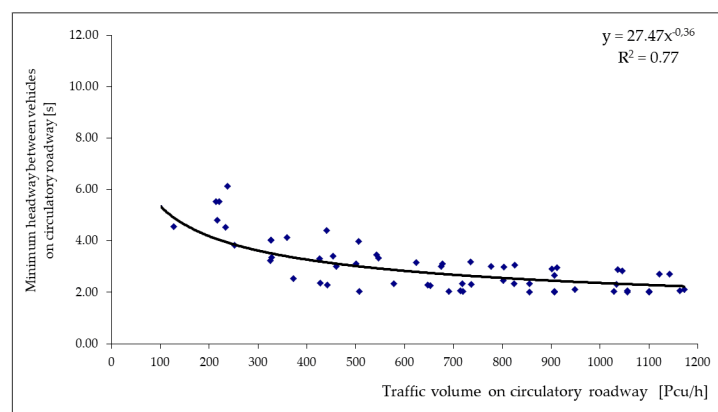


Figure 6. The dependence of the minimum headway between vehicles on the circulatory roadway as a function of the traffic volume on the roundabout circulatory roadway.

For the collected samples, the relationship between the minimum headway t_p and the traffic volume on the circulatory roadway of the roundabout Q_{nwl} was analyzed. Two different forms of the relationship were studied, but the power function was better suited to empirical data. The following form was obtained:

$$t_p = 27.47 \cdot Q_{nwl}^{-0.36} [s] \text{ for } Q_{nwl} > 100 \text{ Pcu/h}, \quad (8)$$

where:

t_p —minimum headway between vehicles moving on the roundabout circulatory roadway [s],

Q_{nwl} —the circulating flow rate (i.e., traffic volume on the roundabout circulatory roadway) [Pcu/h].

The graphical form of the above function and the obtained empirical values are presented in Figure 6.

Based on the analysis of estimation accuracy (Table 3), it was found that the assumed power relationship for logarithmic values is well fit (a relatively small value of the coefficient of residual variation (V_e) of 13% and coefficient of convergence (φ^2) of 23%). Therefore, it can be assumed that the

possible deviation of the actual headways between the vehicles moving on the circulatory roadway of a roundabout from the values of the headways determined based on power function is relatively small. Furthermore, the analysis yielded a satisfactory value of the coefficient of determination (0.77) and the non-linear correlation coefficient (0.88), which confirms the existence of the relationship between the variables under consideration.

Table 3. The evaluation parameters of the estimated power function.

Parameter	Parameter Value
Standard deviation of the residual component (S_e)	0.12
Coefficient of the residual variation (V_e)	0.13
Convergence factor (φ^2)	0.23
Nonlinear correlation coefficient (R)	0.88
Determination coefficient (R^2)	0.77

As the traffic volume on the circulatory roadway of a roundabout increases, the value of the minimum headway between vehicles decreases. Apart from the traffic volume, the t_p values may be affected by other factors not taken into account in the analysis, such as local determinants of geometric solutions, vehicle type structure, size of the city in which the roundabout was located, weather conditions, etc.

4.3. Critical Gaps and Follow-Up Times Parameters for Vehicle Drivers at Roundabouts

M. Raff defined the critical gap as a value of time interval for which the number of accepted gaps shorter than this value is equal to the number of rejected gaps longer than this value [57]. M. Raff and W. Hart are authors of one of the first method of critical gap estimating. According to M. Raff, the critical gap corresponds to the median (i.e., second quartile—50%) In the similar way, the critical gap value was later determined D. Drew [58]. Critical gaps could be also calculated using the maximum likelihood method [27]. In the estimation procedure of the maximum likelihood method, the probability of an event that critical gap value is located between logarithm values: the largest rejected gap and gap accepted by the individual drivers is determined. This method assumes that the sample obtained from the measurements is the implementation of the event with the highest possible probability, which is equivalent to the condition that credibility reaches a maximum.

