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ROUNDABOUT CAPACITY ESTIMATION MODEL CONSIDERING DRIVER BEHAVIOUR ON THE EXITING AND ENTRY FLOWS

ABSTRACT

Roundabout capacity estimation has been the subject of several types of research in recent decades. Most of the analyses are based on the empirical or analytical models (e.g. gap acceptance theory) considering various kinds of conflicting flows, namely entry, circulating, and exiting flow. The drivers on the exiting flow either obey the traffic rule (use the right-turn indicator) or disobey the traffic rule (do not use the right-turn indicator). According to the reviewed literature, the impact of these drivers on the roundabout capacity has not been studied to a greater extent. Therefore, this study aims to develop an analytical roundabout capacity estimation model that also takes into account a share of exiting flow. It extends Brilon-Wu's model, by including the impact of exiting drivers who disobey the traffic rule on the gap acceptance of the entering drivers. The proposed model was validated using the quasi-observation data generated by a microscopic model. The results obtained by our model were compared with Bovy' and Yaps' empirical models as well as Brilon-Wu's analytical model for a single-lane roundabout. Using the RMSE and regression analysis, it is proved that the proposed model outperforms the existing models in terms of estimating the capacity and delays of roundabouts.

KEYWORDS

roundabout; capacity; driving behaviour; entry flow; exiting flow; gap acceptance theory.

1. INTRODUCTION

At-grade intersections are a critical element for the efficiency of the road network, as they cause bottlenecks in urban areas due to limited capacity and low safety levels. Given that their importance is managing traffic flow, roundabouts are often used to address these constraints. There are different designs of roundabouts that can be used for different traffic patterns and locations, namely normal roundabouts, compact roundabouts, double roundabouts, mini roundabouts, and turbo roundabouts (see [1] for more details). For conventional and turbo roundabouts, the selection of the most appropriate roundabout design is usually based on various performance analyses, most of which use empirical and analytical models and consider entry lane capacity and delays as the main performance criteria [1–3].

According to the current traffic regulations in most countries, for unsignalised roundabouts, also known as roundabouts with right-of-way, the entry stream should give right-of-way to vehicles in the circulatory lane. The most commonly used analytical methods for roundabout (entry lane) capacity estimation are gap acceptance-based models, originally developed by [4–6]. They used probability theory to estimate the critical gap accepted by drivers on the minor lane when entering the unsignalised intersection/roundabout. They only considered vehicles in the circulatory lane to be in conflict with vehicles entering the junction/roundabout and did not take into account the geometry of the roundabout and the different driving behaviour. In the later years, a regression model was developed by the UK Transport and Road Research Laboratory (TRRL, now TRL), and recently by [8], to account for roundabout geometry and conflict flows [7]. The TRL model also did not account for the effects of different driving behaviour on estimation of the roundabout capacity. Considering that only a certain percentage of drivers exiting the roundabout make their intention known by using the right turn indicator, one should investigate the impact of such behaviour on the entry flow. From an empirical point of view, when estimating the roundabout capacity, not only should the circulatory traffic flow be taken into account, but also a part of the exiting traffic. According to our observations, the critical gap accepted by

drivers on the entry lane depends on several factors, namely the distance between the exit and the entry, driver behaviour on the exit (show your intention to exit or not by using a turn signal), and the skills or behavioural patterns of drivers on the entry lane.

Hagring [9] derived a capacity equation for a roundabout entry with mixed circulatory and exiting flows, assuming the influence of exiting vehicles from the point of view of their impact on gaps. Mereszczak et al. [10] extended Hagring's work by performing an in-depth comparison of capacity estimation models in the US with and without exiting vehicles and concluded that the inclusion of exiting vehicles leads to better capacity prediction. Moreover, the overall capacity prediction error decreases by almost 20% when exiting vehicles are included in the estimation process. Fortuijn [11] argued that the gap acceptance approach alone is not sufficient because the pseudo-conflict is not taken into account and therefore the exiting flow should be considered as a part of the conflict flow. Yap et al. [12], in an empirical study of 35 roundabouts in the UK, highlighted the importance of the exiting traffic flow when estimating the capacity of the entry lane. They found out that variables such as the distance between the entry and exit lanes and the traffic flows exiting the roundabout have a greater impact on reducing entry capacity than variables such as entry angle and entry radius. Suh et al. [13] also studied the effects of exiting vehicles on the capacity on models of single-lane roundabouts. They developed capacity equations from video recordings and calibrated the HCM [14] capacity model with and without exiting vehicles. They also concluded that vehicles exiting the roundabout just before the conflict zone are likely to affect capacity and indicated the need for alternative models. The impact of exiting vehicles on the capacity of the entrance was also studied by Perme et al [15, 16], but without considering the disregard of the right turn indicator.

