The Comparison of Models for Critical Headways Estimation at Roundabouts

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Abstract The basic parameters that determine traffic capacity on the roundabouts entries include in particular values of main traffic intensity in the collision area on the circular roadway at an entry and two parameters that characterize the process of vehicles entering the roundabout from the entries, such as critical headway and follow-up headway. The paper presents a comparative analysis in terms of studies connected with determination of critical headways for drivers of vehicles at the entries of single-lane roundabouts, two-lane roundabouts and turbo roundabouts.

Keyword Critical headway · Roundabouts · Gap acceptance theory · Traffic engineering

1 Introduction

It is adopted that the critical headway for drivers of vehicles moving from the roundabout entry (tg) is the value of headway between the vehicles in the main stream such that each headway with the value equal or greater will be used for performing a manoeuvre of entering the roundabout lane by the respective driver from the subordinated entry (average in statistic terms) whereas each distance with value lower (that prevents performing the intended manoeuver) cannot be used. Critical headway is not a constant value. It adopts different values for different drivers and for each driver at different times. Critical headway is a random variable, with its value depending on the characteristics of human and vehicle and geometrical and movement conditions of the intersection, which can be characterized by probability distribution.

In the models used for determination of traffic capacity of the entries to intersections with right of way and roundabouts based fully or partially on gap acceptance theory, the critical headway and follow-up headway (t_f) are the basis

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parameters of the decision-making process in organization of vehicle traffic. These parameters usually represent the average behaviours in a population of drivers. In more extended models used in the literature, based on complex probability distributions, the number of model parameters increases. For example, in models based on the Cowan's M3 distribution, apart from parameters t_g and t_f, determination of two other parameters is also needed. These are values of minimal headways between vehicles in the main stream and the share of vehicles moving freely. This group of models includes the models presented in a study [1].

There are a number of studies concerning various problems connected with traffic on roundabouts [2–16]. The paper presents an analysis in terms of studies connected with determination of critical headways for drivers of vehicles at the entries of roundabouts. Due to the very rich set of studies published so far, the focus was on the most important and most popular models and the most recent studies in this field.

2 Methods of Determination of Numerical Values of Critical Headways

Values of critical headway are not measured directly. They can be determined directly based on the headways rejected and headway accepted by individual drivers from the entries. Therefore, apart from typical errors connected with performing measurements, evaluation of this parameter also involves the error that results from indirect method of determination. This fact caused the development of many different methodologies and techniques to determine the consistent and unbiased estimator of the critical headway. There were over thirty various techniques and methods used for evaluation of critical headway at the intersections without traffic lights. Individual methods of estimation often yield very different values of critical headway. The most popular and the most frequently used techniques and methodologies for determination of critical headways are [17–20]:

- Method by M. Raff and Hart based on cumulative curves. It is one of the first methods of estimation, where cumulative curves of rejected and accepted headways are construed. The value t_g is read at the location of intersection of the curves. Therefore, t_g is the value of the headway for which the number of headways accepted shorter than this value is equal to the number of headways rejected longer than this value. According to this method, critical headway corresponds to median (the second quartile, medium value).
- Graphical techniques that use the gap acceptance curve (e.g. Harders method, Blunden method, Ashworth method with correction that depends on the variance of distribution of individual critical headways). It is adopted that t_g corresponds to the value of 50 % of the acceptance curve. The acceptance curve is construed through determination of quotients of the headways accepted and the total of headways rejected and accepted for each class range of headways.

- The method of estimation for parameters of critical headway at the assumed type of probability distribution that uses the tools of mathematical statistics. These include: probit method, logit method and the method of highest credibility [22]. As explained in studies [18, 23], the method of highest credibility has a very high practical importance since it allows for obtaining estimators which are consistent, unbiased, best asymptotically efficient and linear with respect to random variables. The random distribution of the critical headway for the population of drivers is logarithmic-normal distribution which is characterized by the fact that it is rightward skewed and does not adopt negative values although it accepts occurrence of a short headway t_g.

There is a probability in the estimation procedure that t_g should occur between values of logarithms: the highest headway rejected by the driver and the headway accepted. This method assumes that the sample obtained from measurements represents the event with the highest probability possible, which is identical with the condition that credibility reaches maximum. The probability that t_g will be between the values of logarithms of the highest headway rejected by a driver and the headway accepted is evaluated from the equation [18, 22]:

$$L = \prod_{i=1}^{n} [F(a_i) - F(r_i)] \tag{1}$$

where:

$F(a_i)$	cumulative distribution function for headways accepted,
a_i	logarithm of the i headway accepted,
$F(r_i)$	cumulative distribution function for headways rejected,
r_i	logarithm of the i headway rejected.

