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CAPACITY MODEL FOR SINGLE-LANE MINOR ENTRY AT TURBO-ROUNDABOUTS

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Abstract

Spirally arranged and physically separated traffic lanes in the circulatory carriageway of turbo-roundabouts force drivers to choose a particular entry lane and, subsequently, a circulatory traffic lane according to their intended destination. This specificity is taken into account in theoretical capacity models for two-lane turbo-roundabout entries typically evaluated by the lane-by-lane approach. Nevertheless, this specific path of movements is not considered in the most widely used capacity models for single-lane minor entries at oval turbo-roundabouts. In these models, only one entering traffic flow conflicted by two circulating traffic flows in front of the entry is considered. However, the entering traffic flow presents a mixed traffic flow of two movements (right-turning movement and left-turning and through movement) with different capacities due to different number of conflicting traffic streams and traffic volumes allocated into the outer and the inner circulatory lane. This fact is included in the capacity estimation for a single-lane minor entry presented in the article using the existing capacity formula for the mixed traffic flow on a shared minor lane at unsignalized intersections. The entry capacity reflects the proportion of the right-turning movement within a shared entry lane as well as the specific allocation of circulating traffic flow into the outer and the inner circulatory lane. This entry capacity is about 10 % to 30 % higher compared to a single-lane entry capacity estimated according to commonly used models described in the article. Higher entry capacity in a higher proportion of the right-turning traffic within mixed entry traffic flow is confirmed also by the results of average delays estimated by the theoretical delay model and microsimulation.

Keywords:

Capacity;
Turbo-roundabout;
Mixed traffic flow;
Delay.

1 Introduction

Most of capacity models for turbo-roundabout entries are based on empirical or gap acceptance models for roundabout entries. They have been used in several studies focused mainly on the major or minor two-lane turbo-roundabout entries typically evaluated by the lane-by-lane approach. These capacity models take into account spirally arranged and physically separated traffic lanes in the circulatory carriageway, where entering drivers, unlike standard two-lane roundabouts, have to choose the left or the right entry lane and then the inner or the outer circulatory lane according to their intended destination. This is included in the capacity calculation for each entry lane where the corresponding number of conflicting traffic streams in front of the entry lane is considered. Besides, some of the capacity models also consider the traffic flow redistribution into two circulatory traffic lanes and even gap time values for each entry lane or circulatory traffic lane.

In the case of oval turbo-roundabouts, minor entries consisting of a single-lane are estimated by most widely used capacity models assuming only one entering traffic flow conflicted by two circulating traffic flows in front of the entry. However, there is a situation similar to two-lane minor entries. Drivers entering the single-lane minor entry have to use a specific circulatory lane according to their movement, which results in a mixed traffic flow of two movements, see Fig. 1 – right-turning vehicles

$q_{e,R}$ entering the outer circulating lane and conflicted by one outer circulating traffic flow $q_{c,1}$, and left-turning and through vehicles $q_{e,LT}$ entering the inner circulatory lane and affected by both outer and inner circulating traffic flows $q_{c,i}$ and $q_{c,e}$. The capacities of these two entering movements are different due to different number of conflicting traffic streams and traffic volumes allocated into the outer and the inner circulatory lane.

This fact is taken into account in the capacity estimation presented in this article. First, six theoretical capacity models for a single-lane turbo-roundabout minor entry are described and compared. Subsequently, capacity estimation taking into consideration the mixed traffic flow of two movements on a shared entry lane as well as the specific allocation of circulating traffic flow into two circulatory lanes is presented with its analytical expressions. The capacity results of this model are compared based on the most used Hagring model. In the end, results of average delays estimated by the theoretical delay model and microsimulation confirming the influence of the right-turning movement proportion within a shared entry lane are shown.