Considering the limitations of the existing studies, this study aims to develop a new analytical model to estimate the capacity of roundabouts that takes into account the disobedient driving behaviour (those who do not use the right turn indicator), when exiting traffic flows, on the capacity of the roundabout entrance. This paper is organised as follows: Section 2 introduces a basic concept of analytical methods for roundabout capacity estimation. A new model for roundabout capacity estimation is also proposed. Then, in Section 3, we describe the results of roundabout simulation. In Section 4, we compare the delays calculated by simulations with the calculations using different empirical and analytical models. Finally, in Section 5, we summarise the research results, limitations, and describe directions for further studies.

2. METHODOLOGY

Roundabout capacity can be estimated in three different ways: (a) by using empirical models, (b) by using probability models, e.g. gap-acceptance theory and (c) by using microsimulation models.

Since the estimation of the capacity of roundabouts by using microsimulation and empirical models is beyond the scope of this study, only the description of the basic concepts of some well-known analytical models is included, as shown in *Figure 1*.

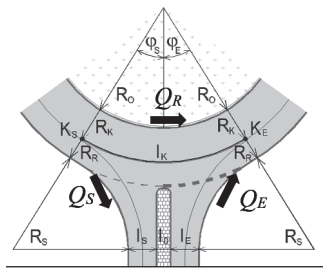

Figure 1 – Basic variables used in capacity calculations

where:

Q_E – entry flow;
Q_R – circulating flow;
Q_s – exiting flow;
R_O – inner radius (radius of the central island) [m];
R_R – outer radius [m];
R_E – entry lane radius [m];
R_S – exit lane radius [m];
R_K – centreline radius of circulatory lane [m];
l_K – distance between the exit point K_S and entry point K_E [m].

The distance between the exit and entry point (K_S–K_E) denoted by l_K can be calculated by the given equation:

$$l_K = \frac{R_K \cdot \pi \cdot \varphi}{180°} \tag{1}$$

The time required to drive from point K_S to point K_E is determined by *Equation 2*:

$$t_K = \frac{l_K}{V} \cdot 3.6 \tag{2}$$

where:

t_K – driving time from point K_S to point K_E [s];
V – vehicle speed at roundabout (circulatory lane) [km/h].

Most methods of traffic analysis which are suitable for the analysis of intersections are derived from probability theory. One of the well-known probability theories commonly used in capacity estimation of unsignalised intersections is the gap acceptance theory. According to the gap acceptance theory, minor street vehicles can only enter the intersection when the lag from the arrival of the minor stream vehicle until the arrival of next major stream vehicle is greater than the critical gap of driver entering the roundabout. There are a lot of methods to calculate critical gap (t_c) and following gap (t_f) in gap acceptance theory, such as: Raff [4], Ashworth [5], Siegloch [6] and maximum likelihood method [17].

The first capacity estimation model based on gap acceptance theory was developed by Brilon [18]. Later on, Wu [19–21] modified and extended Brilon's model and described the necessities of using gap acceptance theory and conflict estimation techniques for roundabout capacity analysis. According to Brilon-Wu model, the capacity of entry flow and the relationship between entry and conflicting flows can be derived from the following equation:

$$C_E = 3600 \cdot \left(1 - \frac{t_{min} \cdot Q_R}{n_c \cdot 3600)}\right)^{n_c} \cdot \frac{n_e}{t_f} \cdot e^{-\frac{Q_R}{3600} \cdot \left(t_c - \frac{t_f}{2} - t_{min}\right)} \quad (3)$$

where:

C_E – basic capacity of one entry [PCU/h];
n_c – number of circulatory lanes;
n_e – number of entry lanes;
t_c – critical gap [s];
t_f – follow-up time [s];
t_{min} – minimum gap between succeeding vehicles on the circle [s].