The condition of the highest credibility is used for determination of the estimators of parameters of critical headway distribution, i.e. mean value $E(t_g)$ and variance $D^2(t_g)$. These estimators are a function of the parameters of logarithmic-normal distribution m and σ^2 and are evaluated using the following relationships:

$$E\left(t_g\right) = \bar{t_g} = e^{m + \frac{\sigma^2}{2}} \tag{2}$$

$$D^2\left(t_g\right) = E\left(t_g\right)^2 \cdot \left(e^{\sigma^2} - 1\right) \tag{3}$$

- The algebraic method that uses the relationship proposed by Drew [21] (this method is similar to the method by M. Raff and Hart):

$$t_g = t + \frac{(t_3 - t_1)\Delta t}{(t_2 + t_3) - (t_1 + t_4)} \quad [s] \tag{4}$$

where:

t_1 t_2, t_3, t_4, are values of headways which are searched in the sample so that they meet the condition that the number of headways accepted (t_1, t_2), lower than the specific value t is similar (or equal in ideal case) to the number of headways rejected (t_3, t_4) greater than the specific value t [s],

T time that corresponds to the beginning of the range where the values t_1, t_2, t_3, t_4 [s] were located,

Δt span of the time range [s].

- The method based on headway histograms. It is assumed that critical headway corresponds to the modal value in the test.
- Method by Weiss and Maradudin [24] that takes into consideration time loss incurred by drivers at the entries and drivers impatience. According to the assumptions of this method, the value t_g decreases with the increase in time loss incurred by drivers at entries. With the increase in time loss, drivers are willing to accept shorter headways, i.e. probability of acceptance of a headway is increasing and the following inequalities are true:

$$\eta_1(t_g) \leq \eta_2(t_g) \leq \ldots \leq \eta_n(t_g) \tag{5}$$

where:

$\eta_i(t_g)$ probability that the headway t_g will be accepted by the driver i at the entry.

- Method by Hagring [25] where t_g is obtained as an optimal value between the values of critical headway that ensures entering to the main roadway of the intersection with maximal safety and the critical headway accepted by the driver in the case of high values of time loss incurred at the entry (in this case, t_g is connected with risky and dangerous entering the circular roadway).
- Method by Siegloch for conditions of saturation with traffic [18] where the value t_g is evaluated from the function of using headways in the main streams.

In many cases, values of critical headways evaluated based on the above methods differ from each other.

3 Comparison of Models for Estimate Critical Headways at Roundabouts

Roundabouts are one of the more interesting road traffic arrangements, so they are frequently elements of multifaceted analysis (f. eg. [26–33]). Due to the importance of gap-acceptance and its impact on roundabouts capacity, a large number of critical headway researches and studies have been conducted. The selected studies characterizing the critical headway for drivers at one-lane roundabouts entries are presented in Table 1. Hagring [34] state that gap acceptance models can be classified as macro and micro approach. Macro approach applies to interactions between traffic streams and geometric considerations and micro approach applies to the driver level. The approach adopted in this article is based on micro analysis using detailed data of drivers behavior and vehicles trajectories. The main challenge of critical headway estimating is that the parameters of the distribution of the critical headways, can be estimated as a function of various explanatory variables like speeds of vehicles, traffic conditions, roundabout location, waiting time for a appear gap, type of vehicle and much more other factors. Depending on the structure of model, for estimation of parameters of the models a number of methods have been employed. For many modeling approaches the maximum likelihood method provides a lot of advantages and gave superior results. Taking into account estimating the critical headway at roundabouts, a number of studies have been conducted but focused mainly on one-lane roundabouts.

Table 1 Comparison of critical headway models for one-lane roundabouts

Country	Author	The model/value of the parameter t_g [s]	The applied calculation method
Australia	Troutbeck [35]	1.4–4.9 (average 3.1)	Regression method
Germany	Baier et al. [36]	For $13m \le D_z \le 24m$: 4.7	N.a.
	Brilon and Wu [37]	For $26m \le D_z \le 40m$: $t_g = 3.86 + \frac{8.27}{D_z}$ 4.07–4.18 (average 4.12)	Regression method
USA	HCM [38]	4.1–4.6 (average 4.35)	N.a.
	NCHRP 572 [39]	4.2–5.9 (average 5.10)	Maximum likelihood method. The probabilistic distribution for the critical headways is assumed to be log-normal
	HCM [40]	5.19	N.a.
	Xu and Tian [41]	For $19m \le D_z \le 37m$: $t_g = 5.21 - 0.00128 \cdot Q_{nwl}\ [s]$ 4.5–5.3 (average 4.85)	Maximum likelihood method
	Hainen et al. [42]	75th percentile: 2.8; median: 2.2	N.a.
Denmark	Greibe [43]	For urban area: 5.1, for rural area: 4.7	Regression method
Slovenia	Tollazzi [44]	Average 4.8	N.a.