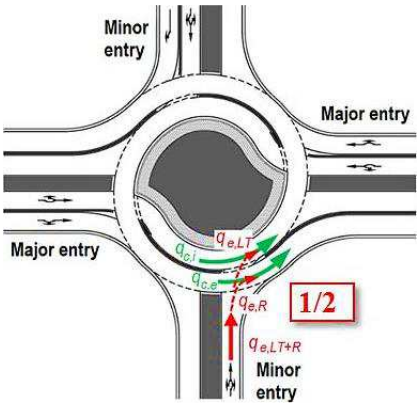


Fig. 1: Traffic flows on single-lane minor entry at turbo-roundabouts.

2 Capacity models for a single-lane minor entry

The capacity of a single-lane turbo-roundabout minor entry can be estimated through various capacity models that have already been developed worldwide and used in several studies. Most of them are adaptations of empirical or gap acceptance models originally proposed for roundabout entries and applied mainly for major or minor two-lane turbo-roundabout entries. Six theoretical capacity models for single-lane turbo-roundabout minor entry with their analytical expressions are described below.

HCM 2010 capacity model [1] was developed as an empirical regression model for capacity calculation of roundabout entry lanes based on field data obtained at the U.S. roundabouts. This exponential regression model has been verified for capacity evaluation of two-lane turbo-roundabout entries for example, within the studies [2, 3]. According to this model, the following equation gives the capacity of a single-lane roundabout entry conflicted by two circulatory traffic lanes:

$$C_{e,1/2} = 1130 \cdot e^{(-0{,}7*10^{-3})\cdot q_c}\ , \tag{1}$$

where: q_c – circulating traffic flow [pcu/h].

Wu capacity model [4] modifying the basic Tanner´s formula [5] is derived from the gap acceptance theory and combines the Cowan´s M3 headway distribution with a step acceptance function. This capacity model for roundabouts has been used for capacity estimation of two-lane turbo-roundabout entries for example, within the study [2]. The capacity estimation for a single-lane minor entry conflicted by two circulatory traffic lanes according to this model is possible by the following equation:

$$C_{e,1/2} = \frac{3600}{t_f} \cdot \left(1 - \frac{\Delta \cdot q_c}{3600 \cdot n_c}\right)^{n_c} \cdot e^{-\frac{q_c}{3600}\cdot\left(t_c - \frac{t_f}{2} - \Delta\right)}\ , \tag{2}$$

where: q_c – circulating traffic flow [pcu/h], n_c – the number of circulatory traffic lanes, n_c = 2 [-], t_c – critical headway [s], t_f – follow-up time [s], Δ – minimum gap time between vehicles on a circulatory carriageway [s].

Capacity comparison of a single-lane turbo-roundabout entry $C_{e,1/2}$ computed by the HCM 2010 model (1) and by the *Wu* capacity model (2) with the gap time values according to the Slovak technical guidelines [6]: t_c = 3.9 s, t_f = 2.7 s, Δ = 2.1 s, is shown in the chart in Fig. 2. Neither of these two capacity models takes into account a traffic flow allocation to the inner and the outer circulatory traffic lane. In both of them, capacity depends only on the total circulating traffic flow in front of the minor entry.

Fortuijn-Harte capacity model [7] is an empirical regression capacity model for turbo-roundabouts. This model is based on modification of the original Bovy linear regression model for roundabout capacity estimation [8] with parameters linked to the influence of exiting vehicles, the number of circulatory lanes, and entry lanes. These parameters were set for turbo-roundabouts by Fortuijn according to Dutch experiments [9]. Foftuijn divided the β parameter into two parameters b_{min} and b_{max} related to two circulating traffic flows, the smaller and the bigger respectively. The correction factor α of the influence of an existing flow was substituted by two parameters a_1 and a_2. This model allows a capacity calculation for different legs in various types of turbo-roundabouts, and it has been used, for example, in case studies of the transformation of a standard roundabout into a turbo-roundabout [10-13]. According to the Fortuijn-Harte model, the single-lane capacity of a minor entry is given by the following equation:

$$C_{e,1/2} = C_0 - b_{\min} \cdot q_{c,\min} - b_{\max} \cdot q_{c,\max} - a_1 \cdot q_S \ , \tag{3}$$

where: C_0 – main value of capacity equal to 1 550 pcu/h, $q_{c,\min}$ and $q_{c,\max}$ – the smaller and the bigger of the two circulating traffic volumes respectively [pcu/h], $b_{\min}$ and $b_{\max}$ – parameters related to the smaller and the bigger of the two circulating traffic flows respectively, $b_{\min}$ = 0.68 and $b_{\max}$ = 0.82, a_1 – parameter taking into account the distance of collision points at entry a_1 = 0.21, q_s – exiting traffic flow [pcu/h].

Although the Fortuijn-Harte capacity model takes into account the traffic flow redistribution into two circulatory lanes, there is no effect of specific allocation into the outer and the inner circulatory traffic lane as can be seen in Fig. 2. The capacity of single-lane minor entry is the same for the 75 % and 25 % proportion of circulating traffic flow in the outer circulatory lane, out/in = 75/25 = 25/75.

Brilon capacity model [14] is based on the Tanner´s basic idea [5] as well as the Wu model. However, this capacity model determined for turbo-roundabouts considers traffic flow allocation into two circulatory lanes, even though there is no specific allocation into the outer and the inner circulatory traffic lane as can be seen in Fig. 2 (out/in = in/out). The Brilon capacity model has been used in the capacity analysis of turbo-roundabouts in the study [15]. The formula for capacity estimation of a single-lane entry to the turbo-roundabout is as follows:

$$C_{e,1/2} = \frac{3600}{t_f} \cdot \left(1 - \frac{\Delta \cdot q_{c,i}}{3600}\right) \cdot \left(1 - \frac{\Delta \cdot q_{c,e}}{3600}\right) \cdot e^{-\frac{\left(q_{c,i} + q_{c,e}\right)}{3600} \cdot \left(t_c - \frac{t_f}{2} - \Delta\right)} \ , \tag{4}$$

where: $q_{c,i}$ and $q_{c,e}$ are traffic flows in the inner and the outer circulatory lane respectively [pcu/h].

Hagring capacity model [16] is the original multi-lane capacity model suitable for the evaluation of the entry lane capacity at turbo-roundabouts. For each conflicting stream on circulatory traffic lanes, the Cowan´s M3 headway distribution and differentiated behavioural and traffic flow parameters are assumed. The single-lane capacity of a turbo-roundabout minor entry can be calculated, under the assumption of Tanner´s bunching model for estimation of distribution parameter φ [22], and different values of t_c, t_f, and Δ for the outer and the inner circulatory traffic lane, by the formula:

$$C_{e,1/2} = \left(q_{c,i} + q_{c,e}\right) \cdot \left(1 - \frac{\Delta_i \cdot q_{c,i}}{3600}\right) \cdot \left(1 - \frac{\Delta_e \cdot q_{c,e}}{3600}\right) \cdot \frac{e^{-\left[\frac{q_{c,i}}{3600} \cdot \left(t_{c,i} - \Delta_i\right) + \frac{q_{c,e}}{3600} \cdot \left(t_{c,e} - \Delta_e\right)\right]}}{1 - e^{-\left[\frac{q_{c,i}}{3600} t_{f,i} + \frac{q_{c,e}}{3600} t_{f,e}\right]}} \ . \tag{5}$$

The Hagring capacity model, considering traffic flow allocation into two circulatory lanes, has been used with some simplifications in several capacity studies of turbo-roundabouts: [13, 17-21]. Two of them used different critical headway values $t_{c,i}$ and $t_{c,e}$ to estimate the left-lane capacity of two-lane turbo-roundabout minor entries [17, 18]. Although different critical headway values make the capacity model more sensitive to traffic flow redistribution to the inner and the outer circulatory lane, it is only

with little final effect. Due to this, the same values for both circulatory lanes were used for further capacity estimation.