Although driving rules require that drivers who are leaving the roundabout have to show their intention by indicators, only some of them obey this rule. On the other hand, if the distance between exit and entry point (l_K) is short, then the driver entering the roundabout does not know whether the vehicle in the roundabout will leave the roundabout or continue in circulating movement. That means that the driver entering the roundabout could take into consideration not only the circulating flow, but also the exiting flow before making decision to enter the roundabout. In simpler terms, this problem will directly influence the entry decision and gap acceptance value of the drivers on the entry leg, consequently it will (negatively) influence the capacity of the roundabout. When the critical gap (t_c) estimated by the driver at the entry lane is shorter than the time needed to drive the distance from the point of exit (K_S) to the point of entry (K_E), so-called t_K, the driver on the entry lane only perceives the confliction with the traffic volume on the circle (Q_R). If the critical gap is longer than the time needed to drive the distance from the point of exit to the point of entry to the roundabout, the driver must also assess the exiting traffic flow (Q_S), in addition to the circulating flow, before making the decision to enter the roundabout.

To our knowledge, there is no study on the influence of behaviour of exiting drivers (do they obey or disobey traffic rules) on the roundabout's capacity. Therefore, the main contribution of this study compared to the existing capacity estimation models such as Brilon-Wu's and Bovy's is to incorporate the impact of the drivers who disobey traffic rules on the capacity.

2.1 Calculating the share of entry drivers

As proposed by Wu [19], we assumed that critical gaps t_c of drivers entering the roundabout are Erlang distributed [22]. The relevant probability density function is as follows:

$$f(t_c) = \frac{\lambda}{(\alpha - 1)!} \cdot (\lambda t_c)^{\alpha - 1} \cdot e^{\lambda t_c} \quad \text{for} \quad t_c, \quad \lambda \geq 0 \quad (4)$$

where:

α – scale/shape parameter of the Erlang distribution function for t_c;
λ – rate parameter; $\lambda = \frac{\alpha}{\overline{t}_c}$
$\overline{t}_c$ – the mean value of the critical gap (t_c).

The cumulative distribution function of Erlang distribution is given in *Equation 5*:

$$F(t_c) = 1 - \sum_{n=0}^{\alpha-1} e^{-\lambda t_c} \cdot \frac{(\lambda t_c)^n}{n!} \quad (5)$$

It is noted by [23], that α=5 and λ=1 are appropriate values of Erlang distribution for drivers on the entry lane of the roundabout. If we presume that α=5, the share of drivers with critical gap (t_c) shorter than time t_K, $P(t_c<t_K)$ can be calculated using the equation below:

$$P(t_c < t_K) = 1 - e^{-\lambda t_K} - e^{-\lambda t_K} \cdot \lambda t_K - \frac{e^{-\lambda t_K} \cdot (\lambda t_K)^2}{2} - \frac{e^{-\lambda t_K} \cdot (\lambda t_K)^3}{6} - \frac{e^{-\lambda t_K} \cdot (\lambda t_K)^4}{24} - \frac{e^{-\lambda t_K} \cdot (\lambda t_K)^5}{120} \quad (6)$$

Consequently, the share of drivers entering roundabout with critical gap t_c longer than time (t_K) can be determined using the equation below:

$$P(t_c \geq t_K) = 1 - (P(t_c < t_K)) \tag{7}$$

2.2 Capacity derivation

When deriving the capacity of the entry, it is important what type of conflicting flow is being considered. We define two different kinds of drivers on the entry lane:

a) if the minimal gap that driver entering the roundabout is willing to accept is shorter than the time needed to drive the distance from the point of exit to the point of entry into the roundabout, the capacity of the entry $C_E(Q_R)$ is only influenced by the traffic volume on the circle (Q_R);
b) if the minimal gap that driver entering the roundabout is willing to accept is longer than the time needed to drive the distance from the point of exit to the point of entry into the roundabout, the capacity of the entry $C_E(Q_R+\beta Q_S)$ is influenced by the part (not giving the right turn signal) of traffic volume on the circle (Q_R), as well as by the exiting traffic flow (Q_S).