(continued)

Table 1 (continued)

Country	Author	The model/value of the parameter t_g [s]	The applied calculation method
Poland	Guidelines from 2004 [45]	For $24m \le D_z \le 36m$: 4.5–5.0 (average 4.75)	Regression method
	Chodur [23]	For $28m \le D_z \le 44m$: $t_g = 1.92 \cdot t_f + 0.316 \cdot b_{wl} - 0.427 \cdot l_{pa} - 0.126 \cdot D_z - 0.00198 \cdot Q_{nwl}\ [s]$ 4.25–5.80 (average 5.03)	Regression method
	Macioszek [19]	For $22\ m \le D_z \le 45\ m$ and $4\ m \le l_{jr} \le 8\ m$: $t_g = 8.83 - 0.11 \cdot D_z - 0.09 \cdot l_{jr}\ [s]$ 3.16–6.05 (average 4.60)	Regression method
Italy	Gazzarri et al. [46]	For $28m \le D_z \le 55m$: 3.83	Maximum likelihood method
Spain	Romana [47]	3.3–3.5 (average 3.4)	N.a.
Portugal	Vasconcelos et al. [48]	3.2–3.7 (average 3.45)	Maximum likelihood method, Raff method, other methods
Israel	Polus et al. [49]	For $22m \le D_z \le 38m$: $t_g = \frac{(10.34 - 0.037 \cdot t_w)}{2.5}\ [s]$ 3.25–4.13 (for t_w = 60 s and t_w = 0 s), (average 3.69)	Logit method

where t_g—critical headway [s], Q_{nwl}—circulating flow [PCU/h], D_z—roundabout external diameter [m], l_{jr}—the width of main road of roundabout [m], l_{pa}—the width of the roundabout entry lane [m], t_f—follow-up headway [s], t_w—driver waiting time at the roundabout entry [s], b_{wl}—the distance between the collision points for: entering and exiting drivers from main road of roundabout [m], N.a.—non available

It can be concluded from Fig. 1 that mean value of the parameter t_g for all models is 4.40 s. The values t_g below the mean can be observed in such countries as Israel, Portugal, Spain, Italy, Australia and the USA (data from HCM 2000 [38]) and Germany (studies by Brilon and Wu [37]). Furthermore, the values of the parameter t_g which are higher than the average were found for such countries as Slovenia, Denmark, Poland and Germany (studies by Baier et all. [36]) and the USA (with is shown in the most recent studies cited in NCHRP 572 [39] and HCM 2010 [40].

Moreover, the potential impact one of psychotechnical parameter t_g on one-lane roundabout entry capacity estimate is examined by varying the parameter t_g from minimum to maximum limits under different circulating flows (Q_{nwl}). Critical gap value change between 2.2 and 5.2 s. This t_g values were adopted on the basis of various authors research presented in Table 1 (see Fig. 2). Follow-up parameter is assumed to be constants. As can be seen from Fig. 2 one-lane roundabout entry capacity is higher if smaller critical gap values are accepted by drivers. Therefore, more accurate determination of the critical headway value is very important because improves the accuracy of roundabout entry capacity estimation.

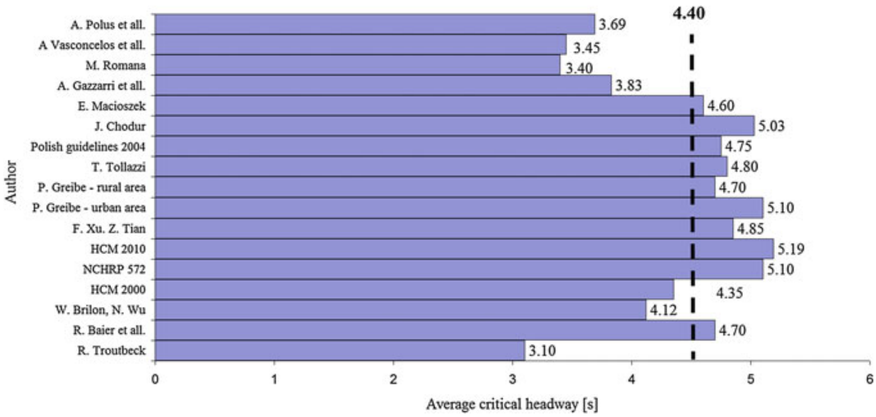
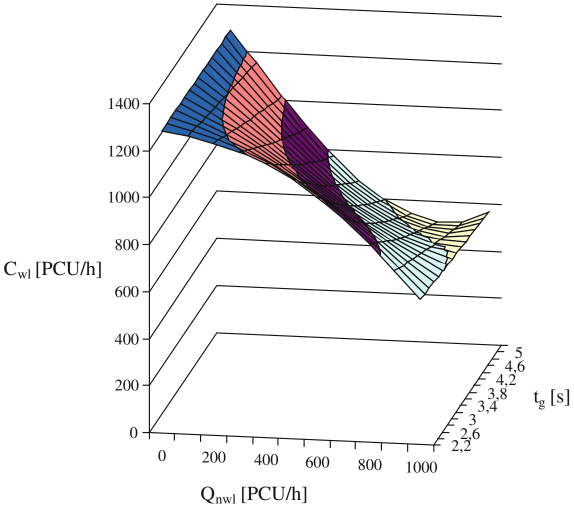


Fig. 1 Critical headways for one-lane roundabouts by different authors (*Source* Own)

Fig. 2 The change in one-lane roundabout entry capacity estimated with different values of parameter t_g (*Source* Own)



Fewer models and results of evaluation of the parameter tg compared to single-lane roundabout can be found in the literature for entries at two-lane roundabouts. Selected models of the parameter t_g for two-lane roundabouts were presented in Table 2. Table 2 shows that part of models were defined with accuracy of a single traffic lane at the entry and part of them concern only the general value of the parameter t_g for the whole entry.