The values of critical gaps were calculated using the cumulative distribution functions of the accepted and rejected gaps as well as using the gap acceptance curves. The gap acceptance curves were also used to calculate the critical gap as the gap for which the probability of acceptance is 50%. The gaps were only collected for the vehicles on roundabout entry without any other vehicles ahead of the entry give way line. An example of how the critical gaps were determined for the entry of the Minami Hanyu roundabout using cumulative curves and the acceptance curve is presented in Figure 7. The cumulative curves were calculated using the S. Raff method [57]. The values of critical gaps were also calculated according to D. Drew dependency [58]:

$$t_g = t + \frac{(t_3 - t_1)\Delta t}{(t_2 + t_3) - (t_1 + t_4)} \quad [s] , \quad (9)$$

where:

t_1, t_2, t_3, t_4 —the value of gaps that are sought in the sample in such a way as to meet the condition that the number of accepted gaps (t_1, t_2) smaller than the specified value t is similar (in the ideal case equal) to the number of rejected gaps (t_3, t_4) larger than the specified value t [s],

t —time value corresponding to the beginning of the interval in which the values were located: t_1, t_2, t_3, t_4 [s],

Δt —time interval [s].

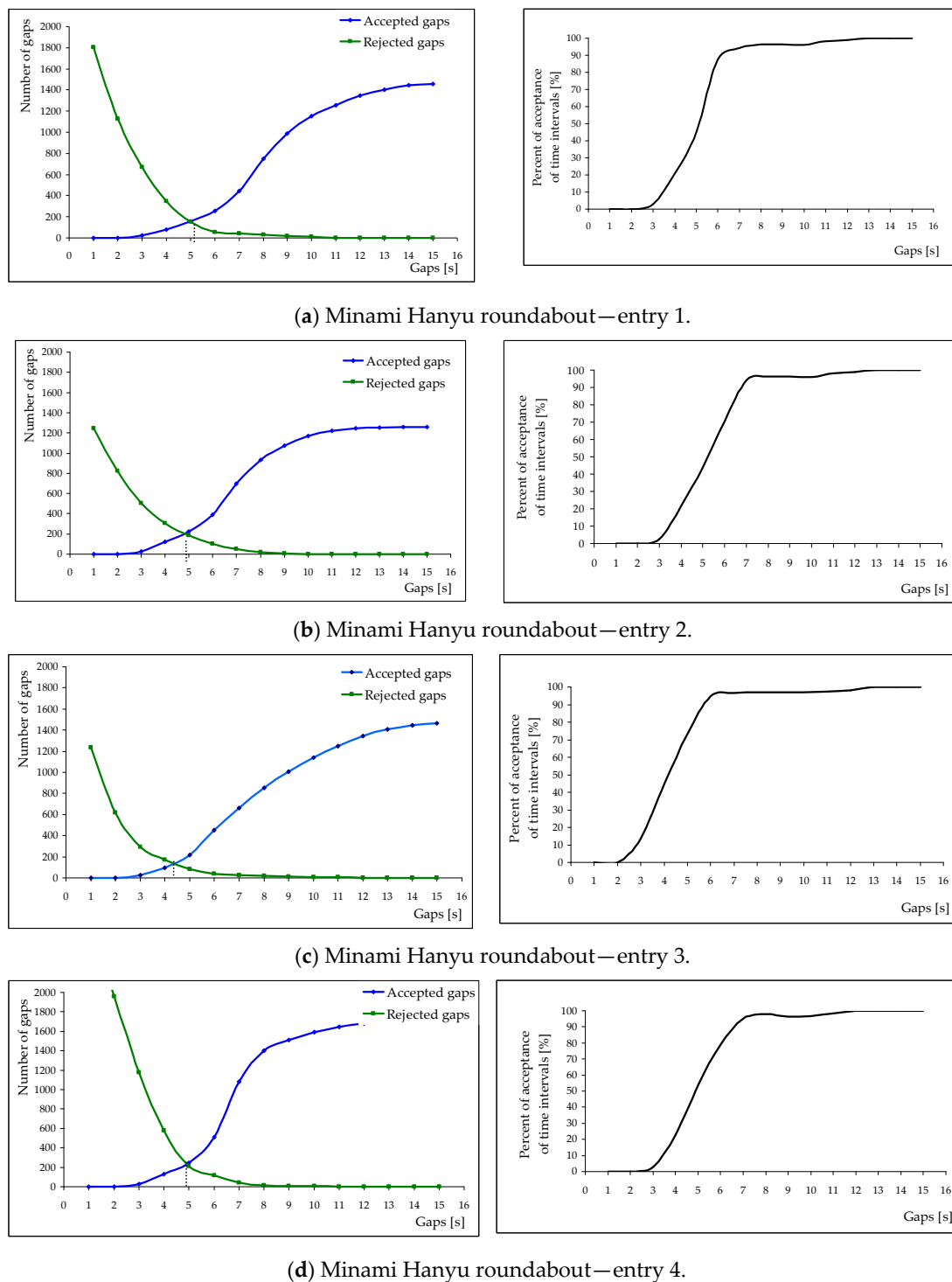


Figure 7. The critical gap values for the Minami Hanyu roundabout entry estimated using (a) cumulative curves and (b) acceptance curve.

The average value of the critical gap was equal to 4.69 s.

Next, the obtained data were subjected to regression and correlation analysis, which yielded the dependence of the critical gap on the outer diameter of the roundabout (D_i) and width of the circulatory roadway (w_c), and has the following form:

$$t_g = 12.80 - 0.19 \cdot D_i - 0.56 \cdot w_c \text{ [s]}, \quad (10)$$

for $24 \text{ m} \leq D_i \leq 37 \text{ m}$, $4.0 \text{ m} \leq w_c \leq 5.0 \text{ m}$,

where:

t_g —critical gap [s],

D_i —external diameter of the roundabout [m],