Capacity comparison of a single-lane turbo-roundabout entry $C_{e,1/2}$ computed by the Fortuijn-Harte model (3), Brilon model (4) and Hagring model (5) with the same gap time values, t_c = 3.9 s, t_f = 2.7 s, Δ = 2.1 s, is shown in charts in Fig. 2. The insensitivity of all these models to the specific allocation into the outer and the inner circulatory traffic lane can be seen. In addition, none of these capacity models takes into account the effect of the right-turning ratio within entry traffic flow.

Mauro-Branco capacity model for turbo-roundabouts [23] is a modification of the *Wu* capacity model for roundabouts [4] based on the gap acceptance theory. First, this model separately evaluates the capacity of the right-turning movement $C_{e,R}$ into the outer circulatory lane and the capacity of the left-turning movement $C_{e,LT}$ into the inner circulatory lane according to (6) and (7). This model assumes only one circulatory lane for both capacity calculations n_c = 1, and differentiates the circulating traffic flow q_c and gap acceptance values of t_c, t_f, and Δ for the right-turning movement and the left-turning movement:

$$C_{e,R} = \frac{3600}{t_{f,R}} \cdot \left(1 - \frac{\Delta_R \cdot q_{c,e}}{3600}\right) \cdot e^{-\frac{q_{c,e}}{3600} \cdot \left(t_{c,R} - \frac{t_{f,R}}{2} - \Delta_R\right)}, \tag{6}$$

$$C_{e,LT} = \frac{3600}{t_{f,LT}} \cdot \left(1 - \frac{\Delta_{LT} \cdot \left(q_{c,i} + q_{c,e}\right)}{3600}\right) \cdot e^{-\frac{\left(q_{c,i} + q_{c,e}\right)}{3600} \cdot \left(t_{c,LT} - \frac{t_{f,LT}}{2} - \Delta_{LT}\right)}, \tag{7}$$

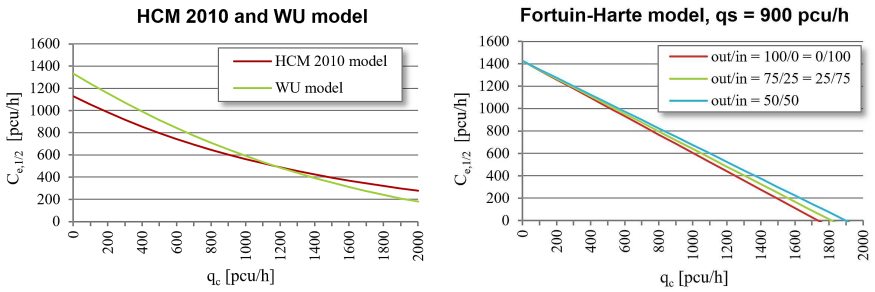
where: $t_{c,R}$ = 4.1 s, $t_{f,R}$ = 2.6 s, and Δ_R = 2.0 s are values for the right-turning movement and $t_{c,LT}$ = 4.5 s, $t_{f,LT}$ = 3.0 s, and Δ_{LT} = 1.0 s are values for the left-turning movement.

For the overall capacity calculation of the single-lane minor entry to the turbo-roundabouts, the Mauro-Branco model uses existing capacity formula for the mixed traffic flow on a shared minor lane at unsignalized intersections according to HCM [1]:

$$C_{e,1/2} = \frac{q_{e,LT} + q_{e,R}}{\frac{q_{e,LT}}{C_{e,LT}} + \frac{q_{e,R}}{C_{e,R}}}, \tag{8}$$

where: $q_{e,LT}$ and $q_{e,R}$ are the left-turning and through traffic volume, and the right-turning traffic volume within a single-lane entry.