Considering these two situations, the proposed entry capacity equation (C_E) is:

$$C_E = P(t_c < t_K) \cdot C_E(Q_R) + P(t_c \geq t_K) \cdot C_E(Q_R + \beta Q_S) \tag{8}$$

where $P(t_c<t_K)$ is the probability or share of drivers who have the critical gap shorter than the time needed to drive the distance from the point of exit to the point of entry, while $P(t_c \geq t_K)$ is the probability or share of drivers who are willing to accept the critical gap that is longer than the time needed to drive the exit-entry distance, and β is the share of exiting drivers not giving the signal. Brilon-Wu's *Equation 3* has been used to calculate capacity related to drivers type a) and b) mentioned above. Adding Q_R and $Q_R+\beta Q_S$ into *Equation 3* makes *Equations 9 and 10.*

Adding *Equation 6, 9, and 10* into *Equation 8*, the proposed capacity is given in *Equation 11*.

$$C_E(Q_R) = 3600 \cdot \left(1 - \frac{t_{min} \cdot Q_R}{n_c \cdot 3600}\right)^{n_c} \cdot \frac{n_e}{t_f} \cdot e^{-\frac{Q_R}{3600}\left(t_c - \frac{t_f}{2} - t_{min}\right)} \tag{9}$$

$$C_E(Q_R + \beta Q_S) = 3600 \cdot \left(1 - \frac{t_{min} \cdot (Q_R + \beta Q_S)}{n_c \cdot 3600}\right)^{n_c} \cdot \frac{n_e}{t_f} \cdot e^{-\frac{Q_R + \beta Q_S}{3600}\left(t - \frac{t_f}{2} - t_{min}\right)} \tag{10}$$

3. RESULTS

To validate the efficiency of the proposed model, the results obtained by our model should be compared with the real-world data under different traffic conditions and roundabout geometries. Since this would require extensive field surveys, we decided to use, for the time being, the data computed by simulation models of a single-lane roundabout (one entry, one exit, and one circulatory lane) created by VISSIM [24] as quasi-observational data. *Figure 2* shows a microscopic simulation model of the roundabout.

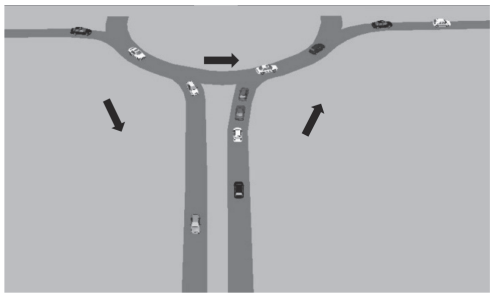

Figure 2 – A conventional single-lane roundabout; simulation model

Since our proposed model assumes that the t_c is Erlang distributed and in VISSIM we cannot enter this distribution in analytical way, we had to discretise it and define several classes of drivers with different critical gap values, which are shown in *Table 1*.

Table 1 – Driving behaviour types modelled by microsimulation software

Type	Mean value of t_c [s]	Share (traffic composition)
A	1.6	0.22
B	2.7	0.32
C	3.8	0.25
D	5.0	0.15
E	6.4	0.06