It should be noted that for two-lane roundabouts the average values of critical headways are different by each entry lane and they are distinguished for the inner and outer circulating lanes. Figure 3 shows that mean value of the parameter tg for drivers from the right and left traffic lane at the entry of the two-lane roundabout amounts to 3.83 and 4.05 s. This means that the drivers from the right lane accept

Table 2 Comparison of critical headway models for two-lane roundabouts entry

Country	Author	The model/value of the parameter t_g [s]	The applied calculation method
Australia	Troutbeck [35]	– Dominant lane: 1.60–4.1 s (average 2.85), – Subdominant lane: n.a.	Regression method
Germany	Brilon and Geppert [50]	4.0	Maximum likelihood method
	Geppert [51]	4.0	Maximum likelihood method
USA	NCHRP 572 [39]	– Right lane: 3.4–4.9 s (weighted average 4.3 s, average 4.20), – Left lane: 4.2–5.5 s (weighted average 4.8 s, average 4.50)	Maximum likelihood method. The probabilistic distribution for the critical headways is assumed to be log-normal
	HCM [40]	– Right lane: 4.11 s, – Left lane: 4.29	N.a.
	Xu and Tian [41]	For $46m \leq D_z \leq 61m$: $t_g = 5.21 - 0.00128 \cdot Q_{nwl}\ [s]$. – Right lane: 4.0–4.8 s (average 4.42 s), – Left lane: 4.4–5.1 s (average 4.75 s)	Maximum likelihood method
	Li. et al. [52]	$t_g = 0,0345 \cdot V_{50th} + 4,4428\ [s]$ – Right lane: 3.6 s, left lane: 4.3 s	Regression method
Denmark	Greibe [43]	For rural area: 4.0	Regression method
Sweden	Swedish highway capacity manual [53]	For right and left traffic lane on entry: $t_g = 4.904 + \frac{0.090}{Q_{nwl}} - 0.52 \cdot l_d + 0.56 \cdot (z - 1) + 1.1 \cdot (u_c - 0.061)\quad [s]$ where: z = 1 for outer traffic lane on main road of roundabout, z = 2 for inner traffic lane on main road of roundabout – Right lane: 4.38 s, – left lane: 4.04–4.86 s (average 4.45)	Maximum likelihood method
	Hagring [25, 34]	– Right lane: 3.68–4.27 s (average 3.97),	Maximum likelihood method

(continued)

Table 2 (continued)

Country	Author	The model/value of the parameter t_g [s]	The applied calculation method
		– Left lane: 4.40–4.68 s (average 4.54)	
Poland	Guidelines [45]	For $D_z \geq 45m$: 3.9–4.1 (average 4.0)	Regression method
	E. Macioszek [1]	For $41.0\ m \leq D_z \leq 75.0\ m$ and $8.0\ m \leq l_{jr} \leq 11.5\ m$: – Right lane: 4.13–4.50 s (average 4.31), – Left lane: 3.99–4.36 s (average 4.17)	Regression method
Italy	Gazzarriet al. [46]	For $34m \leq D_z \leq 49m$: – Right lane: 3.64 s, – Left lane: 3.85 s	Maximum likelihood method
Spain	Romana [47]	3.3–3.5 (average 3.4)	N.a.
Portugal	Vasconcelos et al. [48]	3.2–3.7 (average 3.45)	Maximum likelihood method, Raff method, other methods
Turkey	Ersoy et al. [55]	2.84–3.21 (average 3.02)	Values obtained from Troutbeck's method [54] calibrated for Turkish conditions for $Q_{\mathrm{nwl}} \leq 1200$ PCU/h: $t_g = t_f \cdot \begin{pmatrix} 3.6135 - 3.137 \cdot 10^{-4} \cdot Q_{nwl} \\ -0.339 \cdot w_L - 0.2775 \cdot n_c \end{pmatrix}$ for $Q_{\mathrm{nwl}} > 1200$ PCU/h: $t_g = (3.2371 - 0.339 \cdot w_L - 0.2775 \cdot n_c) \cdot t_f$

where: u_C—the share of heavy vehicles in traffic stream [–], l_d—the length of weaving area [m], $V_{50\mathrm{th}}$—50th percentile speed [m/h], w_L—the average entry lane width [m], n_c—the number of circulating flow lanes [–]

lower headways between the vehicles on the circular roadway than the drivers of vehicles from the left lane at the entry. The values t_g which are over the mean value can be observed in such countries as Sweden, the USA and Poland (study by Macioszek [1]).