w_c —width of the circulatory roadway [m].

A graphical representation of the linear multiple regression function is shown in Figure 8. The evaluation parameters of the estimated linear multiple function for the critical gap is presented in Table 4.

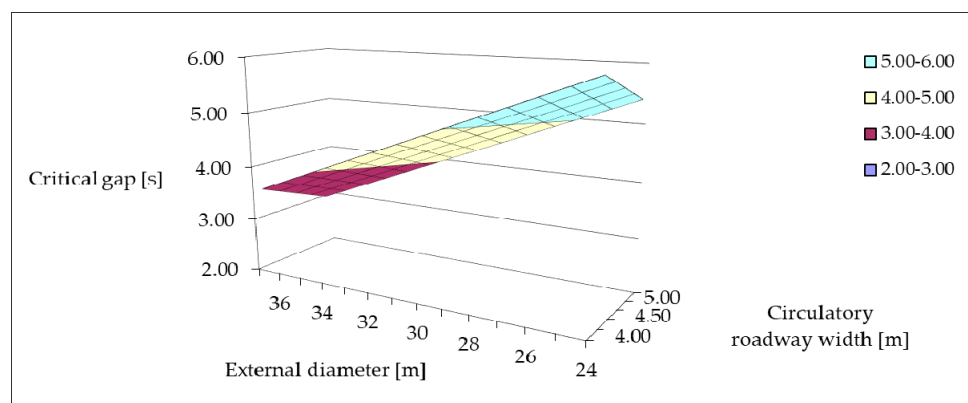


Figure 8. The dependence of the critical gap as a function of the circulatory roadway width and roundabout external diameter.

Table 4. The evaluation parameters of the estimated linear multiple function for the critical gap.

Parameter	Parameter Value
Standard deviation of the residual component (S_e)	0.33
Coefficient of the residual variation (V_e)	0.07
Convergence factor (φ^2)	0.19
Multiple correlation coefficient (R)	0.90
Multiple determination coefficient (R^2)	0.81

It can be concluded from the obtained correlation matrix (Table 4) that there is a linear negative correlation between the variables t_g and D_i (the linear correlation coefficient for t_g and D_i is -0.88), whereas the linear negative correlation between t_g and w_c is lower (linear correlation coefficient for t_g and w_c is -0.60).

The multiple correlation coefficient (R) is 0.90, which indicates a very strong relationship of t_g with D_i and w_c . The multiple determination factor ($R^2 = 0.81$), indicates that 81% of the t_g variability was explained by the variability of both D_i and w_c . The standard deviation of the residual component is 0.33, which indicates that the theoretical values of t_g , determined from the estimated regression function, differ from the actual t_g by ± 0.33 s. The coefficient of residual variability is 0.07. This means that the standard deviation of the residual component accounts for 7% of the average t_g value, which in turn indicates moderate random variation. The coefficient of convergence is 0.19. Based on this measure of fit, it can be concluded that, in terms of the estimated multiple regression function, 19% of the t_g variability was not explained by the simultaneous change of the other two variables.