$$\begin{aligned} C_E = {} & \left(1 - e^{-\frac{5}{t_c}t_K} - e^{-\frac{5}{t_c}t_K} \cdot \frac{5}{t_c}t_K - \frac{e^{-\frac{5}{t_c}t_K} \cdot \left(\frac{5}{t_c}t_K\right)^2}{2} - \frac{e^{-\frac{5}{t_c}t_K} \cdot \left(\frac{5}{t_c}t_K\right)^3}{6} - \frac{e^{-\frac{5}{t_c}t_K} \cdot \left(\frac{5}{t_c}t_K\right)^4}{24} - \frac{e^{-\frac{5}{t_c}t_K} \cdot \left(\frac{5}{t_c}t_K\right)^5}{120}\right) \cdot \left(3600 \cdot \left(1 - \frac{t_{min} \cdot Q_r}{n_c \cdot 3600}\right)^{n_c} \cdot \frac{n_e}{t_f} \cdot e^{-\frac{Q_R}{3600}\left(t_c - \frac{t_f}{2} - t_{min}\right)}\right) \\ & + \left(e^{-\frac{5}{t_c}t_K} + e^{-\frac{5}{t_c}t_K} \cdot \frac{5}{t_c}t_K + \frac{e^{-\frac{5}{t_c}t_K} \cdot \left(\frac{5}{t_c}t_K\right)^2}{2} + \frac{e^{-\frac{5}{t_c}t_K} \cdot \left(\frac{5}{t_c}t_K\right)^3}{6} + \frac{e^{-\frac{5}{t_c}t_K} \cdot \left(\frac{5}{t_c}t_K\right)^4}{24} + \frac{e^{-\frac{5}{t_c}t_K} \cdot \left(\frac{5}{t_c}t_K\right)^5}{120}\right) \cdot \left(3600 \cdot \left(1 - \frac{t_{min} \cdot Q_r}{n_c \cdot 3600}\right)^{n_c} \cdot \frac{n_e}{t_f} \cdot e^{-\frac{Q_R + \beta Q_S}{3600}\left(t_c - \frac{t_f}{2} - t_{min}\right)}\right) \end{aligned} \tag{11}$$

In our simulations, we used traffic conditions and roundabout geometries. The conflicting traffic flows Q_R, and Q_S vary from 0 to 500 PCU/h with steps of 100 PCU/h. The entry flow rate also varies from 0 to 500 PCU/h with the 100 PCU/h. As noted, capacity depends not only on conflicting flows, but also on the geometric characteristics of the roundabout, e.g. the distance between the exit and entry point (K_S–K_E) or l_K length. In this study, single-lane roundabouts with the following geometric characteristics were modelled: R_O=17.25 m, R_R=22.25 m, R_E=14.0 m, R_S=14.0 m, and l_K between 16 and 24 m.

Then, *Equation 2* was used to calculate the time needed to drive the distance (t_K) values as noted in *Table 2*. This means that five separate microscopic models with different length l_K were created.

Table 2 – The l_K length and driving time t_K from the K_S and K_E

K_S–K_E or length l_K [m]	16.0	18.0	20.0	22.0	24.0
Driving time t_K [s]	2.3	2.6	2.9	3.2	3.5

A total of 625 combinations of the traffic volume (*Table 3*) and the distances between the entering and exiting flows (*Table 4*) were simulated for a single-lane roundabout using a microsimulation software to create quasi-observation data. To reduce the stochastic effects of the traffic assignment in the microsimulation software, we used five runs with different random seeds. The average value of delays for these five runs has been considered when comparing the results. The simulation duration for each run was 4,500 s (900 s as warm-up period and 3,600 s as data collection period).

4. DISCUSSION

We calculated roundabout entry capacity using Bovy's [1], Yap's [12], Brilon-Wu's [19] equations and our proposed *Equation 11*. Since it is not possible to directly determine the capacity of roundabout entry by microsimulation, average delays per vehicle were calculated for all 625 cases. To compare the microsimulation results with the empirical and analytical models, the delay for these models was calculated for all 625 cases using *Equation 12* proposed by [14] considering the capacity value obtained by the empirical and analytical models.

$$d_E = \frac{3600}{C_E} + 900 \cdot T \cdot \left[\frac{Q_E}{C_E} - 1 + \sqrt{\left(\frac{Q_E}{C_E} - 1 \right)^2 + \frac{\frac{3600}{C_E} \cdot \frac{Q_E}{C_E}}{450 \cdot T}} \right] \quad (12)$$

where:

d_E –average delay per vehicle on the entry leg [s];
Q_E – entry flow rate [PCU/h];
C_E – capacity of entry lane [PCU/h];
T – analysis time period [h].