Such type of roundabouts like turbo roundabouts are fairly recent development and projects connected with critical headways have only been implemented in a few works (Table 3; Fig. 4). Parameter t_g depending on the scheme of conflict area with one or two circulating streams. So, the t_g values are calculated separately for left and right lane on turbo roundabouts entry. The entering vehicles are faced by one or two circulating streams depending on scheme of conflict area.

The study [20] presented the empirical examinations aimed at determination of the value of the parameter t_g on single-lane roundabouts. For the collected samples, the critical headway t_g was determined graphically based on cumulative curves of the accepted and rejected headways and acceptance gaps as well as by means of the D. Drew's method. Mean values and medians were also evaluated for individual samples of the accepted headways. Values of critical headways estimated using various calculation methods were presented in Table 4 and in Fig. 5.

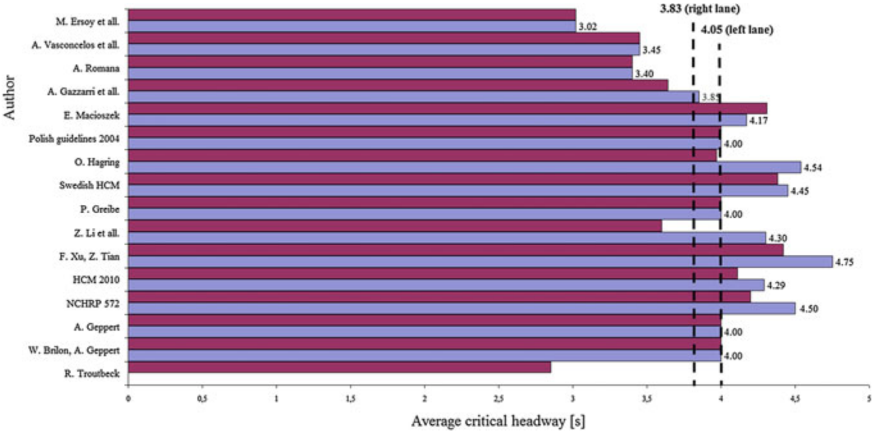


Fig. 3 Estimates of critical headway for two-lane roundabouts by different authors (*Source* Own)

Table 3 Comparison of critical headway models for turbo roundabouts entry

Country	Author	The model/value of the parameter t_g [s]	The applied calculation method
Netherland	Fortuijn [56]	– Right lane: 3.37–4.93 (average 4.15), – Left lane: 2.79–3.72 (average 3.25) depending on traffic control on entry	N.a.
Germany	Geppert [51]	4.0–4.5 (average 4.25) depending on traffic control on entry	N.a.
Poland	Macioszek [1]	– Right lane: 2.88–4.35 (average 3.61), – Left lane: 3.21–4.66 (average 3.93) depending on traffic control on entry	Regression method

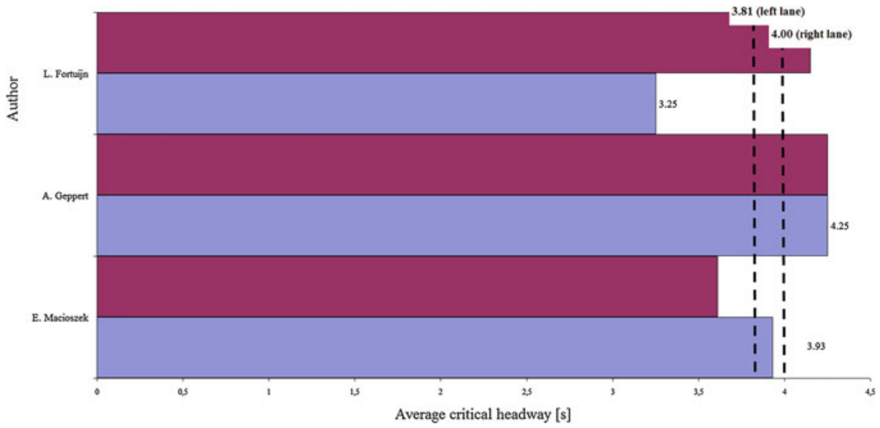


Fig. 4 Estimates of critical headway for turbo roundabouts by different authors (*Source* Own)

Table 4 One-lane roundabouts results comparison for different estimation method

The applied calculation method	One-lane roundabout number											
	1	2	3	4	5	6	7	8	9	10	11	12
Average values for each roundabout [s]	4.45	4.20	5.10	6.55	6.10	5.40	5.00	4.56	4.50	5.10	4.52	5.30
Median [s]	4.45	4.10	5.10	6.52	6.05	5.40	5.00	4.50	4.45	5.10	4.51	5.20
Drew equation [s]	4.44	3.60	4.51	6.10	5.58	4.48	4.50	4.16	4.20	4.38	3.82	4.40
The cumulative curves [s]	4.44	3.60	4.51	6.10	5.58	4.48	4.50	4.16	4.20	4.38	3.82	4.40
The acceptance curve [s]	4.44	3.60	4.51	6.10	5.58	4.48	4.50	4.16	4.20	4.38	3.82	4.40
Average for all roundabouts [s]	4.73											

Values of critical headways evaluated based on the above methods differ from each other. Critical headways estimated from cumulative curves for headways accepted and headways rejected, acceptance curves and using the D. Drew's method adopt the same values. However, these values are slightly lower than the values estimated as mean value and median of headways accepted (maximal difference of ±1.0 s).