In addition to the explanatory variables adopted for the analysis (D_i and w_c), many other variables affect the critical gap simultaneously. Factors that may affect the critical gap values are also: traffic factors (traffic volume for the main relation, distribution of gaps between vehicles of the main relation, type of subordinate and closing vehicles, traffic volume of vehicles leaving the circulatory roadway of a roundabout), and geometric factors (visibility restriction for subordinate vehicles, number of roundabout entries, angle of intersection road axes, inclination of entries, separating islands at the entries, etc.).

Meanwhile, the follow-up times were estimated as an average value from follow-up times of particular vehicle drivers at each roundabout entry. Individual values of follow-up time were analyzed for the vehicles queuing at the roundabout entry, and then the average value of follow-up time was established for the roundabout entry. The average value of follow-up time was equal to 2.93 s (detailed analysis is presented in research work [59]). The obtained data were subjected to regression and correlation analysis, which yielded the dependence of the follow-up time on the outer diameter of the roundabout (D_i) and width of the circulatory roadway (w_c) and has the following form:

$$t_f = 3.70 - 0.02 \cdot D_i - 0.06 \cdot w_c \text{ [s]}, \text{ for } 24 \text{ m} \leq D_i \leq 37 \text{ m}, 4.0 \text{ m} \leq w_c \leq 5.0 \text{ m}, \quad (11)$$

where:

t_f — follow-up time [s],

D_i — external diameter of the roundabout [m],

w_c — width of the circulatory roadway [m].

A graphical representation of the linear multiple regression function is shown in Figure 9. Furthermore, the evaluation parameters of the estimated linear multiple function for follow-up time is presented in Table 5.

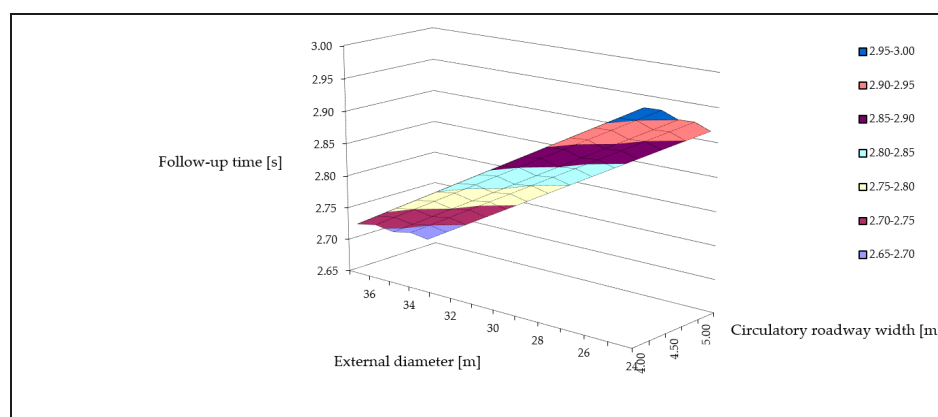


Figure 9. The dependence of the follow-up time as a function of the circulatory roadway width and roundabout external diameter.

Table 5. The evaluation parameters of the estimated linear multiple function for follow-up time.

Parameter	Parameter Value
Standard deviation of the residual component (S_e)	0.02
Coefficient of the residual variation (V_e)	0.01
Convergence factor (φ^2)	0.02
Multiple correlation coefficient (R)	0.99
Multiple determination coefficient (R^2)	0.98

It can be concluded from the obtained correlation matrix (Table 5) that there is a very strong linear negative correlation between the variables t_f and D_i (linear correlation coefficient for t_f and D_i is -0.99) and strong linear negative correlation between t_f and w_c (linear correlation coefficient for t_f and w_c is -0.72). The linear positive correlation between the explanatory variables D_i and w_c is 80% (linear correlation coefficient for D_i and w_c is 0.80).