Only the Mauro-Branco model of the models above takes into account the mixed traffic flow at the entry consisting of two traffic movements with different capacities due to different conflicting traffic volumes. This results in a higher sensitivity of the entry capacity to the traffic flow allocation to two circulatory lanes (out/in) and the right-turning movement proportion R in % – see Fig. 2. Thus the overall capacity of a shared single-lane entry according to this model is higher at a higher right-turning movement proportion due to the higher capacity of the right-turning movement with only one conflicting traffic flow in the outer circulatory lane. However, it should be pointed out that this model assumes only one circulating lane with the follow-up headway of 1.0 s and a total circulating traffic flow without allocation to the inner and the outer circulating lane for the capacity estimation of the left-turning movement $C_{e,LT}$ in (7).



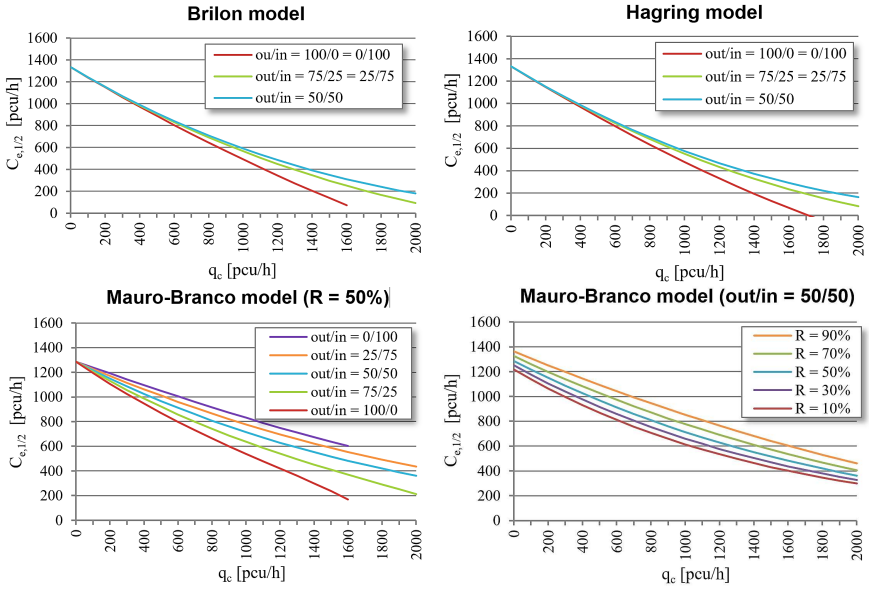


Fig. 2: Sensitivity of capacity models to traffic flow allocation to two circulatory lanes (out/in) and right-turning entry traffic proportion *R* in %.

3 Evaluation of mixed traffic flow capacity on a shared entry lane

Based on the knowledge achieved from the previously described capacity models, proposed capacity estimation for a single-lane minor entry takes into account specifics of turbo-roundabouts, mixed traffic flow of two movements on a shared entry lane, and also redistribution of traffic flows on the circulatory carriageway.

First, the capacity of the right-turning movement $C_{e,R}$ conflicted by one opposing traffic flow in the outer circulatory lane and the capacity of the left-turning and through movement $C_{e,LT}$ conflicted by two opposing traffic flows in both circulatory lanes were calculated according to the following equations based on the Hagring capacity model:

$$C_{e,R} = q_{c,e} \cdot \left(1 - \frac{\Delta \cdot q_{c,e}}{3600}\right) \cdot \frac{e^{-\left[\frac{q_{c,e}}{3600}\cdot(t_{c,R}-\Delta)\right]}}{1-e^{-\left(\frac{q_{c,e}}{3600}\cdot t_{f,R}\right)}}, \tag{9}$$

$$C_{e,LT} = \left(q_{c,i} + q_{c,e}\right) \cdot \left(1 - \frac{\Delta \cdot q_{c,i}}{3600}\right) \cdot \left(1 - \frac{\Delta \cdot q_{c,e}}{3600}\right) \cdot \frac{e^{-\left[\frac{q_{c,i}+q_{c,e}}{3600}\cdot(t_{c,LT}-\Delta)\right]}}{1-e^{-\left(\frac{q_{c,i}+q_{c,e}}{3600}\cdot t_{f,LT}\right)}}, \tag{10}$$