The following parameters' values were used for Bovy's model: γ=1, β=0.95. In addition, Brilon-Wu's model and our proposed model presume the following parameters' values: $\overline{t}_c$=3.3 s, t_f=3.0 s, t_{min}=2.0 s.

Then, RMSE index and regression analysis was used to examine the efficiency of all models when estimating entry capacity and delay.

4.1 RMSE index

Root Mean Square Error (RMSE), another well-known comparison index, was used to examine the performance of our proposed model compared to the existing models. RMSE in this study is the standard deviation of the residuals (prediction errors) between quasi-observation delay data and the delays calculated by equation mentioned above. General form of RMSE is given as:

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(\hat{y}_i - y_i)^2}{n}} \quad (13)$$

where:

y_i – quasi-observation data created by microsimulation;
$\hat{y}_i$ – the delay value calculated by our proposed model, Bovy, Brilon-Wu, Yap, and Yap2 models.

RMSE is always non-negative, and a value of 0 (almost never achieved in practice) would indicate a perfect fit to the data. In general, a lower RMSE is better than a higher one. RMSE results are given in *Table 3* for Bovy, Brilon-Wu, Yap, Yap2 and our models.

As seen in *Table 3*, the RMSE obtained for our model is 0.36 while the RMSE obtained for other models has slightly higher values than the proposed model. Our model is able to calculate more accurate entry delay compared to the Bovy, Brilon-Wu, Yap, and Yap2 by 23.4%, 19.7%, 20.7%, 15.4%, respectively.

Table 3 – Summary of RMSE Index

	MZ	Bovy	Brilon-Wu	Yap	Yap2
RMSE	0.36	0.45	0.43	0.44	0.42
Change (%)		-23.4	-19.7	-20.7	-15.4

4.2 Regression analysis

Regression analysis is an important approach for modelling the relationship between one or more independent variables and the dependent variable. The R^2 coefficient, is called the coefficient of determination and ranges between 0 and 1. If R^2=1 or very close to one, the variables *x* and *y* fit perfectly. If R^2=0 or very close to zero, then there is no relationship between the variables [25].

The regression analysis was used to examine the accuracy of delay estimates of the analytical and empirical models compared to quasi-observed delay data. The highest R^2 (close to one) means that the analytical or empirical model is able to estimate the delay similar to quasi-observation data. *Table 4* presents the results of the regression analysis for all models.

In the table above, R^2 value of the proposed model is 0.80, which shows that the proposed model has appropriate accuracy in estimating entry delay for different traffic conditions and exit-entry lengths. However, other models, namely Bovy (0.48), Brilon-Wu (0.40), Yap (0.33), and Yap2 (0.42) are not able to estimate the entry delay for different traffic conditions and geometries.

In addition, a t-statistic test has been used to examine whether the results estimated by the proposed model have statistically significant difference/improvement (*p-value<0.05, level of confidence: 95%*) compared to the results estimated by the existing models or not. The p-value of the proposed model is less than 0.05 compared to the existing models, which shows the proposed model has statistically significant improvement in estimating the entry delay. Therefore, the proposed model outperforms the existing models considering R^2 value of regression analysis and p-value of the t-test. *Figure 3* demonstrates the relationship between exiting flow, exit-entry distance and entry delay. We assumed that Q_R=400 PCU/h, Q_E=300 PCU/h, Q_S varies from 0 to 500 PCU/h, and l_K varies from 16 to 24 m.

Table 4 – Summary of regression analysis

Regression Statistics	MZ	Bovy	Brilon-Wu	Yap	Yap2
Multiple R	0.89	0.69	0.63	0.58	0.65
R Square (R^2)	0.80	0.48	0.40	0.33	0.42
Adjusted R Square	0.80	0.48	0.40	0.33	0.42
Standard Error	5.25	8.43	9.04	9.55	8.92
Observations	625	625	625	625	625