The multiple correlation coefficient (R) is 0.99, which indicates a very strong relationship of t_f with D_i and w_c . The multiple determination factor ($R^2 = 0.98$), indicates that as much as 98% of the t_f variation was explained by the variability of both D_i and w_c . The standard deviation of the residual component is 0.02, which indicates that the theoretical values of t_f , determined from the estimated

regression function, differ from the actual t_f only by ± 0.02 s. The coefficient of residual variability is 0.01. This means that the standard deviation of the residual component accounts for 1% of the average t_f value, which in turn indicates very low random variation. The coefficient of convergence is 0.02. Based on this measure of fit it can be concluded that, in terms of the estimated multiple regression function, only 2% of the follow-up time variability was not explained by the simultaneous change of the other two variables. With very small traffic volume on the circulatory roadway of the roundabout, the follow-up times mainly determine the capacity of a given entry. Therefore, the relationship describing the follow-up time should adequately reflect the actual conditions at the roundabout entry.

4.4. Implementation of the E. Macioszek Model to the Conditions Representing Driver Behaviour at Roundabouts Located in Tokyo and Tokyo Surroundings

The E. Macioszek model presented in Section 2 was implemented to the conditions representing driver behavior at roundabouts located in Tokyo and its surroundings. The implementation consisted in using the model distribution of headways between vehicles on the circulatory roadway of a roundabout obtained from empirical studies and analyses conducted at roundabouts in Tokyo and Tokyo surroundings (Section 4.1), submodel representing the minimum headways between vehicles moving on the circulatory roadway of a roundabout (Section 4.2), and submodels characterizing the psychotechnical parameters i.e., critical gap and follow-up time representing the behavior of vehicle drivers at roundabout entry (Section 4.3). The graphical form of the E. Macioszek model implemented to the conditions representing the behavior of drivers at roundabouts in Tokyo and Tokyo surroundings compared to the original model is shown in Figure 10.

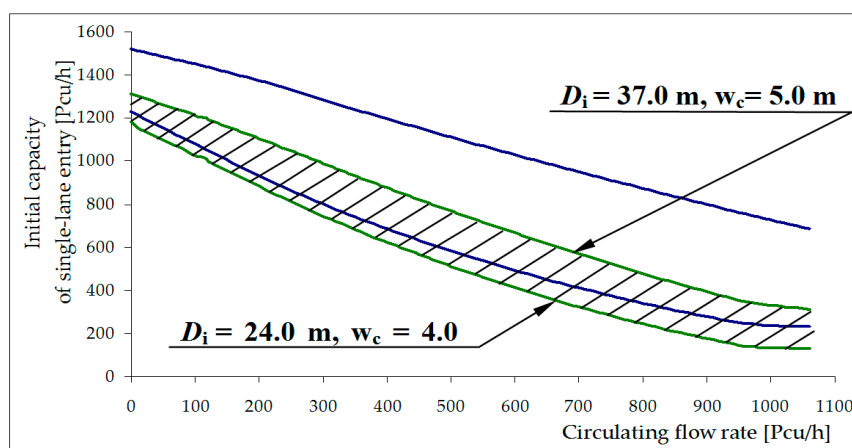


Figure 10. Implemented form of the E. Macioszek model to the conditions prevailing at roundabouts in Tokyo and Tokyo surroundings.

The correctness of the implemented traffic model for single-lane roundabouts was verified by determination of the empirical capacities in the state of entry saturation with traffic. Based on the obtained results, it can be concluded that on each of the analyzed single-lane roundabouts, the relative error values were lower than 9.4% (according to [60], the model can be considered correct in terms of accuracy when the relative error values do not exceed 10.0%). Low absolute error values were also obtained, which in all cases did not exceed 17 Pcu/h. The low values of relative and absolute errors prove that the capacity calculated by the proposed model is highly consistent with the actual capacity of single-lane roundabout entries. This demonstrates the adoption of appropriate headway distributions describing the flow of vehicles on the circulatory roadway of a single-lane roundabout, and functions describing the parameters of these distributions. An additional factor that ensured the most adequate representation of traffic in the area of single-lane roundabouts was the use of digital cameras in measurements which guaranteed the appropriate accuracy of measurement of the tested characteristics.

The results of the analysis of model accuracy also indicate that all the average error values can be considered as small, falling within the accuracy range of the currently used measurement methods.

5. Discussions

The article presents the calculation of roundabout entry capacity as a case study based on roundabouts located in Tokyo and Tokyo surroundings. The analysis was conducted as a part of a project entitled “Analysis of the applicability of the author’s method of roundabouts entry capacity calculation developed for the conditions prevailing in Poland to the conditions prevailing at roundabouts in Tokyo (Japan) and in the Tokyo surroundings” financed by the Polish National Agency for Academic Exchange.