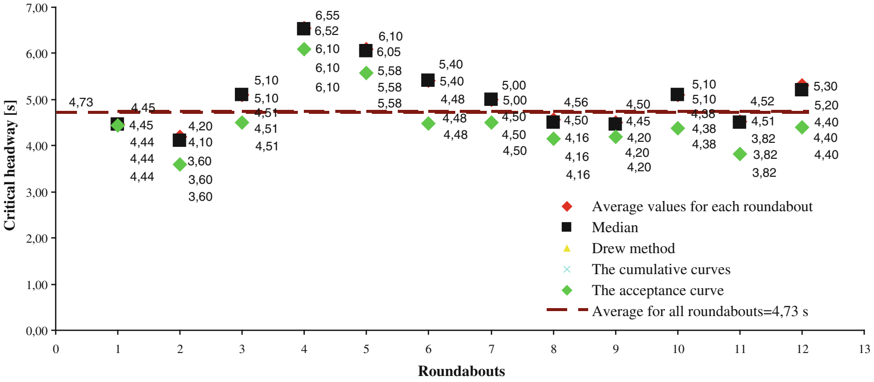


Fig. 5 One-lane roundabouts results comparison for each estimation method (*Source* Own)

4 Conclusions

The comparative analysis presented in the paper in terms of studies connected with determination of critical headways for drivers of vehicles at the entries to single-lane roundabouts, two-lane roundabouts and turbo roundabouts reveals that the values of the parameter tg obtained by individual authors differ from each other. These differences are in particular caused by the fact that values of this parameter cannot be measured in an indirect manner, which causes that, apart from the error connected with measurement, there are also errors that result from direct determination of the parameter tg. The values of the parameter tg presented in Tables 1, 2 and 3 were obtained by different methods such as regression, maximum likelihood method, logit method, Raff method, Troutbeck's and other methods.

Differences in the values of the parameter tg for individual countries are also caused by cultural diversity, differences in behaviours of drivers, their habits and customs. The consequence of this fact is difference in traffic capacity of roundabouts in individual countries. Therefore, the attempt to adapt the model used for determination of traffic capacity at entries of roundabouts built in a country to the conditions of another country requires previous calibration of the model, which should in particular concern psychotechnical parameters of drivers' vehicles at the entries of roundabouts i.e. critical headway and the follow-up headway.

References

1. Macioszek, E.: Modele Przepustowości Wlotów Skrzyżowań Typu Rondo w Warunkach Wzorcowych (Models of traffic capacity in roundabout inlets in ideal conditions). Open Access Library, Gliwice **3**(21), 1–260 (2013)
2. Macioszek, E.: The road safety at turbo roundabouts in Poland. Arch. Trans. **33**(1), 57–67 (2015)