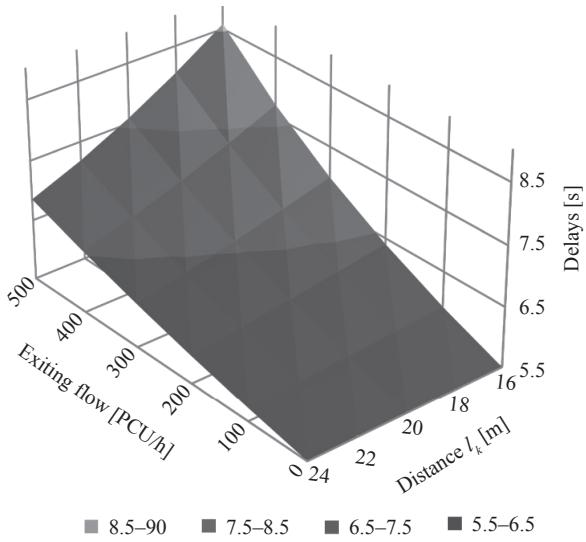

Figure 3 – Entry delays calculated by different models ($Q_{Circulating}$=400 PCU/h, Q_{Entry}=300 PCU/h, $Q_{Exiting}$ between 0 to 500 PCU/h, l_K between 16 to 24 m)

It is evident that the entry delay estimated by the proposed model is maximum when the exiting flow is maximum (here, 500 PCU/h), and the distance between exit and entry points is minimum (here, 16 m), and vice versa. It is shown that delays decrease with increasing distance l_K. Overall, the entry delay is influenced by the number of vehicles on the exiting flow and the distance between exit and entry points on the circulatory lane.

To take a look at the comparison between different models, *Figure 4* depicts the entry delay values for different exit-entry distance assuming that Q_{Entry}=500 PCU/h, $Q_{Circulating}$=400 PCU/h and $Q_{Exiting}$= 400 PCU/h. In this figure, Qsi-Obs is the quasi-observation delay data produced by the microsimulation, MZ is the delay calculated by our proposed model.

It shows that the proposed model is able to incorporate the effects of different exit-entry distances on the entry delay calculation, which is also the case for quasi-observation delay data, while other models produced the same results for

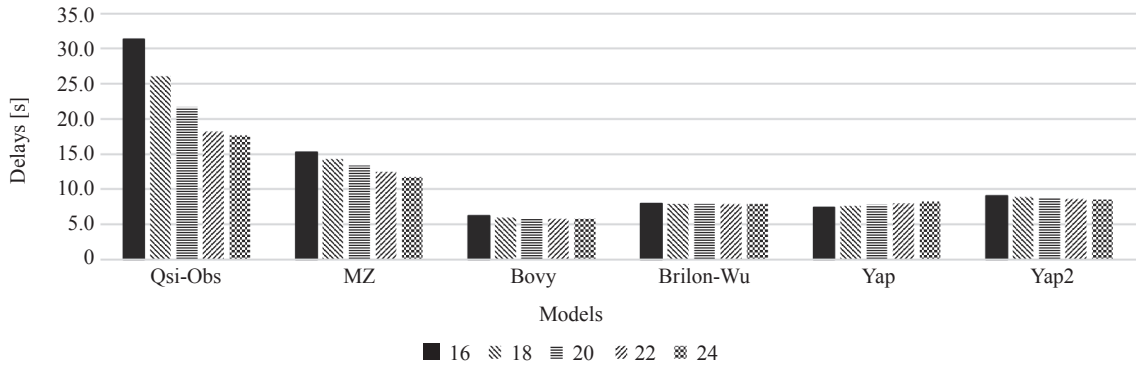

Figure 4 – Entry delays observed and calculated by different models
(Q_{Entry}=500 PCU/h, $Q_{Circulating}$=400 PCU/h, $Q_{Exiting}$=400 PCU/h, l_K between 16 to 24 m)

different exit-entry distances. By increasing the exit-entry length (from 16 to 24 m) the delay is decreasing (see Qsi-Obs on the *Figure 4*). However, when the distance between exit and entry is short (i.e., l_K=16), it is difficult for entry drivers to perceive the intention of the drivers on the circulation and exit flows, and the waiting time of entry drivers will increase resulting in the increased delay. This trend can be calculated by our proposed model (MZ model); however, other models are not able to incorporate the impacts of entry-exit length changes on the delay calculation.