The author’s literature studies, the research and analysis of the results of the research, and the experience gained during the work on the project in Japan lead to the following conclusions:

- The accuracy of the representation of the roundabout entry capacity is significantly influenced by the adopted model of the distribution of headways between vehicles on the circulatory roadway of a roundabout. Undoubtedly, the theoretical distributions which are the most useful for the description of the headways between the vehicles on the circulatory roadways of roundabouts are the Cowan M3 distribution and the shifted exponential distribution as they yield accurate results over the entire range of traffic volumes.
- Based on the implemented model used to calculate the capacity of the entries of single-lane roundabouts with external diameter from 24.0 to 37.0 m and the width of the roadway of the roundabout from 4. to 5.0 m, it can be concluded that the entry capacity depends on many geometrical and traffic factors of the intersection. In addition to the geometric characteristics of the roundabout, the proposed model also takes into account quantitative and qualitative traffic characteristics, such as the vehicle type structure of the traffic and minimum headways between vehicles on the roundabout circulatory roadway. This allows for performing the effective assessment of the entry capacity of such intersections.
- Values of critical gaps and follow-up times between vehicles entering the roundabout circulatory roadway from a queue at the entry of the analyzed single-lane roundabouts in Tokyo and the Tokyo surroundings ranged respectively between 3.10 and 6.60 s for critical gaps and between 2.70–3.10 s for the follow-up times. With reference to the previous studies involving measurements of values of psychotechnical parameters performed at roundabouts in Japan, the following can be established: according to S. Manage, H. Nakamura, K. Suzuki [61], the critical gap values ranging between 3.00 and 3.80 s, and according to N. Kang, H. Nakamura, and M. Asano [62], between 3.5 and 4.0. Meanwhile, the follow-up time values according to S. Manage, H. Nakamura, K. Suzuki [61], ranged between 3.26 and 4.90 s, and according to N. Kang, H. Nakamura, and M. Asano [62], between 2.6 and 3.8. However, it should also be noted that in the studies addressed in both these papers, the relevant measurements were performed at the entries of only one single-lane roundabout. The obtained values of psychotechnical parameters in the author’s own studies conducted at entries of six single-lane roundabouts are similar to the values provided in the mentioned papers for critical gaps and follow-up times.
- Taking into account the obtained results of the analyses, the E. Macioszek model implemented to the conditions representing the behavior of drivers at roundabouts in Tokyo and Tokyo surroundings (Figure 9) can be considered to be correct in terms of accuracy since e.g., relative errors ranged from 2.2% to 9.4%. The advantages of the form of this model from the standpoint of possible further practical implication should be also stressed.

The results of the research and analysis presented in this paper do not exhaust all the problems concerning roundabout entry capacity calculation of roundabouts located in Tokyo and Tokyo surroundings. Some of the research topics started in the paper clearly confirm the need for further

research and the determination of its directions. In the author's opinion, this should concern in particular:

- further field research conducted on much larger number roundabouts throughout Japan. Single-lane roundabouts in Japan are a relatively new road solution and are not too diverse in terms of geometric, moreover the measurements were carried out only on 6 roundabouts,
- further testing of roundabout capacity under traffic saturation conditions with the changing load of individual entries using computerized traffic simulation tools,
- monitoring of trends in the changes in behaviors of drivers moving on roundabouts in Tokyo and Tokyo surroundings for a longer time gap and identification of the factors causing these changes (ongoing monitoring will allow for periodic updating of the implemented model),
- designing the method of capacity calculation and measures for the assessment of traffic conditions based on the E. Macioszek model implemented for traffic conditions at roundabouts in Tokyo and Tokyo surroundings and further implementation work.

Author Contributions: Conceptualization, E.M.; methodology, E.M.; validation, E.M.; formal analysis, E.M.; investigation, E.M.; resources, E.M.; data curation, E.M.; writing-original draft preparation, E.M.; writing-review and editing, E.M.; visualization, E.M.; supervision, E.M.; project administration, E.M.; funding acquisition, E.M. All authors have read and agreed to the published version of the manuscript.

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