3. Macioszek, E.: Relationship between vehicle stream in the circular roadway of a one-lane roundabout and traffic volume on the roundabout at peak hour. In: Mikulski, J. (ed.) Transport Systems Telematics 2014. CCIS, vol. 471, pp. 110–119. Springer, Heidelberg (2014)
4. Macioszek, E.: Turbo-roundabouts signing and marking—current situation in Poland. Arch Transp Syst Telematics **6**(1), 26–30 (2013)
5. Macioszek, E.: Analysis of the effect of congestion in the lanes at the inlet to the two-lane roundabout on traffic capacity of the inlet. In: Mikulski, J. (ed.) Activities of Transport Telematics. Communications in computer and information science, vol. 395, pp. 97–104. Springer, Heidelberg (2013)
6. Macioszek, E.: Geometrical determinants of car equivalents for heavy vehicles crossing circular intersections. In: Mikulski, J. (ed.) Transport Systems Telematics. Communications in computer and information science, vol. 329, pp. 221–228. Springer, Heidelberg (2012)
7. Macioszek, E.: Safe road traffic on roundabouts as an element assisting efficient road transportation system development in the upper Silesia region. In: Janecki, R., Krawiec, S., Sierpiński, G. (eds.) Contemporary Transportation Systems. Selected Theoretical and Practical Problems. The Transportation as the Factor of the Socio-Economic Development of the Regions, vol. 386, pp. 85–95. Silesian University of Technology, Gliwice (2012)
8. Macioszek, E.: Road traffic safety as an element creating mobility culture in cities. In: Janecki, R., Sierpiński, G. (eds.) Contemporary Transportation Systems. Selected Theoretical and Practical Problems. New mobility Culture, vol. 324, pp. 61–71. Silesian University of Technology, Gliwice (2011)
9. Macioszek, E.: The influence of motorcycling and cycling on small one-lane roundabouts capacity. In: Mikulski, J. (ed.) Transport Systems Telematics. Communications in computer and information science, vol. 239, pp. 291–298. Springer, Heidelberg (2011)
10. Macioszek, E., Sierpiński, G., Czapkowski, L.: Problems and issues with running the cycle traffic through the roundabouts. In: Mikulski, J. (ed.) Transport Systems Telematics. Communications in computer and information science, vol. 104, pp. 107–114. Springer, Heidelberg (2010)
11. Macioszek, E., Sierpiński, G., Czapkowski, L.: Methods of modeling the bicycle traffic flows on the roundabouts. In: Mikulski, J. (ed.) Transport Systems Telematics. Communications in computer and information science, vol. 104, pp. 115–124. Springer, Heidelberg (2010)
12. Macioszek, E.: The passenger car equivalent factor for heavy vehicles on roundabouts. In: Janecki, R., Sierpiński, G. (eds.) Contemporary Transportation Systems. Selected theoretical and practical problems. The development of transportation systems, vol. 256, pp. 127–137. Silesian University of Technology, Gliwice (2010)
13. Macioszek, E., Woch, J.: The follow-up time issue on small roundabouts. Transp. Probl. Int. Sci. J. **3**(3), 25–31 (2008)
14. Macioszek, E.: The movement model for small roundabouts with minor roads capacity estimating. Transp. Probl. Int. Sci. J. **2**(1), 87–94 (2007)
15. Szczuraszek, T., Macioszek, E.: Proportion of vehicles moving freely depending on traffic volume and proportion of trucks and buses. Baltic J. Road Bridge Eng. **8**(2), 133–141 (2013)
16. Szczuraszek, T., Macioszek, E.: Analiza Rozkładów Odstępów Czasu Pomiędzy Pojazdami na Obwiedni Małych Rond. Drogi i Mosty, Instytut Badawczy Dróg i Mostów, Warszawa **3**, 87–99 (2010)
17. Brilon, W., Vandehey, M.: Roundabouts-the state of the art in Germany. ITE J. (1998)
18. Brilon, W., Koenig, R., Troutbeck, T.: Useful estimation procedures for critical gaps. Transp. Res. Part A, **33**, 161–186 (1999)
19. Macioszek, E.: Model Ruchu na Małych Rondach dla Potrzeb Obliczania Przepustowości. Raport serii PRE, Wrocław, **15** (2007)
20. Macioszek, E.: Graniczny Odstęp Czasu Jako Jeden z Parametrów Procesu Decyzyjnego w Obsłudze Pojazdów z Wlotów Rond. Transport Miejski i Regionalny, Kraków, **2**, 8–16 (2009)
21. Drew, D.: Traffic Flow Theory and Control. Mc Graw-Hill Series in Transportation, New York (1968)

22. Troutbeck, R.J.: Estimating the Critical Gap Acceptance from Traffic Movements. Research report, Brisbane, **92**(5). (1992)
23. Chodur, J.: Funkcjonowanie Skrzyżowań Drogowych w Warunkach Zmienności Ruchu, Kraków, **347**, 1–205 (2007)
24. Hazim, N.G.: Badanie i Symulacja Ruchu Drogowego na Skrzyżowaniach Typu Rondo. Rozprawa doktorska, Wrocław, **273255** (1992)
25. Hagring, O.: Estimation of critical gaps in two major streams. Transp. Res. Part B, **34**(4), 293–313 (2000)
26. Celiński, I.: Trójwymiarowa Symulacja Procesów Ruchu Drogowego. Autostrady, Katowice, **1–2**, 53–57 (2016)
27. Młyńczak, J., Celiński, I., Burdzik, R.: Effect of vibrations on the behaviour of a vehicle driver. Vibroeng. Procedia, **6**, 243–247 (2015)
28. Młyńczak, J., Burdzik, R., Celiński, I.: Research on vibrations in the train driver's cabin during maneuvers operations. In: Awrejcewicz, J., Kaźmierczak, M., Olejnik, P., Mrozowski, J. (eds.) 13th Conference on Dynamical Systems Theory and Applications. Abstracts DSTA 2015, pp. 218. Łódź University of Technology, Łódź (2015)
29. Piecha, J., Staniek, M.: The context-sensitive grammar for vehicle movement description. In: Bolc. L., Tadeusiewicz, R., Chmielewski, L.J., Wojciechowski, K. (eds.) Computer Vision and Graphics. Lecture Notes in Computer Science, **6375**, part II, pp. 193–202. Springer-Verlag, Berlin (2010)
30. Płaczek, B., Staniek, M.: Model based vehicle extraction and tracking for road traffic control. In: Kurzyński, M., Puchała, E., Woźniak, M., Żołnierek, A. (eds.) Computer Recognition Systems 2. Advances in intelligent and soft computing, vol. 45, pp. 844–851. Springer-Verlag, Berlin (2007)
31. Sierpiński, G.: Model of incentives for changes of the modal split of traffic towards electric personal cars. In: Mikulski, J. (ed.) Transport Systems Telematics 2014. Telematics-support for transport, CCIS, vol. 471, pp. 450–460. Springer, Heidelberg (2014)
32. Sierpiński, G., Staniek, M., Celiński, I.: Research and shaping transport systems with multimodal travels–methodological remarks under the green travelling project. In: Proceedings of 7th international conference of education, research and innovation ICERI, pp. 3101–3107, Seville (2014)
33. Sierpiński, G.: Theoretical model and activities to change the modal split of traffic. In: Mikulski, J. (ed.) Transport Systems Telematics 2012. Telematics in the transport environment, CCIS, vol. 329, pp. 45–51. Springer, Heidelberg (2012)
34. Hagring, O., Rouphail, N.M., Sorensen, H.A.: Comparison of capacity model for two lane roundabouts. Transp. Res. Rec. **1852**, 114–123 (2003)
35. Troutbeck, R.J.: Evaluating the performance of a roundabout. Australian Road Research, Australia, **45** (1989)
36. Baier, R., Leu, P., Reinartz, A., Maier, R., Schmotz, M.: Ableitung von Einsatzbereichen und Grenzen von Minikreisverkehren. Final report FE 77.491/2008 for the Federal DOT. Germany (2011)
37. Brilon, W., Wu, N.: Kapazitaet von Kreisverkehren-Aktualisierung. Strassenverkehrstechnik, Fraunhofer, **5**, 280–288 (2008)
38. Transportation Research Board: HCM 2000, Washington (2000)
39. Transportation Research Board: NCHRP 572: Roundabouts in the United States. Washington (2007)
40. Transportation Research Board: HCM 2010. Washington (2010)
41. Xu, F., Tian, Z.Z.: Driver behavior and gap-acceptance characteristics at roundabouts in California. Transp. Res. Rec. **2071**, 117–124 (2008)
42. Hainen, A.M., Rivera-Hernandez, E.M., Day, C.M., McBride, M.T., Grimmer, G., Loehr, A.J., Bullock, D.M.: Roundabout critical headway measurement based on hi-resolution event-based data from wireless magnetometers. Trans. Res. Board **13–3316**, pp. 1–21 (2013)
43. Greibe, P.: Roundabout Design and Capacity. Denmark country report. In: Proceedings of 6th international symposium on highway capacity. Stockholm (2011)