where: $q_{c,i,}$ and $q_{c,e}$ are traffic flows in the inner and the outer circulatory lane respectively [pcu/h]. Values of t_c and t_f for the right-turning movement and for the left-turning and through movement were assumed: Δ = 2.1 s, $t_{c,R}$ = 4.0 s, $t_{c,LT}$ = 3.9 s, and $t_{f,R}$ = 2.8 s, $t_{f,LT}$ = 2.7 s. These values are set for the left lane and the right lane of turbo-roundabout minor entry in the Slovak technical guidelines [6].

The dependence of a movement capacity on the traffic volume proportion in the outer and inner circulatory lanes (out/in) is shown in Fig. 3. The capacity of the right-turning movement $C_{e,R}$ strongly depends on the traffic allocation to the outer and the inner circulatory lane. Unlike the Mauro-Branco model, the capacity of the left-turning and through movement $C_{e,LT}$ also depends on the circulating traffic flow redistribution.

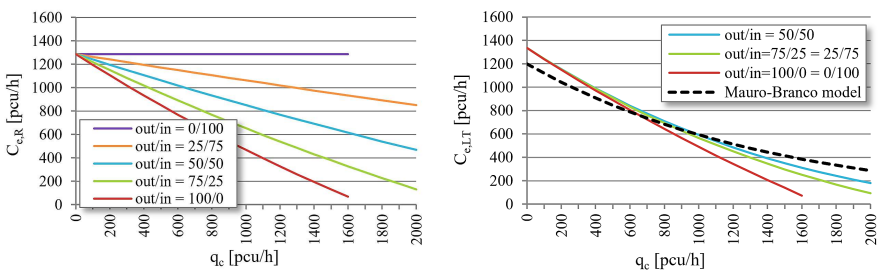


Fig. 3: Influence of circulating traffic flow redistribution on movement capacity.

Subsequently, the overall capacity of the mixed traffic flow of two traffic movements on a shared minor lane at a turbo-roundabout $C_{e,1/2}$ can be calculated according to *Wu* [24] by the following formula:

$$C_{e,1/2} = \frac{q_{e,LT} + q_{e,R}}{x_{LT+R}}, \tag{11}$$

with the definition of the degree of saturation for shared lane:

$$x_{LT+R} = \frac{q_{e,LT}}{C_{e,LT}} + \frac{q_{e,R}}{C_{e,R}}. \tag{12}$$

The overall capacity of the shared entry lane estimated by (11) reflects the proportion of the right-turning traffic. It is about 10 % to 30 % higher in comparison to the capacity of the single-lane turbo-roundabout entry calculated by the Hagring model by (5) in real condition of traffic patterns. The difference depends on the proportion of the right-turning movement, traffic volume on the circulatory carriageway, and its redistribution to two circulatory lanes. The comparison of these two capacity models, if an equal traffic flow allocation to the inner and the outer circulatory lane is considered (out/in = 50/50), is shown in Fig. 4 on the left. To illustrate the single-lane entry capacity for different allocation of total circulating traffic volume 1 000 pcu/h to the inner and the outer circulatory lane (out/in), the 3-D plot for a whole range of the right-turning movement proportion at the entry lane (R = 0 % to 100 %) was created (see Fig. 4 on the right). Theoretical capacity ranges from 500 pcu/h to 1,300 pcu/h. Of course, in reality there are no such extreme boundary conditions.