5. CONCLUSIONS

It is a fact that only a certain percentage of drivers obey the rule that they must indicate their intention to exit the roundabout with the right-turn indicator. In order to consider this kind of behaviour of exiting drivers when estimating the entry capacity of roundabouts, this study proposes a new equation based on gap acceptance theory. It extends the most widely used model, Brilon-Wu's, which incorporates both circulating and exiting traffic flows. Microscopic simulation models of single-lane conventional roundabouts were used to generate quasi-observation data for different traffic conditions and roundabout geometries. Five different driving behaviour models according to the Erlang critical gap distribution have been used in the microscopic simulation models. Then, capacity and delay results estimated by the proposed model have been tested out and validated using quasi-observed data. Calculated delays were then compared with Bovy's and Yap's empirical models and Brilon-Wu's analytical model using RMSE index and regression analysis. The results prove that the proposed model outperforms these empirical and analytical models in terms of estimating delay and capacity for a single-lane conventional roundabout. With respect to the hypotheses mentioned during the development of the proposed model and the related case-based tests, the following conclusions can be made:

- The proposed model is the upgraded version of Brilon-Wu's model. Unlike the original model, it takes into account different driving behaviour on the exiting flow. Preliminary "quasi" validations show that the proposed model is more accurate than Brilon-Wu's model.
- The RMSE index and regression analysis results confirmed that the proposed model is able to calculate entry delay and capacity more accurately compared to Bovy, Brilon-Wu, Yap, and Yap2. The proposed model has the lowest RMSE value (0.36), and the highest R^2 value (0.80) in regression analysis compared to the existing models. Using t-statistics test, it is also shown that the proposed model outperforms the existing models with statistically significant improvement in estimating delay and capacity values.
- The entry delay results for different exit-entry distance, and flows (Q_{Entry}, $Q_{Circulating}$ and $Q_{Exiting}$) show that the proposed model is able to account for effects of different exit-entry distances on the capacity, and consequentially on entry delay calculations, as it can be seen from quasi-observation delay data, while other models produced the same results for different exit-entry distances.

Limitations and directions for further studies:

- The efficiency of the proposed model has only been tested on a single-lane conventional roundabout. Thus, the validity of the proposed

model for two or three-lanes roundabouts (on entry, circulating, and exiting flows) as well as turbo roundabouts needs further validation.

- As we currently cannot model the impact of the exit indicator in VISSIM simulations, in our validations we had to assume that none of the drivers show their exiting intention. For the future studies, development of custom driving behaviour model in VISSIM is planned, and extensive field data collection for real validation is needed.

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MODEL ZA OCENO PREPUSNOSTI KROŽIŠČ Z UPOŠTEVANJEM OBNAŠANJA VOZNIKOV PRI VHODU IN IZHODU IZ KROŽIŠČA

IZVLEČEK

Ocena prepustnosti krožišč je bila tema vrste raziskav v zadnjih desetletjih. Večina analiz bazira na empiričnih ali analitičnih modelih (npr. teorija sprejemljivih vrzeli), pri čemer upošteva različne vrste konfliktnih tokov (vhodni, krožni in izhodni tokovi). Vozniki na izvozu lahko upoštevajo ali pa ne upoštevajo pravila obvezne uporabe desnega smernega kazalca. Glede na pregledano literaturo vpliv voznikov, ki ne upoštevajo tega pravila, na prepustnost krožišča, ni dobro raziskan. Zato smo se odločili razviti analitični model, ki upošteva tudi del izvoznega prometnega toka. Ta model nadgrajuje model Brilon-Wu. Predlagani model je bil preverjen z uporabo "kvazi" opazovanih podatkov, ki so bili generirani z uporabo mikroskopskih simulacij. Rezultate smo primerjali z rezultati empiričnih modelov Bovy in Yap ter z analitičnim modelom Brilon-Wu za enopasovna krožišča. Z uporabo RMSE in regresijske analize smo dokazali, da predlagani model daje boljše rezultate kot do sedaj uporabljani modeli.

KLJUČNE BESEDE

krožišče; prepustnost; obnašanje voznikov; vhodni tok; izhodni tok; teorija sprejemljivih vrzeli.

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