44. Tollazzi, T.: The contribution to the procedure of capacity determination at unsignalized priority controlled intersections. Promet–Traffic, Zagreb, **16**(1), 31–36 (2004)
45. Generalna Dyrekcja Dróg Krajowych i Autostrad: Metoda Obliczania Przepustowości Rond. Instrukcja Obliczania. Warszawa (2004)
46. Gazzarri, A., Martello, M., Pratelli, A., Souleyrette, R.: Gap Acceptance Parameters for HCM 2010 Roundabout Capacity Model Applications in Italy. In: Pratelli, A. (ed.) Intersections control and safety. Transportation systems and traffic engineering, pp. 1–13. WitPress, Southampton, Boston (2013)
47. Romana, M. G.: Roundabout practice and research in spain. international roundabout design and capacity seminar. In: Proceedings of 6th international symposium on highway capacity. Stockholm (2011)
48. Vasconcelos, A.L.P., Seco, A.J.M., Silva A.M.C.B.: Comparison of procedures to estimate critical headways at roundabouts. Promet—Traffic and Transportation, Zagreb, **25**(1), 43–53. (2013)
49. Polus, A., Shiftan, Y., Shmueli-Lazar, S.: Evaluation of the waiting time effect on critical gaps at roundabouts by logit model. Eur. J. Transp. Infrastruct. Res. **5**(1), 1–12 (2005)
50. Brilon, W., Geppert, A.: Verkehrsqualitaet an zweistreifigen Kreisverkehren unter Berücksichtigung der Abbiegebeziehungen und aktueller Grenz-und Folgezeitluecken. Research Report FE, vol. 02.278/2006/ARB. Bochum (2012)
51. Geppert, A.: Verkehrsqualitat und Verkehrssicherheit an Zweistreifigen Kreisverkehren und an Turbokreisverkehren. Schriftenreihe. Lehrstuhl für Verkehrswesen, Bochum, **37**, 1–274 (2013)
52. Li, Z., DeAmico, M., Chitturi, M.V., Bill, A.R., Noyce, D.A.: Calibration of vissim roundabout model: a critical gap and follow-up headway approach. In: 92nd Annual Meeting TRB, pp. 1–23. Washington (2013)
53. Trivector Traffic A.B.: Capacity Model of Roundabout. Capacity Analysis (CAPCAL). Stockholm (2004)
54. Troutbeck, R.J.: A Review on the process to estimate the cowan M3 headway distribution parameters. Traffic Eng. Control, **38**(11), 600–603 (1997)
55. Ersoy, M., Celikoglu, H.B.: Capacity analysis on multi-lane roundabouts: en evaluation with highway capacity manual 2010 Capacity Model. Pamukkale Univ. J. Eng. Sci. **20**(6), 225–231 (2014)
56. Fortuijn, L.G.H.: Turbo roundabout. Estimation of capacity. Transp. Res. Rec. **2130**, 83–92 (2009) (Source: own)