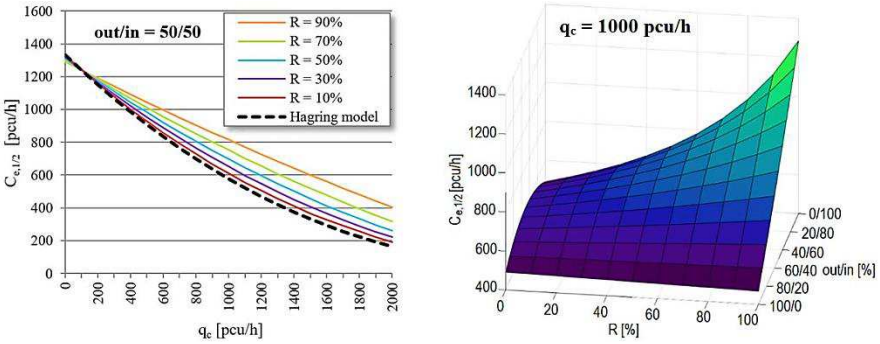


Fig. 4 – Influence of right-turning traffic proportion *R* in % and circulating traffic flow redistribution (ou/in in %) on the capacity of single-lane minor entry $C_{e,1/2}$.

Because the level of service for intersections is determined based on average delay, the influence of the right-turning proportion within the mixed-entry traffic flow on an average delay is presented in Fig. 5. This has been estimated under the assumption of the total circulating traffic volume of 1,000 pcu/h with an equal traffic flow redistribution into the outer and the inner circulatory lane out/in = 50/50, for different entry traffic volume $q_{e,LT+R}$ and different proportion of the right-turning movement, *R* in %. Considering only one entering traffic flow conflicted by two circulating traffic flows in front of the entry (Hagring model), there is no influence of the right-turning traffic proportion. In contrast, considering the mixed traffic flow of two entry movements with different capacities, the influence of the right-turning proportion is evident.

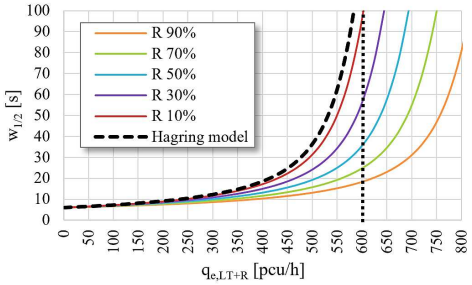


Fig. 5: Influence of the right-turning traffic proportion on an average delay, q_c = 1 000 veh/h, out/in = 50/50.

Due to the current capacity manuals containing no methodologies to estimate average delays for two movements within a shared entry lane, a new approach by Wu and Brilon for a shared lane on the minor street at unsignalized intersections [25] has been applied in this article. According to this new delay model, two average delays for two movements *LT* and *R* in the shared lane are calculated according to the formulas below, considering the relevant service time and assuming an M/G/1 queueing system with the means and the variances of the service times for each movement.

In this paper, the following formula to calculate the average delay of the left-turning and through movement *LT* within a shared lane at a minor turbo-roundabout entry was used:

$$w_{1/2,LT} = b_{LT} + 900T\left[(x_{LT+R}-1)+\sqrt{(x_{LT+R}-1)^2+\frac{8\cdot x_{LT+R}}{C_{e,1/2}\cdot \mathrm{T}}\cdot C_{0,LT+R}}\right], \quad (13)$$

and the following formula for the right-turning movement *R* within a shared lane:

$$w_{1/2,R} = b_{R} + 900T\left[(x_{LT+R}-1)+\sqrt{(x_{LT+R}-1)^2+\frac{8\cdot x_{LT+R}}{C_{e,1/2}\cdot \mathrm{T}}\cdot C_{0,LT+R}}\right], \quad (14)$$

with parameter $C_{0,LT+R}$:

$$C_{0,LT+R} = \frac{1}{2}\left(1+\frac{var(b_{LT+R})}{b_{LT+R}{}^2}\right), \quad (15)$$

where: the mean value of the service time of the left-turning and through movements *LT*, the right-turning movement *R*, and the shared lane *LT+R* are:

$$b_{LT} = \frac{3600}{C_{e,LT}} \qquad b_R = \frac{3600}{C_{e,R}} \qquad b_{LT+R} = a_{LT}\cdot b_{e,LT} + a_R \cdot b_{e,R}\ , \quad (16)$$

and the variance of the service time for the shared lane *LT+R* is:

$$var(b_{LT+R}) = a_{LT}\left[\left(\frac{3600}{C_{e,LT}}\right)^2+\left(\frac{3600}{C_{e,LT}}-b_{LT+R}\right)^2\right]+a_R\left[\left(\frac{3600}{C_{e,R}}\right)^2+\left(\frac{3600}{C_{e,R}}-b_{LT+R}\right)^2\right], \quad (17)$$

here: a_{LT} and a_R are the proportions of the left-turning and through movement *LT* and the right-turning movement *R* respectively.

A significant influence of the right-turning movement proportion on an average delay at the single-lane minor entry to the turbo-roundabout has been proven also by microsimulation results, Fig. 6. A microscopic model of an oval turbo-roundabout created and calibrated in the PTV Vissim within the case studies [19, 26, 27] was used for these purposes. Simple traffic conditions at a single-lane minor entry within this model were simulated, specifically: the total entry traffic volume of 600 veh/h with a different right-turning proportion *R* = 10 %, *R* = 50 %, *R* = 90 %, and the total circulating traffic volume of 1 000 veh/h with an equal traffic flow redistribution into the outer and inner circulatory lanes. The time period for evaluation was 3 600 s; however, the simulation period was set for 4 200 s with a warm-up period of 600 s. The values of microsimulation results are the average values of 10 simulation runs with 10 different values of Random Seed.

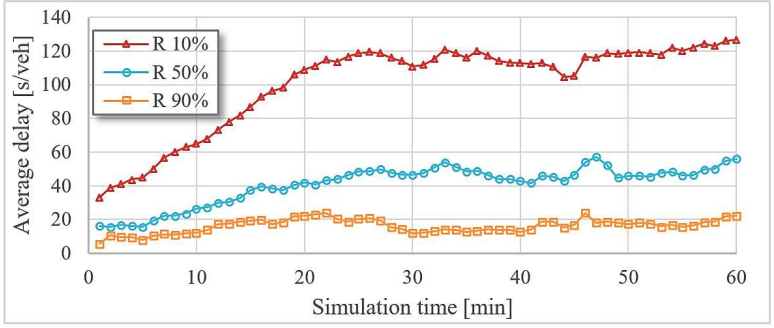


Fig. 6: Mmicrosimulation results: influence of the right-turning traffic proportion on average delay, q_e = 600 veh/h, q_c = 1 000 veh/h, out/in = 50/50.

4 Conclusion

The results presented in this paper indicate that in the capacity model for a single-lane minor entry at turbo-roundabouts, the entry should be treated as a shared entry lane with the mixed traffic flow of two movements rather than one entry traffic flow. This is caused by different capacities of these two movements due to the different number of conflicting traffic streams and traffic volumes allocated into the outer and the inner circulatory lane. This results in a higher sensitivity of the entry capacity model to the traffic flow allocation to two circulatory lanes and the right-turning traffic proportion.

Thus the overall capacity of a shared single-lane entry according to the presented model is about 10 % to 30 % higher at a higher right-turning traffic proportion due to the higher capacity of the right-turning movement with only one conflicting traffic flow in the outer circulatory lane. This is confirmed also by the results of average delays estimated by the theoretical delay model and microsimulation. In this paper, a new delay model by Wu and Brilon originally proposed for a shared lane on the minor street at unsignalized intersections has been used due to the fact that it better reflects the interaction of vehicles of two streams within the mixed traffic flow.

Thanks to the fact that the capacity model considers two movements within the mixed traffic flow, there is a possibility to estimate the capacity of a shared-short lane on minor turbo-roundabout entries. The use of these types of turbo entries in practice is not uncommon, but so far no papers have been published about this topic.

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